DESIGN AND CONSTRUCTION OF A BAFFLED PLUG-FLOW ANAEROBIC DIGESTER IN A RURAL FARM IN TROPICAL SOUTHERN MEXICO

By

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To my wife, Ing. Martha Garcia Ramos, who gives me love, support and her time.

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Chairperson: Dr. Thomas Crisman
Cochairperson: Dr. David Chynoweth
Major Department: Environmental Engineering Sciences

A baffled plug-flow anaerobic digester was designed and constructed at a small ranch in southern Mexico. The purposes of the digester in the ranch were to sanitize wastes, provide an alternative renewable source of energy, compost for crop fields, and serve as a demonstration for local people.

Equipment developed for running laboratory small scale studies in the field proved to be adequate for giving an approximate idea of the production of methane for different organic matters (pig, goat, chicken, and liquid septic tank). The methane yield obtained in the field for a pig sample (250 mL CH_4 (g VS added)$^{-1}$) was lower than another pig sample run in a lab (400 mL CH_4 (g VS added)$^{-1}$) using the biochemical methane potential (BMP) technique. The higher

value obtained in the lab using the BMP assay was attributed to the more ideal conditions in the lab.

The full-scale digester installed at the ranch consists of three separate units: input chamber, digester and gas collectors. The 8,000 L unit is fed with wastewater, animal manures and VGF (vegetable, garden and fruit) wastes. The digester has a hydraulic retention time (HRT) of 24 d, a solids retention time (SRT) of 84 d, and a loading rate (L) of 4.5 kg VS m^{-3} d^{-1}. The 3,500 L estimated daily biogas production will be used for cooking. The high cost ($200 US m^{-3} including labor and materials) of the digester was due to the construction of the input chamber and the gas collectors as separate units.

The biggest problem found during the construction phase of the digester was that the flat movable concrete covers were too heavy for future manipulation and gas leaks were detected between the covers and the walls. These were replaced with metal sheet covers which formed a better hydraulic seal with the liquid.

Future work such as analysis for pathogen reduction, gas production and composition, material balance, and residue application will be done to evaluate the performance of the digester.

CHAPTER 1
INTRODUCTION

Objective

The objective of this project was to design and construct an anaerobic digester and determine its suitability at a small ranch southern Mexico. A literature review was conducted on different types of digesters that have been used for several applications in developing countries. The inexperience of the residents in implementing and running digesters was taken into consideration for the selection of the digester for our application. The proposed digester was tested at an experimental ranch in a real-scale design.

This ranch consists of 18 acres where 30 junior high and high school students live. The ranch has plantings of coffee, maize and beans. There are 65 animals including pigs, goats, and chickens. The ranch also has vegetable gardens and fruit trees (e.g., oranges, lemons, and bananas). All the wastewater and organic waste generated in the ranch will contribute to the feedstock for the digester. The methane generated from anaerobic digestion will be used for cooking. The liquid effluent and the solid residues will be used as fertilizers. The results of the operation of this digester, e.g., maintenance, biogas production, residues, durability of materials, economy, etc., will be compared with other digester designs (Gobar-Hindu and Chinese) that are already in operation close to the area of this project (Guatemala and South Mexico).

Rationale

Anaerobic digesters, also known as biogas plants, are reactors used for treatment of wastes and production of methane and compost and have a variety of environmental, economic, and social benefits. Digesters in Asiatic countries (China, India, and Taiwan) are commonly used as a source of energy (methane production) to decrease consumption of wood as a fuel. Treatment of human excreta to prevent diseases and production of soil conditioners and fertilizers are other reasons to use anaerobic digesters.

Lack of sanitation facilities in rural communities in southern Mexico is an important factor in disease and mortality among local people. In the study area, only 20% of the 215 rural Indian-Maya communities have a sewage system and none have a wastewater treatment facility (INEGI, 1990). As a consequence, 20% of the total mortality among people under 30 years old occurs because of sanitation problems, and more than 40% of infant mortality under one year old is caused by microbial-related diseases.

Villages, ranches, and small towns discharge their wastewater directly into the rivers without any treatment.

Besides the ecological impact of this discharge on the bodies of water, there are many families and small communities that use these rivers as a source of drinking water resulting in serious health problems. Communities that get their drinking water from springs or wells have serious problems of water contamination because of lack of appropriate disposal and treatment systems for human and animal feces. Spread of feces-related diseases is increased because livestock (e.g., chickens, pigs, dogs, etc.) roam the villages freely. Studies done by UNEP (1981) in Kenya have shown that, after digesters are installed in an area, there are significant declines in parasitic infections, enteritis, and bacillary dysentery (Gunnerson and Stuckey, 1986).

Anaerobic digestion may reduce the deforestation rate in developing countries by providing an alternative source of energy (methane gas) for cooking. According to Caceres and Chiliquinga (1985), the 1984 energy balance for Latin America revealed that firewood accounted for 19% of the total energy consumption, second to hydrocarbons. A study in India (Ravindranath et al., 1980) reported that 97% of the biomass energy comes from firewood, 80% of which is used for domestic cooking.

In addition, the health of the population using wood as an energy source is adversely affected. A typical Mayan family in Mexico (using firewood) generates soot and smoke inside the house causing respiratory and eye diseases. The use of a more efficient stove and another source of energy such as methane could improve the health of the family. Several other benefits would include the elimination of smoke discoloration in the house and the time savings for the wood gatherers who are generally the females of the household.

Besides the housework, the Indian women fill important roles in the agricultural activity mainly in the cultivation of bananas and squash, and other activities such as collection of wood for fuel and handcraft work (e.g., hammocks, blouses). Depending on the time invested in the collection of crop residues, manures, etc., for feeding the digester, the use of methane for cooking might improve the economy of the family by freeing time for other activities.

A properly managed anaerobic digester can generate a slurry which is suitable for conditioning and fertilization of soils. Many investigators have stated that the sludge produced by anaerobic digestion may have a fertilizer value greater than that of the original raw waste, that no offensive odors result when it is stored in lagoons or spread on land, and that rodents and flies are not attracted by the remaining solid or liquid residues (Fry, 1973, 1974; Meynell, 1978; NAS, 1981). Application of digested sludge over a period of years has provided continuing increase in crop production. It has led to significant increases in pore size, organic carbon and cation exchange capacity. This slurry can also be discharged into ponds where adequate aquaculture can be carried on.

The reasons that have been mentioned before are enough to justify the construction of digesters for the application addressed in this work. If this design (after testing) gives better results in the technical and economical aspects than other traditional digester designs (at experimental scale) that already exist in the area, the design at the ranch can be modified if necessary, and extended to the community level.

CHAPTER 2
REVIEW OF THE LITERATURE

Anaerobic Digestion

Anaerobic digestion is a process that provides anaerobic conditions and other appropriate operating conditions for a consortium of bacteria to decompose complex organic matter into methane and carbon dioxide. The advantages of anaerobic treatment are a high degree of waste stabilization, low production of waste biological sludge, low nutrient requirements, no oxygen requirements, and methane as a useful endproduct. Some disadvantages are: relatively high temperatures (30 to 35°C) are required for optimum operation in cold weathers; dilute wastes may not produce sufficient methane for waste heating; and the rate of growth of the methane-producing bacteria is slow, sometimes requiring long retention times for the process.

The degradation of organic matter to produce methane relies on the complex interaction of different groups of bacteria. The first group consists of a mixture of hydrolyzing and fermenting bacteria known also as hydrolytic bacteria. These hydrolyze the complex organics such as carbohydrates, proteins, and lipids to simple compounds such as short chain fatty acids, alcohols, carbon dioxide, ammonia, and some hydrogen. The second group of hydrogen-producing acetogenic bacteria convert the products of the first group into hydrogen, carbon dioxide, and acetic acid. The third group, known as methanogens, consists of two physiologically different groups of methane-forming bacteria, one converting hydrogen and carbon dioxide to methane, and the other forming methane from decarboxylation of acetate (McCarty, 1981). More recently, a fourth group of bacteria has been identified in the fermentation, the homoacetogenic bacteria, which ferments a wide spectrum of compounds such as hydrogen, carbon dioxide, and formate to acetate (Chynoweth, 1992). The anaerobic conversion to methane gas yields relatively little energy to the microorganisms. Thus their rate of growth is slow and only a small portion of the waste is converted to new cells, the major portion of the degradable waste being converted to methane gas (McCarty, 1964a).

Stable digester operation requires that these bacterial groups be in dynamic and harmonious equilibrium. Optimum conditions for anaerobic treatment are optimum temperature (mesophilic range: 30-38°C; thermophilic range: 50-58°C), anaerobic conditions, sufficient biological nutrients (nitrogen, phosphorous, etc.), optimum pH (6.6-7.6), and an absence of toxic materials (McCarty, 1964b). However, at lower temperatures (0-30°C) the fermentation occurs but at low rates. Changes in environmental conditions, such as temperature variations or shock loadings of substrate, can affect this equilibrium and result in the buildup of fatty acids and hydrogen which inhibit the overall process.

Important Variables in Digesters

pH

The methanogenic group of organisms is the most pH sensitive. Low pH can stop the chain of biological reactions in digestion. Acetate and other fatty acids produced during digestion tend to lower the pH of digester liquor.

However, the bicarbonate equilibrium in digesters exerts substantial resistance to pH change. This resistance or buffer capacity is quantified by the amount of strong acid (or base) added to the solution in order to bring about a change in pH. Thus the presence of bicarbonate and other bases helps prevent adverse effects on microorganisms (methanogens) which would result from low pH caused by excessive production of fatty acids during digestion. A bicarbonate alkalinity of 2,500 to 5,000 mg L^{-1} provides a desirable buffering capacity so that a large increase in volatile acids can be handled with a minimum drop in pH (McCarty, 1964b).

The system is also buffered by ammonia and phosphates. In general, free ammonia levels should be kept below about

80 mg L^{-1} to prevent inhibition (Gunnerson and Stuckey, 1986).

An "unbalanced digester" is defined as one which is operating at less than normal efficiency. In extreme cases the efficiency may decrease to almost zero in which case it is referred to as a "stuck" digester (McCarty, 1964b). Some indicators of unbalanced performance are: reduction in methane generation; increase in volatile acids concentration and carbon dioxide (CO_2) composition of the gas; and the decrease in pH, total gas production, and waste stabilization. A sudden increase in volatile acids concentration is considered an indicator of digester imbalance and often will lead to imbalance. Some factors causing unbalanced treatment are sudden change in temperature, organic loading, nature of waste, presence of toxic materials, drop in pH, and slow bacterial growth during start-up.

There are two main operational strategies for correcting an unbalanced low pH condition in a digester. First, stopping the feed slows the activity of the fermentative bacteria thereby reducing acid production and it gives time to the methanogenic population to reduce the fatty acid concentration, thus raising the pH to an acceptable level (around seven). A second strategy involves addition of chemicals such as calcium hydroxide (lime) to raise the pH and provide additional buffer capacity

(McCarty, 1964b; Gunnerson and Stuckey, 1986; Eckenfelder, 1989; Chynoweth, 1992).

Temperature

The rates of chemical and biochemical reactions tend to increase with temperature as do microbial growth rates. Excessively high temperatures, however, will cause the microbial metabolic rate to decline due to degradation (denaturing) of enzymes which are critical to cell metabolism. Methanogenic bacteria are more sensitive to changes in temperature than other organisms present in digesters (Gunnerson and Stuckey, 1986). The methane fermentation is classified at three different temperature ranges: psychrophilic (5-30°C), mesophilic (30-40°C), and thermophilic (45-60°C). An advantage of thermophilic digestion is that the rate of methane production is approximately twice that of mesophilic digestion, so reactors can be half the volume of mesophilic digesters, but some energy (CH_4) from digestion is required for maintenance of this higher temperature.

Nutrient Requirements and Feedstock

In addition to the need for an organic carbon energy source, methane bacteria appear to have relatively typical nutrient requirements for nitrogen and phosphorus, sulfur, and trace elements such as magnesium, sodium, manganese, calcium, potassium and iron. The bacteria also require cobalt, nickel and tungsten.

In general, most natural organic wastes can be digested except lignin. Biodegradability is usually measured as either percent carbon oxygen demand (COD) removal or percent volatile solids (VS) destruction and varies considerably for different feedstocks. For example, experiments done by Gunnerson and Stuckey (1986) show that the percent VS destroyed in cattle manure at a hydraulic retention time (HRT) of 80 days was 28.1%, and swine manure at a HRT of 15 days was 60.9%. Most of the common digester feedstocks contain a considerable portion of plant material, either added directly as crop residues or indirectly as animal manures. Many of the constituents of plant matter are highly biodegradable. Lignin, however, is essentially 100% refractory (Chynoweth, 1993, personal communication), and is believed to reduce biodegradability rates of carbohydrates to which it is linked. Since lignin is a major component of plants responsible for providing structural support to plant cell walls, it has a great effect on overall biodegradability of typical digester feeds. A good example to illustrate this is the biodegradability of peat that has a high lignin content and shows a small conversion, i.e., 11.1% of VS (Gunnerson and Stuckey, 1986). Since most common digester feeds are only 40 to 60% degradable, substantial increases in gas yield could be achieved if the substrate could be rendered 100% biodegradable. This is particularly true for feeds which contain a large amount of refractory lignocellulosics such as agricultural residues. Some methods for increasing biodegradability are: 1) physical-chemical methods that involve reaction with an acid or alkali at ambient or elevated temperatures (100 to 200°C). These methods do not appear to be economical due to the high cost of chemicals or heating equipment involved; 2) physical methods that include cutting, grinding or shredding of the feedstock to increase surface area for enzymatic attack; and 3) biological pretreatment methods which include aerobic composting, mainly used in China (UNEP, 1981). The latter method is obviously a widespread practice in developing countries although during the aerobic composting pretreatment a significant amount of organic matter that could be transformed in potential methane is lost.

Ammonia nitrogen and the portion of the organic nitrogen released during waste degradation are the forms used under anaerobic conditions for biological growth. Nitrogen present in the feedstock provides an essential element for synthesis of amino acids, enzymes and protoplasm; and it is converted to ammonia which, as a strong base, neutralizes the volatile acids produced by fermentative bacteria and thus helps maintain neutral pH conditions essential for cell growth. However, an overabundance of nitrogen in the substrate can lead to excessive ammonia formation, resulting in toxic effects. The carbon/nitrogen (C/N) ratio of 30 is often cited in the literature as optimum (Fry, 1974; UNEP, 1981; Chynoweth, 1992). Researchers have reported C/N ratios varied from about 1 for human or animal urine to from 5 to 10 for human feces, 7 to 15 for poultry or swine manure, 15 to 30 for sheep, and 20 to 35 for cattle and horse. Ratios for forage, grasses, hay, and water hyacinth are from about 10 to 30 and for straw and plant stalks from 30 to 150. Raw and rotted sawdust are about 500 and 200, respectively. Household garbage varies from 20 to 35. Optimum C/N ratios can be determined for specific cases. For feedstocks with non-optimum C/N ratios, adjustment of the ratio may improve performance or may even be essential for successful operation. For example, the C/N ratio of a feed could be empirically adjusted upwards by mixing it with a carbohydrate-rich material (e.g., straw added to nightsoil).

Animal manures are often selected as feedstocks because of the large quantity available and the need to treat these wastes throughout the world. In developing countries the primary substrate is cattle dung from large cattle populations (Gunnerson and Stuckey, 1986), although waste generated in urban areas of these countries (garbage, organic domestic and industrial wastes) are also good sources for anaerobic digestion. The range of biodegradability of animal waste is partly due to the diet of the animals. In developing countries where cattle are fed agricultural wastes, the manure is less biodegradable than wastes cattle from feedlots in the United States. Also, fresh manure is much more biodegradable than aged and/or dried manure because of the substantial loss of volatile solids over time. Cattle dung is a good substrate since it is moderately degradable and is well balanced nutritionally with a carbon/nitrogen (C/N) ratio of 25:1. However, swine and poultry manures produce even more biogas per unit weight and at higher rates than cattle manures. Human wastes (nightsoil), while high in nitrogen (C/N of 6), can also be digested easily, although carbohydrate wastes should be added to raise the C/N ratio and thereby provide more gas. Agricultural residues, such as wheat and rice straw are usually readily available, and while they have high C/N ratios, they can be digested in a mixture with manures and nightsoil. These wastes are usually quite biodegradable, and can be made more so by physical size reduction. However, problems can arise with these materials because they float in the digester and form hard scum layers on the surface. Plants such as water hyacinth, duckweed, kelp, etc., can also be degraded easily, and give quite high gas yields (Chynoweth, 1979, 1987, 1992). The best indication of organic waste strength is that given by laboratory anaerobic waste treatment studies. An indication of the relative concentration of carbohydrates, proteins, and fats in the waste is also helpful in anaerobic treatment evaluation (Chynoweth, 1979).

Toxicity

An essential nutrient can become toxic to organisms if its concentration in the substrate becomes too great. Toxic compounds affect digestion by slowing the rate of metabolism at low concentrations or by poisoning or killing the organisms at high concentrations. Two common indicators of failure are the reduction in methane yield over time and the increase in volatile acids concentration exceeding the normal range of about 250 to 500 mg L^{-1}. Many substances have been shown to be toxic or inhibitory to anaerobic digestion. Some of these, e.g., nitrogen, sodium, calcium, potassium, and magnesium, are stimulatory at very low concentrations but toxic at higher levels. The major toxicants usually encountered with natural feedstocks are ammonia, volatile acids, and heavy metals. There are also many organic materials such as alcohols and long-chain fatty acids that, in high concentrations, inhibit the digestion process.

Ammonia toxicity is often a problem in feedstocks with a high protein content. Ammonia is rapidly formed in a digester by decomposition of protein constituents. Free ammonia has been found to be much more toxic than ammonium ions, and the concentration of these forms are related by equilibrium reactions and pH. Free ammonia levels should be maintained below 80 mg L^{-1} while ammonium ions can generally be tolerated up to 1500 mg L^{-1} as N (Gunnerson and Stuckey, 1986). According to McCarty (1964c), if the concentration of ammonia-N is between 1,500 and 3,000 mg L^{-1}, and the pH is greater than 7.4 to 7.6, the ammonia gas concentration can become inhibitory.

High concentrations of volatile acids such as acetate, propionate or butyrate are associated with toxicity. It is not clear whether these acids are themselves toxic, or whether acid buildup ($pH < 6.8$) is merely a manifestation of toxicity (Gunnerson and Stuckey, 1986).

Certain heavy metals are toxic to anaerobic organisms, even at low concentrations. It is the soluble fraction that is the toxic form and toxicity is thus affected by the solubilities of heavy metals under various digester conditions. Many heavy metals form insoluble sulfides and phosphates. Thus the presence of sulfate and other sulfur forms in the feed can reduce the toxic effects of cadmium, nickel, lead, zinc, and copper during digestion. Some methods which can be used to control toxicity are 1) remove toxic substances from the feed; 2) dilute the feed to below the toxic threshold value; and 3) add chemicals to form a non-toxic complex or insoluble precipitate.

Gas Production

Methane is one of the major products of interest in digester operation. In anaerobic treatment, a portion of the organic waste is converted to biological cells, while the remainder is stabilized by conversion to methane and carbon dioxide. The quality of the biogas depends on the relative amounts of CH_4 and CO_2 ultimately produced. The methane content obtainable from a given feedstock material can be estimated if the average chemical composition of the feed is known. The proportion of methane to carbon dioxide in biogas depends on the substrate, and can be predicted by the Symons and Buswell's equation (McCarty, 1964a; Gunnerson and Stuckey, 1986; Chynoweth, 1987):

$$C_nH_aO_b) + (n - a/4 - b/2)H_2O \text{ ---> } (n/2 - a/8 + b/4)CO_2 + (n/2 + a/8 - b/4)CH_4$$

The results of methane in this equation are overestimated, and should be corrected for effects such as diversion of substrate into cell growth, and solubility of CO_2 in substrate. Chynoweth (1979) in his paper of "Anaerobic Digestion of Kelp", gives an example for calculating the maximum theoretical yield corrected by bacteria growth.

Pure methane has a calorific value of 38,102 Mj $(m^3)^{-1}$ at 15.5°C and one atmosphere; the calorific value of biogas varies from 20,098 to 28,890 Mj $(m^3)^{-1}$. In terms of energy equivalents, 1.33 to 1.87, and 1.5 to 2.1 m^3 of biogas are equivalent to one liter of gasoline and diesel fuel respectively.

Performance Parameters

Loading Rate

The loading rate determines the culture volume (the volume occupied by the liquid in the digester) required to process certain amounts of feedstock. This is generally expressed as lb volatile solids (VS) added $(ft^3)^{-1}$ d^{-1} or kg VS added $(m^3)^{-1}$ d^{-1}. For example, as the loading is increased, the digester size required for the operation will be decreased. Values found in existing literature for loading rates are around 3 kg VS added m^{-3} d^{-1} (Fannin et al., 1987; Meynell, 1978; Stafford et al., 1980; WPCF, 1987).

Retention Time

The retention of biomass solids, microorganisms, and biomass liquids is determined by reactor design, operating techniques and by feedstock composition. The retention time is generally expressed in days.

Hydraulic retention time. The hydraulic retention time (HRT) in anaerobic digesters is determined by calculating the number of days required for displacement of the fluid volume of the culture. At a given organic loading rate, the HRT is lower when using high-water-content feeds than when using those containing less water. When undiluted feed is used, the HRT in a digester operated at a given organic loading rate is a function of the water content of the biomass. The solids content of different biomass feeds determines the HRT.

Solids retention time. The solids retention time (SRT) is determined by reactor design, operating techniques, and by feedstock composition. Long SRTs can be attained by reducing the loading rate or by retaining the solids but removing the liquid. This latter procedure permits both long SRTs and short HRTs.

Microorganisms retention time. One important method for stabilization of the biomass digester at very short HRT is to promote the retention of microorganisms (MRT) in the system. Increased microorganism retention prevents development of imbalance by preventing washout of slow-growing methanogenic bacteria. Microorganism retention can be accomplished by employing attached film or some other microorganism-retaining reactor.

Methane Yield and Methane Production Rate

Since the ultimate products of biomethanation are methane and carbon dioxide, gas production is the primary indicator of overall performance. The methane yield is calculated from methane content data based on gas production. This parameter (methane yield) relates the quantity of methane produced to the amount of organic matter added, and represents ultimate yield at long hydraulic retention times (Chynoweth, 1979). The methane yield is expressed as m^3 (kg VS added)$^{-1}$ or ft^3 (lb VS added)$^{-1}$.

The methane production rate (MPR) is a measurement of the rate of the overall process and is expressed as methane volume per unit culture volume (not digester volume) per day. The MPR can be calculated with the following equation:

$$MPR = (M_y)\ (L)$$

where

MPR = methane production rate, $m^3\ (m^3)^{-1}$ culture-day

M_y = Methane yield, m^3 (kg VS added)$^{-1}$

L = kg VS added (m^3 culture-day)$^{-1}$

Materials Balance

Because mass is neither created nor destroyed, a mass balance affords a convenient way of defining what occurs within the system as a function of time. Carbon and energy balances are usually calculated in the system (Chynoweth, 1979). The total carbon in the input should equal the carbon in the digested solids plus the carbon in the gas produced (methane and carbon dioxide). Around ten percent difference is accepted as a valid data. The same principle applies for energy balance.

Reactor Designs

Maximizing methane yields and optimizing production rate, increasing process stability, decreasing processing energy requirements, and decreasing digester costs through simplification of design and operation should be the goals for digester's design.

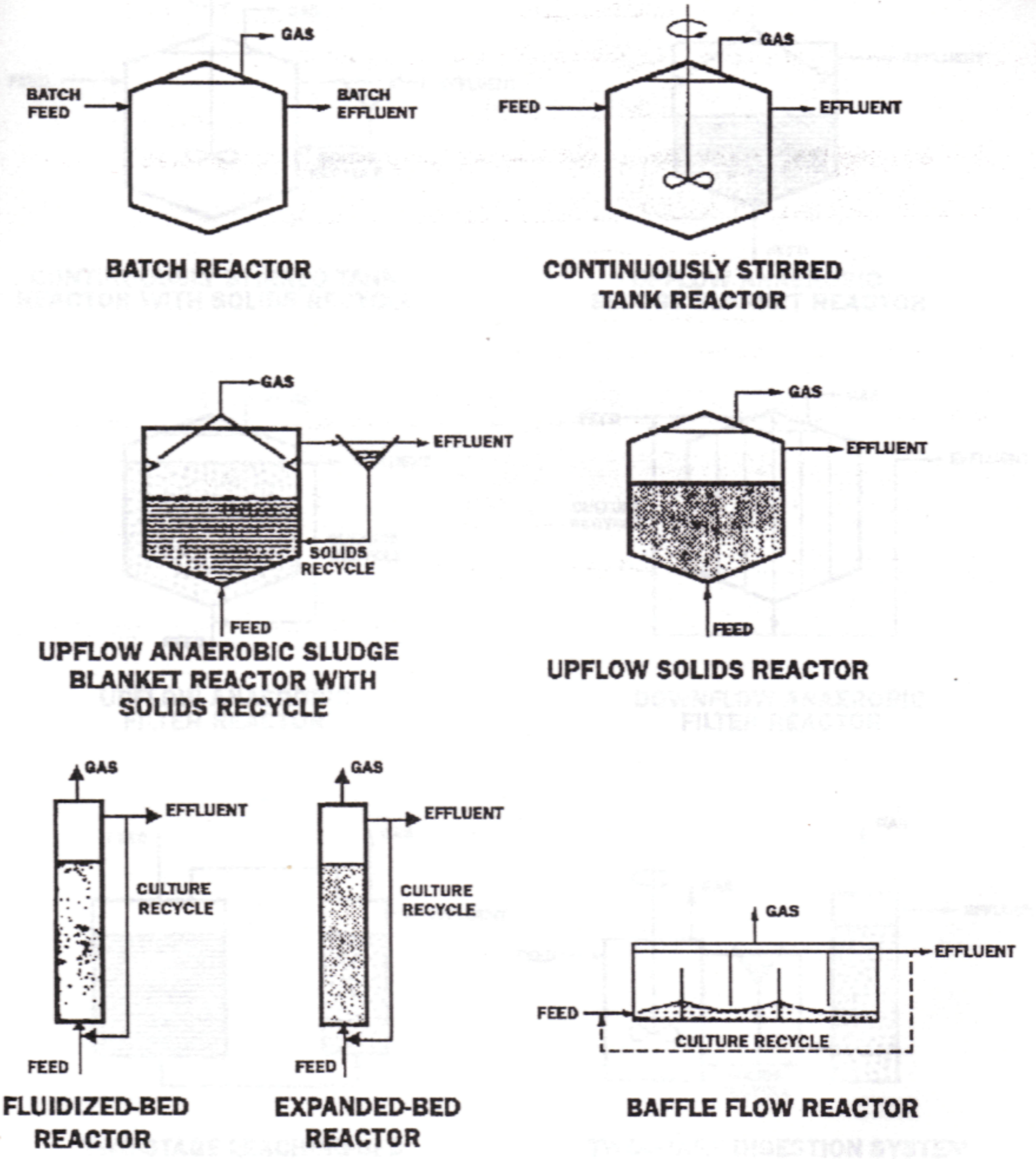
Reactor designs are usually classified by the total solids concentration (TS) of the feedstock in three categories: 1) low solids feeds with a TS less than 3%

(e.g., anaerobic contact, anaerobic filter, etc.), 2) medium solids feeds with a TS between 2 and 15% (e.g., continuously stirred tank, solids concentrating, baffle flow, etc.), and 3) high solids feeds with a TS greater than 15% (e.g., batch reactor, sequential batch, two-phase, etc.) (Figure 2-1).

Low Solids Feeds

In this category is considered the anaerobic contact or continuously stirred tank reactor with (CSTR/SR) or without solids recycle (CSTR), anaerobic filter reactor (AFR), upflow anaerobic sludge blanket reactor (UASBR), and the fluidized-bed and expanded-bed reactors (FBR-EBR). These types of digesters perform well with a low solids feedstock (around 2% of TS), and the main purpose of this design is to keep the microorganisms in the system so they are not washed out.

Continuously stirred tank reactor (CSTR). This type of digester is widely used and considered conventional for sewage sludge digestion. The design incorporates stirring or agitation of the contents to achieve good mixing using pumps, mechanical stirrers, gas recycle, or other options. In this reactor the solids and hydraulic retention times are equal. With high loading rates and because of mixing, unreacted solids and microorganisms are washed out. Some advantages of this reactor are the ability to process feeds with high levels of suspended solids and the prevention of scum layer formation when properly mixed. Complete mixing



BATCH REACTOR

CONTINUOUSLY STIRRED TANK REACTOR

UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR WITH SOLIDS RECYCLE

UPFLOW SOLIDS REACTOR

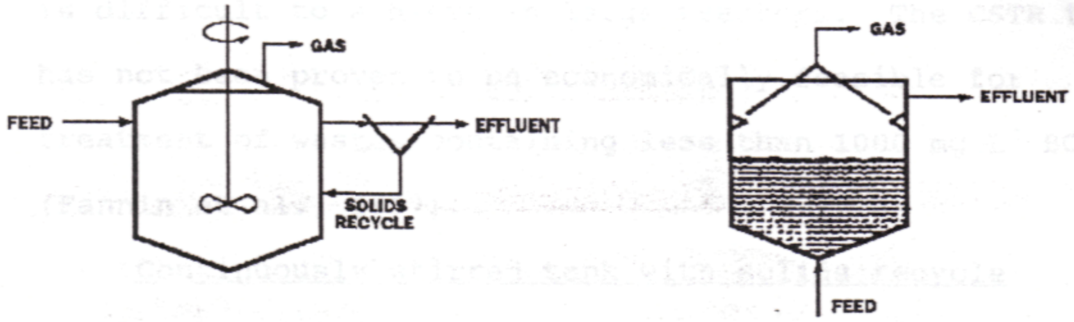
FLUIDIZED-BED REACTOR

EXPANDED-BED REACTOR

BAFFLE FLOW REACTOR

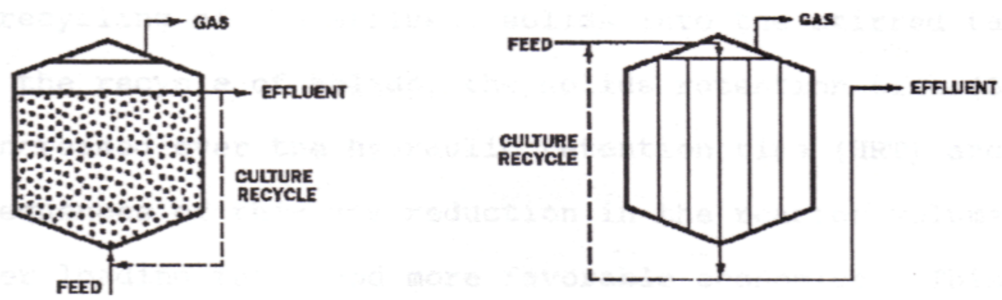
Source: Chynoweth and Isaacson, Eds, 1987.

Figure 2-1 Types of Digesters.



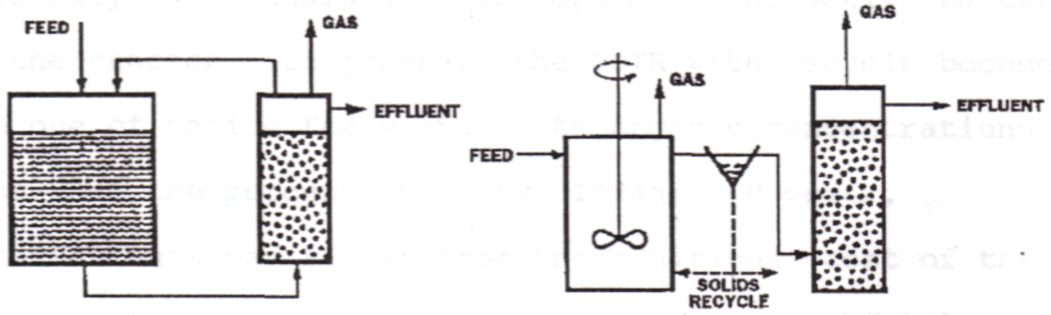
CONTINUOUSLY STIRRED TANK REACTOR WITH SOLIDS RECYCLE

UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR



UPFLOW ANAEROBIC FILTER REACTOR

DOWNFLOW ANAEROBIC FILTER REACTOR



TWO-STAGE LEACHING-BED LEACHATE FILTER

TWO-STAGE DIGESTION SYSTEM

Source: Chynoweth and Isaacson, Eds. 1987.

Figure 2-1 --continued.

is difficult to achieve in large reactors. The CSTR tank has not been proven to be economically feasible for treatment of wastes containing less than 1000 mg L^{-1} BOD (Fannin et al., 1987).

Continuously stirred tank with solids recycle (CSTR/SR). This reactor promotes the retention time of microorganisms (MRT) and unreacted solids by the settling and recycling of the effluent solids into the stirred tank. With the recycle of solids, the solids retention time (SRT) is increased over the hydraulic retention time (HRT) and the consequences of this are reduction in the reactor volume, higher loading rates and more favorable economics. This process has been widely applied as a treatment of soluble industrial wastes and other feeds where solids recycle is necessary to maintain a large population of active bacteria in the reactor. In general, the CSTR with recycle becomes the one of choice for wastes with organic concentrations of less than one percent (McCarty, 1964a). However, disadvantages may result from the additional cost of the settling basin and recycle pumps and from the heat losses in the recycle loop.

Anaerobic filter reactor (AFR). The anaerobic filter consists of a filter bed filled with inert support material such as gravel, rocks, charcoal, or plastic media. The media may be random or oriented and the flow up or down. The use of oriented packing rather than random packing and downflow operation is believed to reduce plugging problems. Bacteria attach to the filter media as a film and absorb nutrients from the flow of influent. This type of system results in rapid-rate biomethanogenic conversion of soluble wastes. The biggest disadvantage is the higher cost of packing material and the greater possibility for plugging the digester with suspended solids.

Upflow anaerobic sludge blanket reactor (UASBR). These reactors are based on the upward movement of soluble organic feeds through an expanded dense blanket of solids (mainly composed of microorganisms). Three layers in this reactor can be identified. First is the sludge bed, a dense and granular sludge, in which most of the biomass is found. The sludge-bed zone has been reported to be responsible for 80 to 90% of waste degradation in the reactor, and to occupy 30% of the reactor volume (Fannin et al., 1987). A second layer, the sludge blanket is a blanket of flocculated sludge particles, and allows a preliminary separation of gas bubbles from the sludge flocks and granules. The third layer is the settler for gas/solid/liquid separation and for sludge recycling. Various types of separators are employed to separate gas from solids and to prevent solids flotation and washout. As the liquid moves through the floc, increased MRT and SRT are achieved relative to the HRT. The sludge which forms in UASB reactors is usually very dense and it may granulate. The biggest disadvantage of this type of reactor is that requires an effective gas and liquid separator.

Fluidized-bed and expanded-bed reactors (FBR-EBR). These types of reactors contain inert particles (0.3-0.5 mm) small enough to be hydraulically expanded or fluidized. Bacteria attach to particles and are retained in the reactor. These types of digesters promote longer MRTs than HRTs. In the fluidized-bed, the support medium is suspended completely by sufficient hydraulic mixing. In the expanded-bed, the hydraulic flow causes only an expansion of the support medium from its settled state without achieving a completely mixed state. The biggest advantage of these designs over anaerobic filter reactors is that a larger surface area is available for attachment of organisms, and these digesters (FBR-EBR) are best suited for highly biodegradable feeds containing low concentrations of particulate-associated solids that require short SRTs for effective conversion.

Medium Solids Feeds

The upflow solids reactor (USR), the continuously stirred tank reactor (CSTR), the continuously stirred tank reactor with solids recycle (CSTR/SR), the solids concentrating reactor (SOLCON), the plug-flow reactor (PFR), and the two-stage reactor are examples of this category. These type of reactors are suited for feedstock with medium solids content between 2 and 15%.

Upflow solids reactor (USR). The upflow solids digester is a modification of the Upflow Anaerobic Sludge Blanket Reactor (UASBR). In the USR, unreacted solids and microorganisms are maintained in the reactor by passive settling, promoting higher SRTs and MRTs relative to the HRTs. The dense accumulation of solids in the bottom of the digester promoted by a relatively high length-to-diameter ratio (2:1) results in high SRTs.

Solids concentrating reactor (SOLCON). This reactor design is a non-mixed system and employs passive settling and flotation to concentrate solids. Effluent is removed from the level of lowest solids concentration and feed added to the top is inoculated by recycle of digester contents. This system achieves a 2 to 3-fold increase in solids retention time (SRT) over the hydraulic retention time (HRT) resulting in conservation of organisms, increased stability, lower nutrients requirements, and solids conversion (Chynoweth and Legrand, 1988).

Plug-flow reactor (PFR). This reactor is the most economical for farm applications. These reactors typically receive feed at one end and remove effluent from the other. While some vertical mixing of the digester contents occurs during gas production, longitudinal mixing is minimal, thus promoting phase separation of the digestion process (Chynoweth, 1987). In other words, feedstock hydrolysis and acids production occur initially in the digester while methane production increases toward the effluent end. Vertical baffles (baffle-flow reactors) have been installed in some digesters to create dead space for harboring suspended solids including active organisms thereby reducing washout. Most biomass feeds will require solids recycle or baffle-flow construction to maximize retention of feed solids and microorganisms in the digester. These reactors have advantages that include improved stability, higher conversion efficiencies, simplicity, and low cost.

Two-stage reactor. The two-stage (leaching-bed and leachate filter) and the two-stage digestion system (Figure 2-1) are considered in the two-phase anaerobic digester group. In conventional digestion, it is impossible to optimize conditions (e.g., pH, temperature, retention time, etc.) for both groups of bacteria (nonmethanogenic and methanogenic) in the same reactor. So two-phase schemes promote separation of nonmethanogenic and methanogenic bacteria in different reactors making the system more stable because the independent control of pH, temperature, etc., in each phase. The two-phase concept can be employed with several reactor configurations, provided the MRT in the second phase exceeds that in the first phase digester.

High Solids Feeds

The batch-fed reactor, the continuously stirred tank reactor with slow mixing, the sequential batch anaerobic digester, and the two-phase reactor belong to this category.

The main characteristic of these reactors is to handle high concentrations of solids (greater than 15%) in the feedstock.

Batch-fed reactor (BFR). This is the simplest and most common type of digester used worldwide. In batch-fed reactors the total feed volume is added to the reactor where it remains until digestion is completed. Because the total feed is retained, the SRT, HRT, and MRT are the same. This process is particularly suited for seasonally produced biomass feeds and for feeds with a very high solids content. This type of operation is used widely at the household or farm scale. These systems are relatively inexpensive to construct and operate compared to CSTRs, and it is simple in both design and operation. A major disadvantage of batch digestion is that it is relatively unstable and uncontrollable due to changes in the bacterial population during the course of the fermentation process.

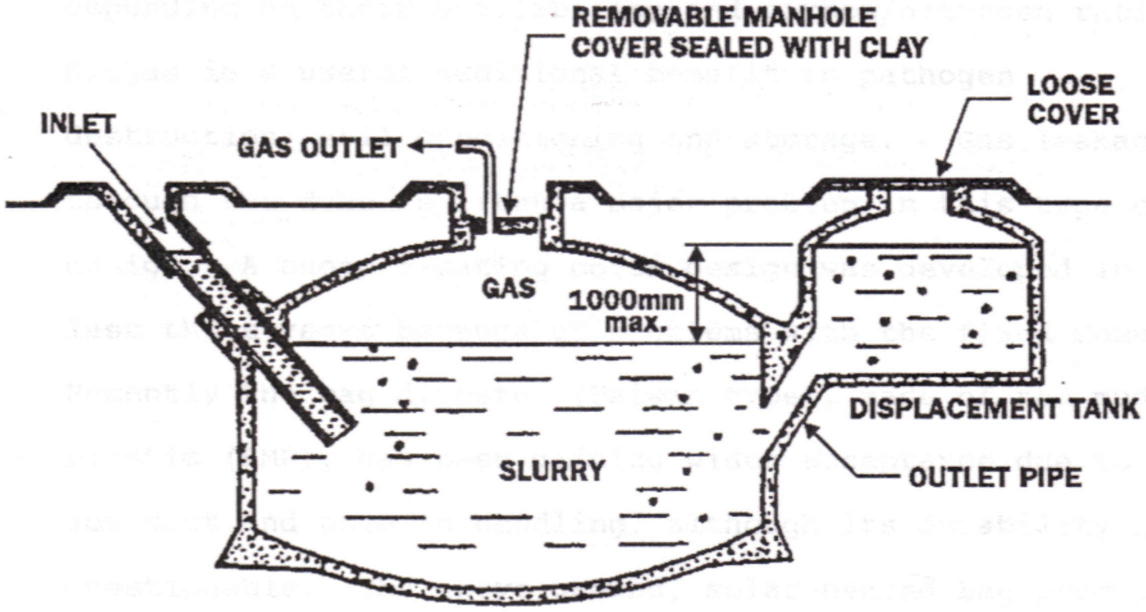
Sequential batch anaerobic composting (SEBAC). The sequential batch anaerobic composting (SEBAC) is a process that was developed and evaluated at the pilot scale for processed municipal solid waste (MSW) and yardwaste for treatment of high solids concentration waste (O'Keefe et al., 1993). This process employs recycle of leachate between new and active cells (or reactors) for inoculation and addition of moisture and nutrients for cell startup. The leachate also removes volatile organic acids formed during startup which, in excess, inhibit the process. It also eliminates the need for mixing and is the only process that provides for removal of inhibitory intermediates associated with startup and imbalances that may arise during operation. SEBAC has two untested unique features that are lacking in aerobic and other competing anaerobic technologies. First, SEBAC is a suitable process for methane enrichment by aeration of leachate to remove carbon dioxide prior to recycle. Second, the passage of leachate through the waste bed provides an opportunity for removal of heavy metals and other soluble toxic substances thus resulting in a clean compost.

CHAPTER 3
DIGESTERS IN DEVELOPING COUNTRIES

Overview

Anaerobic digestion has been strongly accepted in Asiatic countries such as China, India, and Taiwan. The main reasons have been the generation of methane for cooking purposes due to the lack of an alternative energy source, and for sanitizing wastes. Typical rates of production of biogas for digesters designs in developing countries have been 0.1 to 0.4 volumes of gas per volume of digester per day. Much higher rates may be achieved when using optimized designs and operating conditions.

The rapid spread of anaerobic digester use in China was due to strong government support. The government established a well integrated program of expansion, financial support, biogas extension offices at all levels, meetings, training courses, and publicity on a vast scale through newspapers, radio, and television. The three main designs in use in rural areas in China are, in order of decreasing numbers, fixed dome, floating cover, and bag digester. In terms of absolute numbers, the more than six millions fixed dome (Chinese) digesters are by far the most common digester type in developing countries (Figure 3-1)



Source: Gunnerson and Stuckey, 1986.

Figure 3-1 Fixed Dome (Chinese) Digester.

(Gunnerson and Stuckey, 1986). The fixed dome (Chinese) has a typical retention time of 60 days at 25°C with a gas production rate on the order of 0.1 to 0.2 volumes of gas per volume of digester per day. The typical feed to these digesters is usually a mixture of swine or cattle manure dung, water hyacinth, nightsoil, and agricultural residues, depending on their availability and carbon/nitrogen ratios. Biogas is a useful additional benefit to pathogen destruction, soil conditioning and storage. Gas leakage through the dome is often a major problem in this type of design. A cheap floating cover design was developed in the last three years because of problems with the fixed dome. Recently the bag digester (Taiwan type), made of red mud plastic (RMP), has been gaining wider acceptance due to its low cost and ease in handling, although its durability is questionable. The above-ground, solar-heated bag produces 50 to 300% more gas than the fixed dome digester (Gunnerson and Stuckey, 1986).

In India, fuel supply in the rural areas is a much more critical problem. The Indian Agriculture Research Institute, The Khadi and Village Industries Commission (KVIC), and The Gobar Gas Research Station have been working on the design and evaluation of digesters that are suitable for that country. The floating cover (Indian or KVIC) design has a typical retention time of 30 days in warm climates (20-40°C). The typical feedstock is cattle dung.

The daily average gas yield varies form 0.20 to 0.60 volumes of gas per volume of digester per day in cold to warm climates.

As mentioned before, the bag design (a Taiwanese plug flow unmixed type reactor) is gaining popularity because of its low cost and simple construction. Typical retention times vary from 60 days at 15 to 20°C, to 20 days at 30 to 35°C, with a feed of swine manure, which is a common substrate in Taiwan, Korea and Fiji. Volumetric gas production rates are reported of 0.20 to 0.60 volumes of gas per volume of digester per day. The main disadvantage of the bag type is the durability and resistance to the weather of the membrane-walls such as the red mud plastic.

In 22 Latin American countries there are biogas projects with implementation in the field (Caceres and Chiliquinga, 1985). The Latin American Energy Organization (OLADE) carried out a project to transfer biogas technology to rural areas. This project was developed in ten Latin American countries (Bolivia, Dominican Republic, Ecuador, Guatemala, Grenada, Guyana, Honduras, Haiti, Jamaica and Nicaragua), where theoretical-practical training courses and technical seminars were offered.

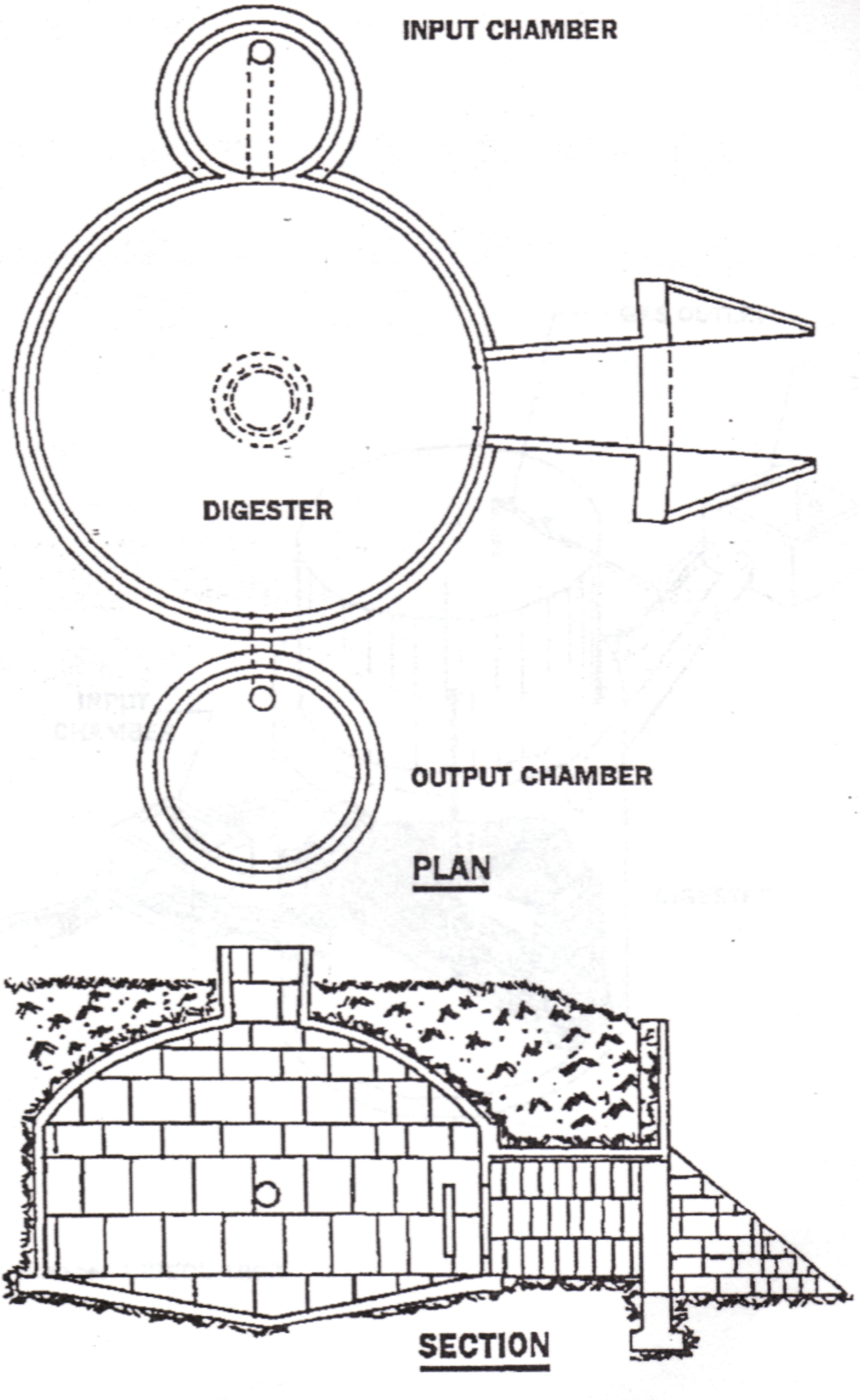
In Guatemala, The Center of Mesoamerican Studies for Appropriate Technology (CEMAT), has been working in rural communities with a modified fixed dome Chinese design. The modification consists of a lateral access for removal of sludge from the digester (Figure 3-2). The capacity of these digesters is around 10-12 m^3 (353-424 ft^3) with an approximate cost of US$ 100-200 $(m^3)^{-1}$.

In Chiapas, the southern most state of Mexico, The Indigenous Center for Integral Development "Fray Bartolome de las Casas" (CIDECI) has been doing experimental work with the Gobar type (Indian design) with a brick baffle in the middle of the digester to avoid short-circuiting of the feedstock (Figure 3-3). Data related to gas production are not available at the moment.

Constraints

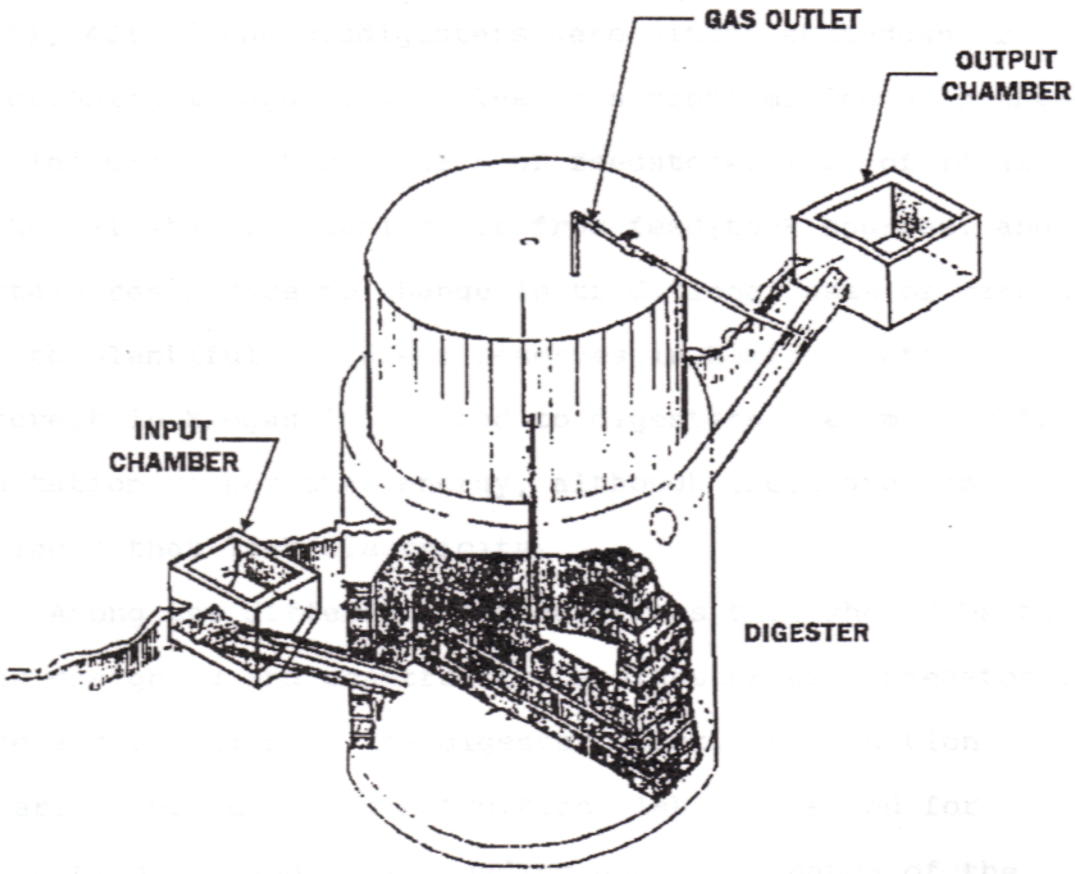
The major criteria used to evaluate performance of anaerobic digestion of different feeds or new digester reactor designs are methane yield, methane production rate, reduction in organic matter, culture stability, thermal efficiency, and process economics (Chynoweth, 1987). It is important not only to optimize the digester size in order to achieve maximum methane production per unit volume of digester capacity, but also to provide a sufficient margin of safety to allow for occasional environmental stress within the digester caused by such conditions as temperature variations and irregular periods and volumes of digester loadings.

In Thailand, an empirical study of Indian design plants by Prasith-Rathsint et al. (1979) found that the high cost of plants, a lack of technical know-how, the availability of



Source: CEMAT, 1993.

Figure 3-2 Modified Chinese Design



Source: CIDECI, 1993.

Figure 3-3 Gobar (Indian Design) Digester.

other fuels, and the shortage of dung were the main reasons that many people abandoned the use of digesters.

In an in-the-field inventory in Latin America (1983-1984) of anaerobic digesters (Caceres and Chiliquinga, 1985), 40% of the biodigesters were either shut-down or functioning irregularly. The main problems found in these "failed digesters" were lack of feedstock, lack of local technical staff, location far from feedstock sources, and certain resistance to change in traditional uses of manure. Due to plentiful petroleum reserves in Mexico, national interest in biogas is limited to digesters used mainly for sanitation rather than energy, although there are some villages that lack electricity.

Among the different considerations that should be taken when designing and constructing a digester are: feedstock, size and function of the digester, cost, construction material, process of construction, labor invested for collection of feedstock, feeding and maintenance of the digester, technical assistance, and social acceptance.

Feedstock

In developing countries, an important consideration are the differences in the quantity and quality of waste material produced from various sources and solids waste disposal. Raw materials may be obtained from a variety of sources including wastes from livestock and poultry, humans, crops, and food processing. Different problems may be encountered with each of these wastes with regard to collection, transportation, processing, storage, residue disposal, and eventual use. For a given waste, such as animal manure, the economic feasibility of gas production may also be greatly influenced by qualitative differences. The quality and quantity of animal manure is influenced by the diet and general health of the animals (NAS, 1977). In rural areas of many developing countries, crop residues are used as animal fodder and so may not be available in sufficient quantity to generate enough methane to meet household needs. Forest litter is still abundant in the bush country in some parts of the world and, if circumstances justify its transportation, might well be included in the feedstock. Manure is the major feedstock for most of the digesters in the developing world (NAS, 1977).

Community and Family Digesters

Most biogas production and use in developing countries has been generated from family digesters (NAS, 1977). Community digesters are also feasible in many situations but resource requirements differ from those for the smaller family digesters. Community digesters require a larger supply of raw materials and perhaps different technological design.

Cost and Construction Material

Evidence on adoption behavior suggests that, in practice, the financial cost of construction materials in relation to farm cash incomes is the most important factor. In order for a methane-generation program to be successful in a developing country, some initial financial and continuing technical assistance from central and local governments is needed (NAS, 1977).

Collection, Storage, Feeding, and Maintenance of Digesters

An important consideration in the generation of methane from agricultural and other wastes is the collection, preparation, and storage of the raw materials to be used in the anaerobic digestion process. In labor-intensive economies, methods should be considered that utilize available human and animal resources for the handling and processing of these wastes.

It is usually assumed in India that an equal amount of labor is required to collect dung for traditional uses as for the biogas plant, so frequently no extra value is assigned in financial analysis for labor costs of dung collection. Poor maintenance has been said to be the single most important cause of failure in the KVIC (Indian) design, particularly the failure to paint the gas holder to avoid corrosion.

Other main tasks to run the digester are mixing water and dung, feeding the digester, and spreading an equivalent amount of slurry from the digester onto the compost pit, or fields. A constant water supply might be a requirement which often restricts possible digester locations since many villages do not have adequate year-round supplies. In the absence of a constant water supply, a design for high solids feed is recommended (dry fermentation) depending on feedstock composition.

Technical Assistance

An often neglected major input which should be incorporated into a social cost-benefit analysis is extension education. Survey evidence suggests that access to technical assistance is a major determinant of digester performance, and yet social benefit-cost studies rarely considered this as a cost item.

Social Acceptance

Social or cultural acceptability is often a major factor influencing the success or failure of an innovation. The most important factors to be consider are: The social and environmental implications of the technology, institutional factors such as the ability to insure and finance the project, assurance of systems reliability and service of the technology, and regulatory and legal decisions influencing farm practices. There are a number of social factors which tend to inhibit the adoption of biogas plants. First, there exists social taboos about the handling of excreta (especially human) and other wastes.

Second, the division of domestic tasks (eg. collecting fuel and cooking) and agricultural activities between women and men, and the question of who makes the major household decisions is extremely important, since in developing countries women usually perform the former and men the latter. Finally, there is a strong correlation between the educational level of the digester owner, and acceptance of biogas, although this may merely reflect the superior economic status of most educated people in developing countries (Stuckey, 1983).

Study Area

In our work we planned to install and test a digester in Yajalon, State of Chiapas, Mexico. The physical and social characteristics of the test community (in this case, the experimental farm) will determine the acceptance or failure to this technology.

Of the 125,300 localities in the Mexican Republic, 98% are smaller rural communities of less than 2,500 inhabitants. These account for 34% of the total population. The availability of potable drinking water at the national level is 76% and sewer is 40%. In the rural environment, the water service supplies 50% of the population (13.8 million inhabitants) and only 26% (7.17 million inhabitants) of the rural population has sewer systems. In the rural environment and in marginal areas, 26.1 million inhabitants lack drinking water and 44.6 million lack sanitary drainage

(PAHO, 1992). According to the Pan American Health Organization (1992) figures published by the Health Secretary of Mexico in 1990, water-borne diseases are the fourth leading cause of death at the national level. Morbidity from amoebiasis is 985 per 100,000 population, for typhoid fever, 13 per 100,000, and for salmonellosis, 86.5 per 100,000.

Chiapas, the southern-most state of Mexico, is the biggest producer of oil in the country and is rich in natural resources. The annual production of oil and natural gas in 1988 was 33,487,000 barrels, and almost 6,000,000 m^3, respectively (INEGI, 1990). Ironically, 35.6% of the population does not have tap water and almost 60% of the total population does not have any sewage treatment (PEE, 1990). In 1987, 40% of the visits to the doctor in the state had problems caused by bacterial diseases (INEGI, 1990). By 1989, almost half of the population of the state had electricity (PEE, 1990).

The municipality of Yajalon is in the northeast part of the state of Chiapas. The town of Yajalon, which is the main political and economical center of the municipality of the same name, is located at 17°10′15" north latitude and 92°19′51" west longitude (Figure 3-4) (SG-GEC, 1988; INEGI, 1990). Yajalon is at 800 m (2,625 feet) above sea level with an extension of 109.3 sq. km. (27,009 acres). The town is nestled in the mountains of northern Chiapas, so most of

Figure 3-4 Location of Study Area.

its terrain (90%) is steep. The climate varies with altitude, and can be tropical, semi-tropical or temperate, with humidity and rainfall all year around. The mean annual temperature and precipitation are 22°C and 2,000 mm (79 in) respectively (SG-GEC, 1988; PEE, 1990). Yajalon has around 45 rural Indian communities. Sixty-percent of these communities have a population less than 100 people. The total population of the municipality is 30,000 (INEGI, 1990). Half of the population live in the town of Yajalon and the rest in small villages in the highlands. The Tzeltales, the Mayan group who lives in the area of study comprises more than 60% of the population of the municipality. The illiteracy rate is around 43% of the population greater than 15 years old (SG-GEC, 1988). In the region, only 20% of the communities have a sewer system, and only 34% have electricity (PEE, 1990). More than 40% of the infant mortality is attributed to "parasitic" sickness and more than 20% of the total deaths among people less than 30 years old are related to sanitation problems (bacteria, etc.) (INEGI, 1990).

The main economic activities are the production of coffee, maize, and black beans, and the raising of cattle. Almost 63% of the total "livestock" (includes: cattle, pigs, goats, and sheep) are cattle, followed by 25% pigs in the region.

CHAPTER 4
LABORATORY STUDIES

Objective

A laboratory-scale experiment was performed in the field with three objectives: 1) to obtain data for methane yield [m^3 (kg VS added)$^{-1}$] from animal manures (pig, goat and chicken); 2) to give local people a real small-scale demonstration of production of methane via the fermentation of organic matter; and 3) to test a simplified design for measuring methane production in the field where more sophisticated instruments for running biochemical methane potential (BMP) assay are not available.

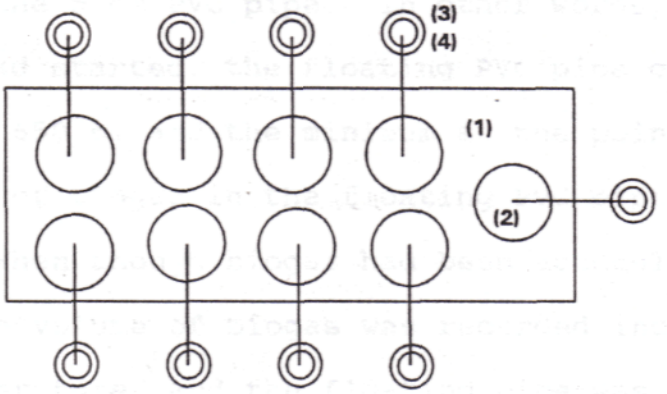
Methods

Feedstock

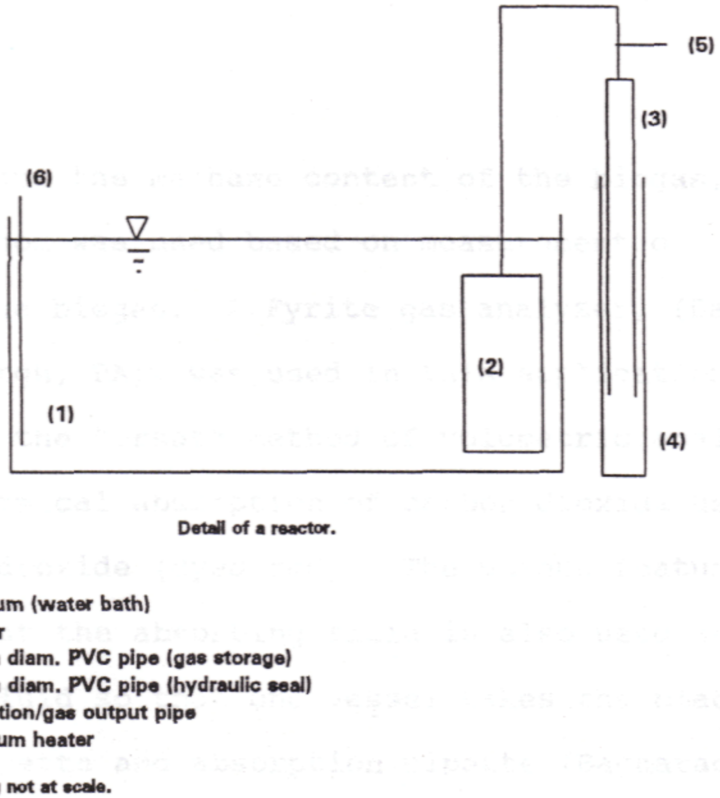
Pig, goat and chicken manures were chosen for the small-scale demonstration because they are abundant on the ranch and in the town. Pig manure samples were taken from an agricultural high school in the town. Pigs are raised in a pigpen with concrete floor and are fed with concentrated food. The goat and chicken manure samples were collected on the ranch. The goats are fed alfalfa, other vegetables and pasture. The chickens are fed with some grains such as corn and also roam in the field freely. The inoculum used in the experiment was taken from a two year old septic tank located in the ranch. Table A-1 lists the amount of manures and inoculum used for the small-scale demonstration.

Digester Setup

Fifty grams of sample were added to 750 ml of inoculum in 1,100 ml glass bottles. Duplicates were run for the pig, goat and chicken manures, and triplicates were run for the control (inoculum). The gas tight bottles were incubated in a waterbath using an aquarium tank (50 cm large, 22 cm width, and 25 cm height) during the forty-four days of experimentation (Figure 4-1). The temperature was controlled around 35°C, heating the water with an aquarium heater. A thermometer was placed in the water to read the temperature and adjust the heater if needed. The bottle head space was 350 ml. The biogas generated in the experimental bottles was collected in 4 cm diameter PVC pipes inverted in a water seal contained by a 5 cm diameter PVC pipe (detail in figure 4-1). The length of each pipe was 65 cm. The volume of the floating 4 cm PVC pipe was calibrated and marked by injecting air with a syringe through the calibration pipe. The external temperature was recorded for correction of volume. Barometric pressure was assumed to be constant (1 atmosphere). Not more than 650 ml were allowed to be stored in the pipe for this specific design. After this volume, bubbles of biogas started



Arrangement of the reactors.



Detail of a reactor.

Explanation:
(1) Aquarium (water bath)
(2) Reactor
(3) 4.0 cm diam. PVC pipe (gas storage)
(4) 5.0 cm diam. PVC pipe (hydraulic seal)
(5) Calibration/gas output pipe
(6) Aquarium heater
Note: Drawing not at scale.

Figure 4-1 Field Experiment Set-up.

rising up into the atmosphere through the hydraulic seal of the 2" PVC pipe. Increments of 20 ml were marked starting at the zero point when the 4 cm PVC pipe just started floating in the 5 cm PVC pipe. In other words, when the experiment had started, the floating PVC pipe could rise to a maximum of 650 ml and the minimum at the point zero. The accumulation of biogas in the floating PVC pipe was checked routinely. When enough biogas had been accumulated from the reactors, the volume of biogas was recorded including ambient temperature, and the floating pipe was reset to the zero point (Table A-3). This procedure was repeated 18 times for reading biogas production from the different reactors.

Analyzer

To measure the methane content of the biogas, an indirect method was used based on measurement of carbon dioxide in the biogas. A Fyrite gas analyzer, (Bacharach Inc. Pittsburgh, PA), was used in this application. This unit employs the "Orsat" method of volumetric analysis involving chemical absorption of carbon dioxide using potassium hydroxide (dyed red). The unique feature of the Fyrite is that the absorbing fluid is also used as the indicating fluid so that one vessel takes the place of both measuring burette and absorption pipette (Bacharach, 1992). The appropriate scale of this instrument for measuring carbon dioxide in biogas was 0 to 60%. The assumption is that the rest of the biogas is methane (the two most significant components of biogas are carbon dioxide and methane which account for around 99.5% of the total gas composition). The reagent (potassium hydroxide) should be replaced after approximately 350 samples (containing 10% carbon dioxide) have been analyzed or when the variation is ± 5% of carbon dioxide in repetitive readings. If the sample is trapped over water, which is the case in this small-scale demonstration, a good practice is to use 10 to 15% of NaCl (table salt) in the water to minimize absorption of carbon dioxide by water. The measurement of methane should be done simultaneously with the readings of biogas production.

Results and Discussion

To determine solids (TS and VS) of the animal manures and inoculum, samples were taken to the closest laboratory in the town, and TS and VS methods were run using the procedures specified in Standards Methods Procedures (APHA-AWWA-WPCF, 1989). The total solids and volatile solids of the inoculum were 1.0 and 0.7 % of the total wet weight, respectively (Table A-2).

The experiment was run for 44 consecutive days. The biogas volumes were corrected for temperature at 35°C. The maximum amount of biogas (650 ml) that could be stored in the floating PVC pipe was not enough to run gas analysis using the Fyrite gas analyzer (Bacharach, 1992). According to the Bacharach instructions, at least 900 ml of biogas are required to have a confident reading of CO_2 when the biogas is water saturated. Assumption of 60% CH_4 content in the biogas was used for the animal manure samples (Fry, 1973; Overcash et al., 1983b), and 10% CH_4 for the inoculum. These assumptions were taken based on previous experiments run with similar samples and characteristics (animal weight, feed type, site, etc.) using BMP (biochemical methane potential) assay at the Bioprocessing Engineering Laboratory of the University of Florida.

Appendix B lists information related to the biochemical methane potential (BMP) assay run for 44 days on cow and pig manure, cellulose and control (inoculum). In Appendix C, analysis of the data obtained during the field experiment are presented.

In Figures C-1 through C-4, the experimental data and theoretical methane yield are presented for pig, goat, chicken and control (inoculum). The degradation of each sample was assumed to follow a first order rate of decay (Owens and Chynoweth, 1992). Thus, the production of methane was assumed to follow

$$Y = Y_u * [\ 1 - \exp(-k*t)\ ]$$

where

Y is the accumulative methane yield at time t

Y_u is the ultimate methane yield

k is the first order rate constant

The parameters, Y_u and k, were estimated using a nonlinear regression fit to the yield data. The regression was performed on a PC compatible computer using the Marquardt-Levenberg algorithm available in SigmaPlot 4.0.

The methane yield obtained in the field for the pig sample (250 ml CH_4 (g VS added)$^{-1}$ (Figure C-1)) was lower than another pig sample run in the lab (400 ml CH_4 (g VS added)$^{-1}$ (Figure B-2)). The higher value obtained in the lab using the biochemical methane potential (BMP) assay was attributed to the more ideal conditions in the lab. The methane yield of goat manure (300 ml of CH_4 (g VS added)$^{-1}$ (Figure C-2)) was much higher than the value for pig manure.

The methane yield for the control (inoculum) in the field of 20 ml CH_4 (g VS added)$^{-1}$ (Figure C-4) was much lower than the methane yield of the control (120 ml CH_4 (g VS added)$^{-1}$ (Figure B-4)) used during the BMP assay in the laboratory. The inoculum in the field was taken from the 2 year-old septic tank in the upper 30 cm layer of the septic tank liquid. Although some inaccuracy existed while doing the readings of the biogas in the 4 cm floating PVC pipe, maintaining temperature in the water bath, and maintaining homogeneity of the inoculum (liquid septic tank) for the different reactors, this field experiment was appropriate to give an approximate idea of the methane yield production of animal manures or other organic matter in sites where more sophisticated assays, such as BMP, could not be performed.

CHAPTER 5
DIGESTER DESIGN AND CONSTRUCTION

Purpose of Digester

The objectives for establishing an anaerobic digester on the ranch were to sanitize wastes, provide an alternative renewable source of energy and compost for crop fields, and serve as a demonstration for educational purposes. The digester is fed crop residues (i.e., coffee pulp, etc.), VGF (vegetable, garden and fruit wastes) from the ranch and fruit stores, animal manures (i.e, pigs, goats, chickens, etc.), and wastewater from the bathroom. By anaerobic treatment of human feces, a significant reduction of pathogens is expected. The effluent containing digested solids will be used as compost in the fields. The production of methane should be sufficient to satisfy the energy demand for cooking. Because the ranch houses 35 students, the digester will also serve for educational and experimental purposes.

Design Criteria

Feedstock

The experimental farm where the digester was constructed is still under development. It was difficult to design a digester for future needs of the ranch when they are not well defined. The design and size of the digester were therefore based on a best guess of future types and quantities of feedstock, and a plan to supplement the feed with fruit, garden and vegetable (VGF) wastes imported from Yajalon. Table 4-1 lists the daily amount of organic waste generated from the farm and projected additional VGF. The amount of feces produced per animal per day, wet weight, total solids (TS) and volatile solids (VS) were obtained from existing literature (Bewick, 1980; Fry, 1974; Gunnerson and Stuckey, 1986; Merkel, 1981; Pain and Hepherd, 1985; Stuckey, 1983), and from results obtained in the laboratory studies described in the previous chapter. An estimated guess of present total wastes generated in the ranch are around 170 kg wet weight d^{-1} with a composite TS and VS of 30 and 20% of wet weight, respectively.

Digester System Characteristics

Size. The total amount of waste for determining the size of the digester is around 170 kg wet d^{-1} (Table 4-1). Assuming an overall density of 1 kg wet L^{-1} (Overcash et al., 1983a), we have a volume of 170 L d^{-1}. Assuming 4 L of water per flushing toilet and considering 35 people in the ranch, 140 L of water will be added to the digester every day from the wastewater stream from the bathroom (Figure 4-2). The total digester daily feed volume is 310 L d^{-1} (there is around 50% dilution). Assuming a hydraulic retention time (HRT) of 24 days, the working volume of the tank is 7,440 L

(7.4 m^3). Allowing for a head space of 10%, the total digester volume is 8 m^3. Using this volume the following internal dimensions were chosen:

length = 3.30 m

width = 1.50 m

height = 1.60 m

Assuming an overall value of 20% VS of wet weight (Table 4-1), the loading rate can be calculated as follows:

1) Calculation of VS added d^{-1}.

170 kg wet d^{-1} x 0.20 kg VS added (kg wet)$^{-1}$ =

34 kg VS added d^{-1}

2) Calculation of loading rate.

Culture volume = 7.4 m^3

Loading rate = 34 kg VS added d^{-1} x (7.4 m^3)$^{-1}$ =

4.5 kg VS m^{-3} d^{-1}

Configuration. Based on the characteristics of the feedstock, the economics, the availability of construction materials, and the site topography, a baffled plug-flow digester (Figure 4-3) seemed to be the most appropriate design for the application in the ranch. The reasons to support the selection of this design are: 1) based on laboratory results of the TS concentration for the inoculum, animal manures and VGF, and combined with the diluted wastewater from the bathroom, the estimated overall TS concentration is around 5-15% of wet weight; 2) local masons are skilled in building rectangular concrete water tanks for

Table 4-1 Amount of Daily Waste Generated on the Farm.

Description	Number of units	Waste per animal wet kg/day	Total waste wet kg/day	Water % of wet weight	TS % of wet weight	VS % of wet weight
Poultry	50	0.12	6.00	75	25	20
Goats	16	1.40	22.40	60	40	31
Pigs	5	4.40	22.00	70	30	25
People	35	1.40	49.00	90	10	6
VGF (vegetable, garden and fruit wastes)			70.00	65	35	30
Total			170.00	72	28	22

water containers (the plug-flow reactor has a rectangular shape); 3) addition of baffles to the plug-flow design should increase the retention time of the solids (SRT) and the microorganisms (MRT) and reduce short circuiting in the tank; 4) a rectangular shape was more appropriate to the topography of the site because one lateral wall could be used for locating the effluent of the tank without constructing an output chamber; 5) the rectangular design with two baffles (Figure 4-3) favors the construction of removable covers that are convenient for operation; and 6) the two chambers (as a safety factor) diminish the probability that the whole digester becomes unbalanced. In the event of overloading only the acids buildup in the first chamber.

<u>Other considerations.</u> Although many digesters are operated in the mesophilic range (30°C to 40°C), this digester will be operated at ambient temperature (mean annual temperature of 22°C) because of reduced costs and simplicity. Animal manure and VGF wastes are fed to the digester through a feed chamber (Figure 4-4) without dilution. Human feces and water required for flushing the toilets are transferred directly via a 10 cm PVC pipe to the digester. The effluent of the digester will be removed through a 10 cm flexible pipe (Figure 4-3). Grit can be removed through a two cement pipes located at the bottom of the digester. Maintenance inside of the digester can be

done through the removable chamber's covers. Gas generated in the digester will be collected in a separated gas collector unit (Figure 4-5).

Site

The farm is located in the highlands of the state of Chiapas on steep slopes with unstable soils. Although this topography was difficult for carrying out construction work and transporting materials, the slope of the terrain could be used for facilitating the construction of the digester. Instead of placing the digester completely underground, it was constructed into the side of the slope. The exposed wall contains the effluent pipes and the slurry and grit would be removed by gravity; therefore an output chamber is no longer needed. Labor for excavation and construction cost were reduced. However, taking advantage of the slope for placing others digesters should be carefully evaluated because the disadvantage of internal heat will be lost to the atmosphere through the exposed wall. Soils in the ranch are very unstable with a high clay content causing swelling and shrinking as a function of the moisture content in the soil. Steel sheet mesh in the concrete floor were added to the structure of the tank to support differential soil movements.

Materials

Cost-benefit was an important variable in the design of the digester. Using local materials reduced the cost of construction significantly. The units (digester, feed chamber, and gas collectors) were built with cement blocks and concrete because of their resistance to outside exposure, and the availability of these materials in the town. The skills of the local masons to build concrete tanks were also taken in consideration for using these materials. High resistant plastic materials or bags that could be used for the digester's cover and gas collectors were not available in the vicinity of the town, therefore, the covers were built with reinforced concrete.

Ease of Operation

Another important factor that influenced the selection of the digester was to take into consideration the skills of people who will be running the system. Removable covers in each chamber of the digester will allow people to repair or clean a specific section of the tank without disturbing the rest of the digester. Having a separate gas collection unit, although more expensive, allows operators to do specific repairs separately.

Design and Construction Details

Overview of System

The system includes three units: the digester tank, the feed chamber, and the gas collector (Figure 4-2). The flow of the wastes and gas production are shown in that figure. The distribution of the units were placed taking advantage of the slopes of the site. The digester was placed in a

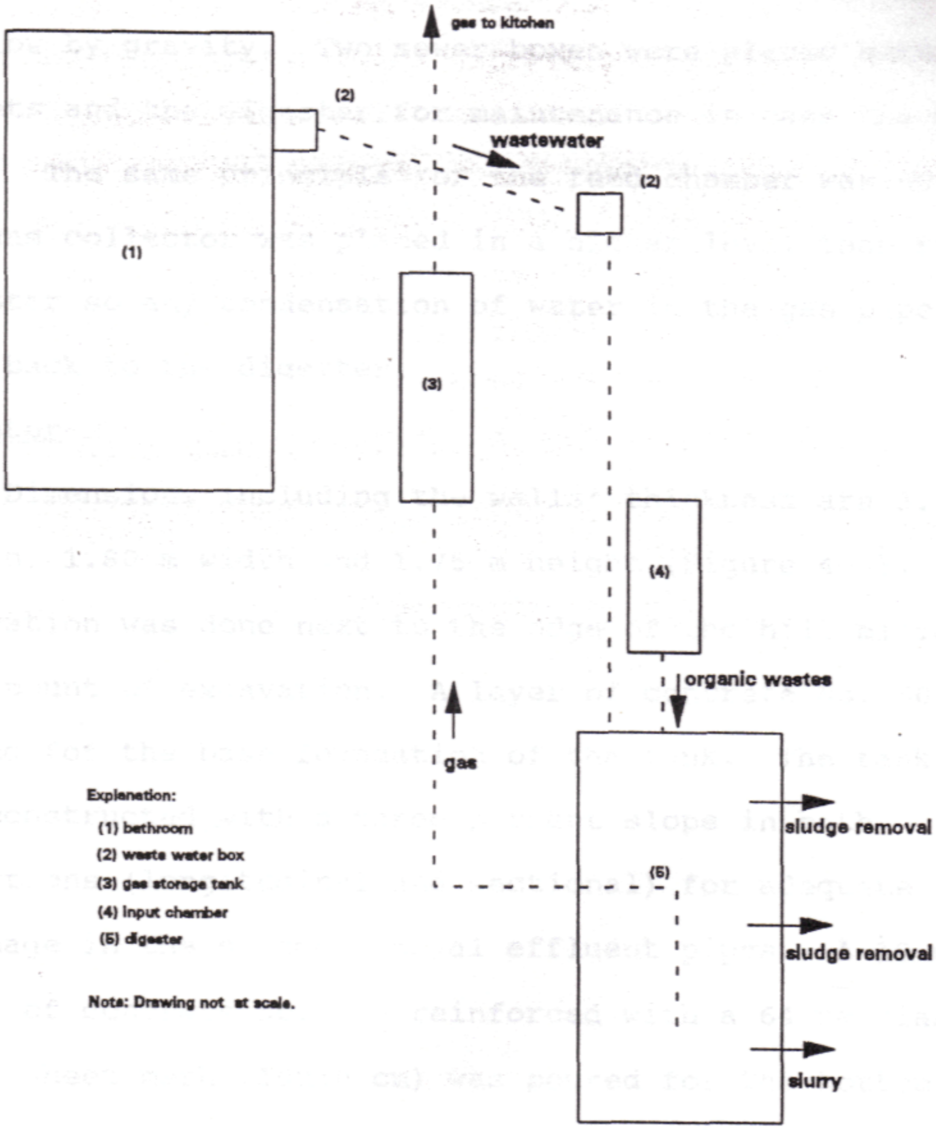


Figure 4-2 Plan of System.

lower level than the bathroom allowing the wastewater stream to flow by gravity. Two sewer boxes were placed between the toilets and the digester for maintenance in case the pipes clog. The same principle for the feed chamber was used. The gas collector was placed in a higher level than the digester so any condensation of water in the gas pipe will drip back to the digester.

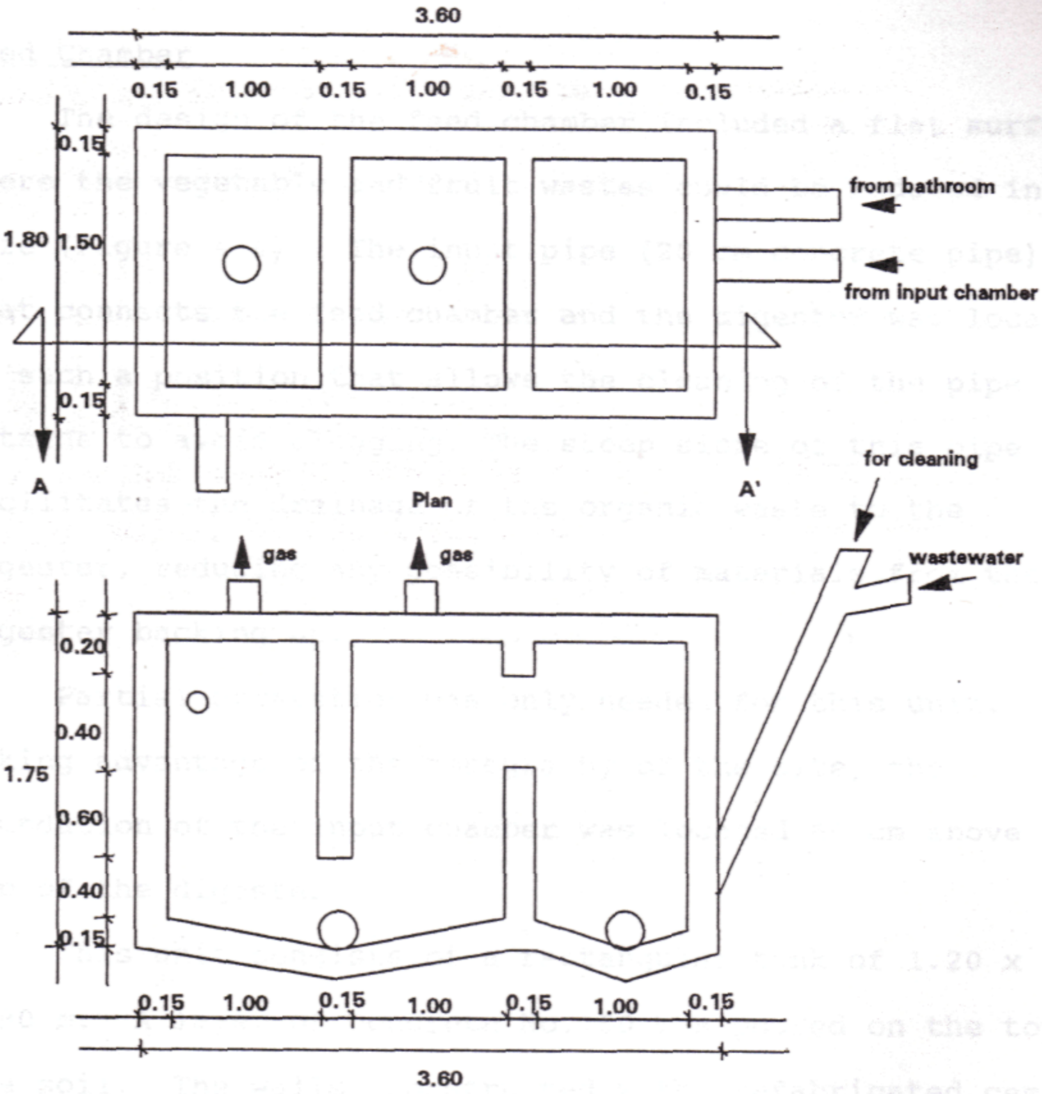
Digester

Dimensions including the walls' thickness are 3.60 m length, 1.80 m width and 1.75 m height (Figure 4-3). The excavation was done next to the edge of the hill minimizing the amount of excavation. A layer of concrete No. 50 was poured for the base foundation of the tank. The tank floor was constructed with a three percent slope in both directions (longitudinal and sectional) for adequate drainage in the sludge removal effluent pipes. A 10 cm layer of concrete No. 200 reinforced with a 64 mm diameter steel sheet mesh (10x10 cm) was poured for the bottom floor of the tank. Plaster with a pure cement paste was applied in the top of the floor layer to avoid infiltration into the ground.

All the walls of the tank were built with prefabricated cement block and plastered with a cement-sand mortar (1:3). The interior walls were finished with a pure cement paste. The walls were hydraulically sealed. At 40 cm above ground, two 20 cm prefabricated cement pipes were placed on the front wall having a steep slope for efficient drainage by gravity. One of these pipes corresponded to the animal manure and VGF wastes fed from the feed chamber, and the other to the sewer coming from the bathroom. The connection of the sewer pipe and the digester was done with a "Y" connection, allowing for cleaning from outside in case of clogging (See section A-A′, figure 4-3). To support tensional forces from the ground and pressures from inside the digester, steel "armex" were located at each corner of the walls and also in the intersections with the baffles. To support the second wall baffle at 40 cm above ground, a 15x30 cm reinforced concrete beam was built. Another beam was built at the top of the digester between the first and second chamber to support the flat movable covers.

A 10 cm plastic pipe was located in one of the extremes of the exposed wall. The flexibility of this pipe, with an approximate length of 1.50 m, sets the level of the liquid inside the digester and discharges slurry to the outside.

The three flat movable covers (1.60x1.10 m each) were built with cast-in-place concrete, but later, leaks were found between the concrete cover and the connections with the adjacent walls. In addition to the leak problems, each cover had an approximate weight of 250 kg making it very difficult to manipulate and seal the connections with the walls. To keep the design with movable covers, it was



Note: Drawing not at scale.
Dimensions are in meters.

Figure 4-3 Digester.

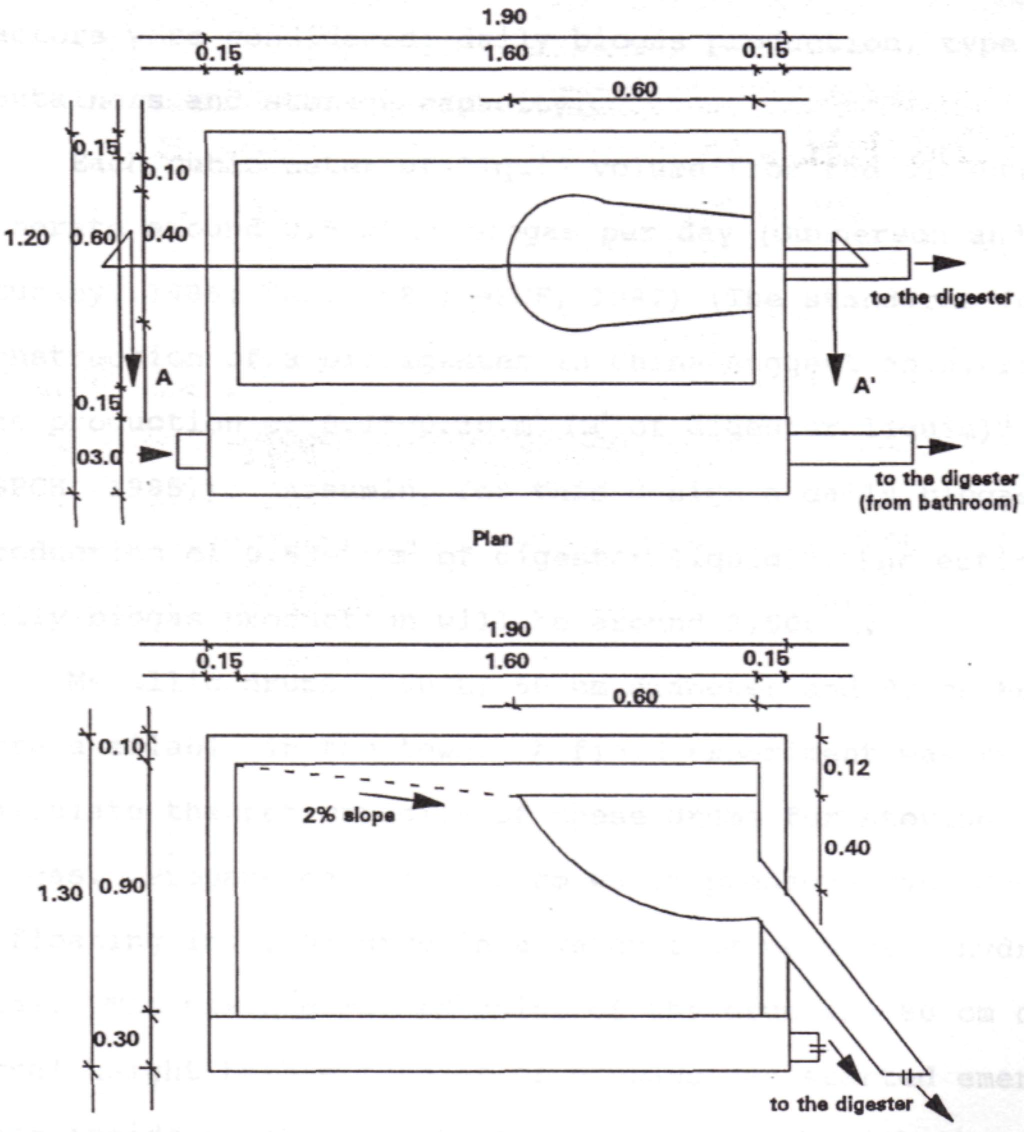
suggested that the covers with light metal sheet material be substituted.

Feed Chamber

The design of the feed chamber included a flat surface where the vegetable and fruit wastes could be reduced in size (Figure 4-4). The input pipe (20 cm concrete pipe) that connects the feed chamber and the digester was located in such a position that allows the cleaning of the pipe from outside to avoid clogging. The steep slope of this pipe facilitates the drainage of the organic waste to the digester, reducing any possibility of materials from the digester backing up.

Partial excavation was only needed for this unit. Taking advantage of the topography of the site, the foundation of the input chamber was located 60 cm above the top of the digester.

This unit consists of a rectangular tank of 1.20 x 1.90 m. A layer of concrete No. 50 was poured on the top of the soil. The walls, constructed with prefabricated cement blocks, have a height of 1.30 m. The top layer of the input chamber was plastered and finished with a pure cement paste having a 2% slope for facilitating the drainage of the organic wastes from this chamber to the digester (Section A-A′, figure 4-4).



Note: Drawing not at scale.
Dimensions are in meters.

Figure 4-4 Feed Chamber.

Gas Collection and Use

For the design of the gas storage tank the following factors were considered: daily biogas production, type of containers and storage capacity.

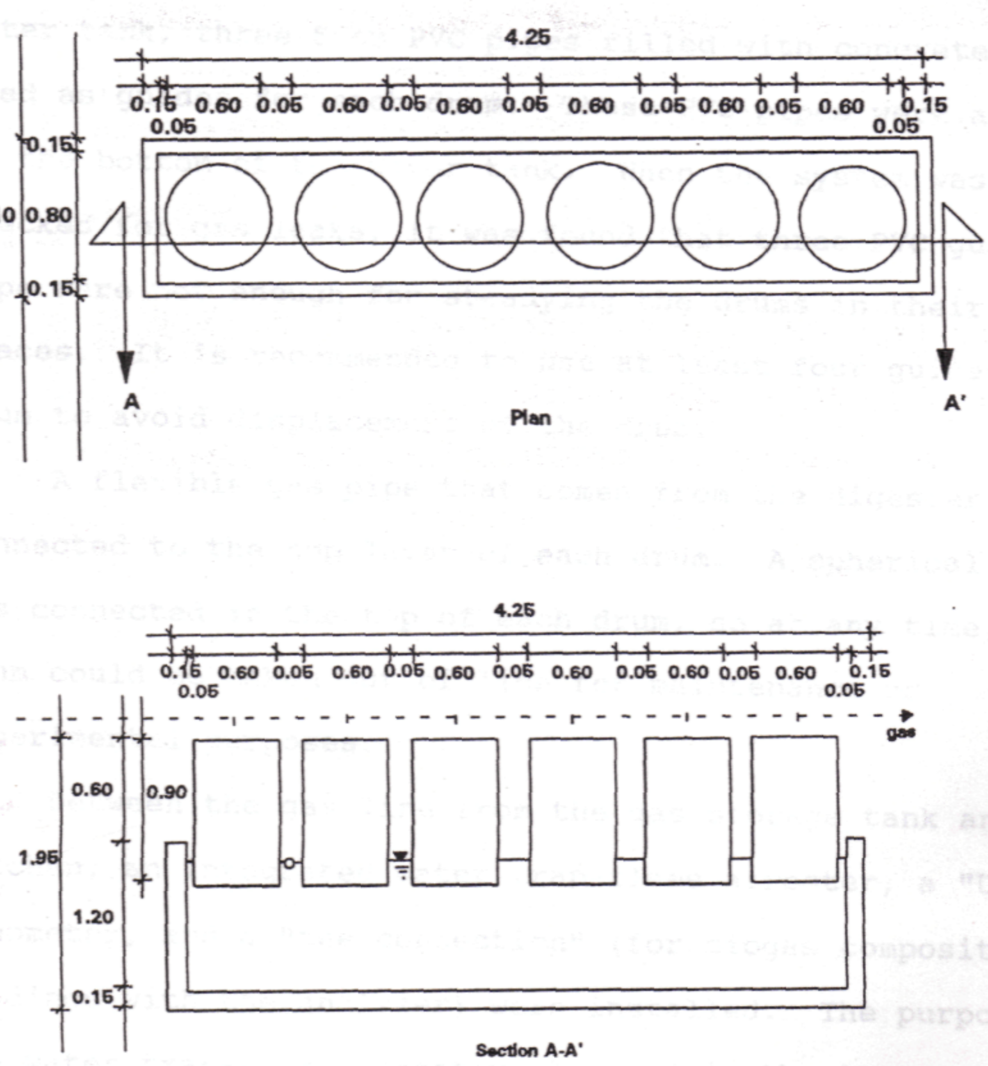
Each cubic meter of liquid volume from the digester can generate around 0.5 m^3 of biogas per day (Gunnerson and Stuckey, 1986; NAS, 1981; WPCF, 1987) (The standards for construction of a biodigester in China suggest an average gas production of 0.15-0.30 m^3 (m^3 of digester liquid)$^{-1}$ (SPCH, 1985)). Assuming for this design a daily biogas production of 0.5 m^3 (m^3 of digester liquid)$^{-1}$, the estimated daily biogas production will be around 3,500 L.

Metallic drums (250 L; 60 cm diameter and 90 cm height) were available in the town. A field experiment was run to calculate the net capacity of these drums for storing biogas. Propane gas at 8-10 cm water pressure was added to a floating inverted drum in a water tank used as a hydraulic seal. The maximum raised point of the drum was 80 cm of its total height before bubbles of propane gas started emerging from inside of the drum to the atmosphere through the hydraulic seal. Based on this observation, the net gas capacity of each floating drum was estimated to be 230 L.

According to the SPCH (1985) standards, the normal gas storage amount should be 50% of the daily gas production. Assuming that the gas will be used for cooking in two shifts per day, one early in the morning and the other late in the afternoon, the storage capacity of the system was estimated to be 1,750 L per shift. Based on these data, the gas collection unit can be constructed using six floating inverted drums in a concrete water tank (Figure 4-5). The total biogas storage capacity is 1,380 L, which is approximately 40% of the assumed daily biogas production of the digester. This storage capacity should be enough for handling the daily requirements of biogas for cooking on the ranch.

The gas collection unit consists of two parts: 1) the water tank and 2) the gas storage drums (Figure 4-5).

The size of the water tank is 4.25 x 1.10 m. Excavation was not required for the foundation of this tank. A layer of concrete No. 50 was poured on the top of the soil. The tank floor was reinforced with steel sheet mesh (10x10 cm) in a 15 cm thick layer of concrete No. 200. The walls were constructed with prefabricated cement blocks, and plastered with a cement mortar (1:3). A finish layer of pure cement plaster was added for sealing both sides of the walls and the concrete floor. A 5 cm PVC drainage pipe was placed at 1.10 m above ground in a wall to discharge excess water from rain. If the rate of evaporation is noticed to be extremely high, a water input pipe with an automatic floater should be installed to maintain an adequate water level.



Note: Drawing not at scale.
Dimensions are in meters.

Figure 4-5 Gas Collectors.

Six metallic drums were used for collection of gas. To keep the floating drums in place and reduce the friction that could generate between the drums and the walls of the water tank, three 5 cm PVC pipes filled with concrete were used as guides for each drum. These PVC pipes were anchored at the bottom of the water tank. When the system was checked for gas leaks, it was found that three PVC guides pipe were not enough for steadying the drums in their proper places. It is recommended to use at least four guides per drum to avoid displacement of the drum.

A flexible gas pipe that comes from the digester was connected to the top layer of each drum. A spherical valve was connected in the top of each drum, so at any time, any drum could be taken out of line for maintenance or experimental purposes.

Between the gas line from the gas storage tank and the kitchen, an integrated water trap-flame arrester, a "U" manometer, and a "tee connection" (for biogas composition readings with the analyzer) were installed. The purpose of the water trap-flame arrester, located in the lowest elevation point of the gas line, is to collect all condensation of water between these two points and dissipate any flame coming back to the system from the stove. This trap was built with a 30 L metallic drum filled with clean gravel. The input gas pipe was placed in the middle height of the drum and the output pipe is located at the top of the drum. At the bottom of the drum there is a drainage valve for discharging excess water periodically.

The "U" manometer was built with the same type of flexible pipe used for the gas line. A tee connection was used for installing the in-place built manometer. Next to the "U" manometer, another "tee gas connection" was installed to allow for indirect reading of methane by using the Fyrite analyzer described previously.

Materials and Construction Specifications

Materials used in the construction of the system are listed in Appendix D. Basically the tanks were made of concrete floor with walls of prefabricated cement blocks. Most of the materials were available in the town.

Some of the materials used for construction of the units and its specifications are

-Cast-in-place concrete No. 50 (f'c= 50 kg $(cm^2)^{-1}$).

-Cast-in-place concrete No. 200 (f'c= 200 kg $(cm^2)^{-1}$).

-Prefabricated concrete block (12x20x40 cm) No. 150.

-Common clay brick (6x12x24 cm) above No. 75.

-Masonry mortar No. 75 with a proportion of cement:sand 1:3.

-Inlet/outlet pipes prefabricated with concrete No. 200.

The reinforced bars used for joining walls, beams, and foundations chains are prefabricated steel bars called "armex" with four 64 mm diameter steel bars welded together with rectangular steel rings at every 15 cm. The main design parameters are listed in Table 4-2.

All these main technical specifications and design parameters applied to all the units (feed chamber, digester, and gas collectors).

Costs

In Table D-1 a list of the materials and the labor involved in the construction of the system is presented. The time of construction of the system took approximately two months. Including materials and labor, the cost of the digester is \$200 US per m^3. This is double the cost compared to the family-size digesters built in Guatemala of \$100 US $(m^3)^{-1}$ per digester (CEMAT, 1993). The cost of the construction of the gas storage tank and the required connection for the gas line counted for 47% of the total cost of the system. The digester tank and the input chamber represented 46% and 7% of the total cost, respectively. Based on this experience, the cost of the digester could be significantly reduced using a different type of gas collector design. Further work is going to be done in measuring the methane production so control of the gas input in each drum is required. Construction of other similar digesters could be economically improved by reducing the connections in the gas line (around 7% of the total cost). In a stable soil where no additional reinforce bars are needed for supporting tensional forces, the cost of the

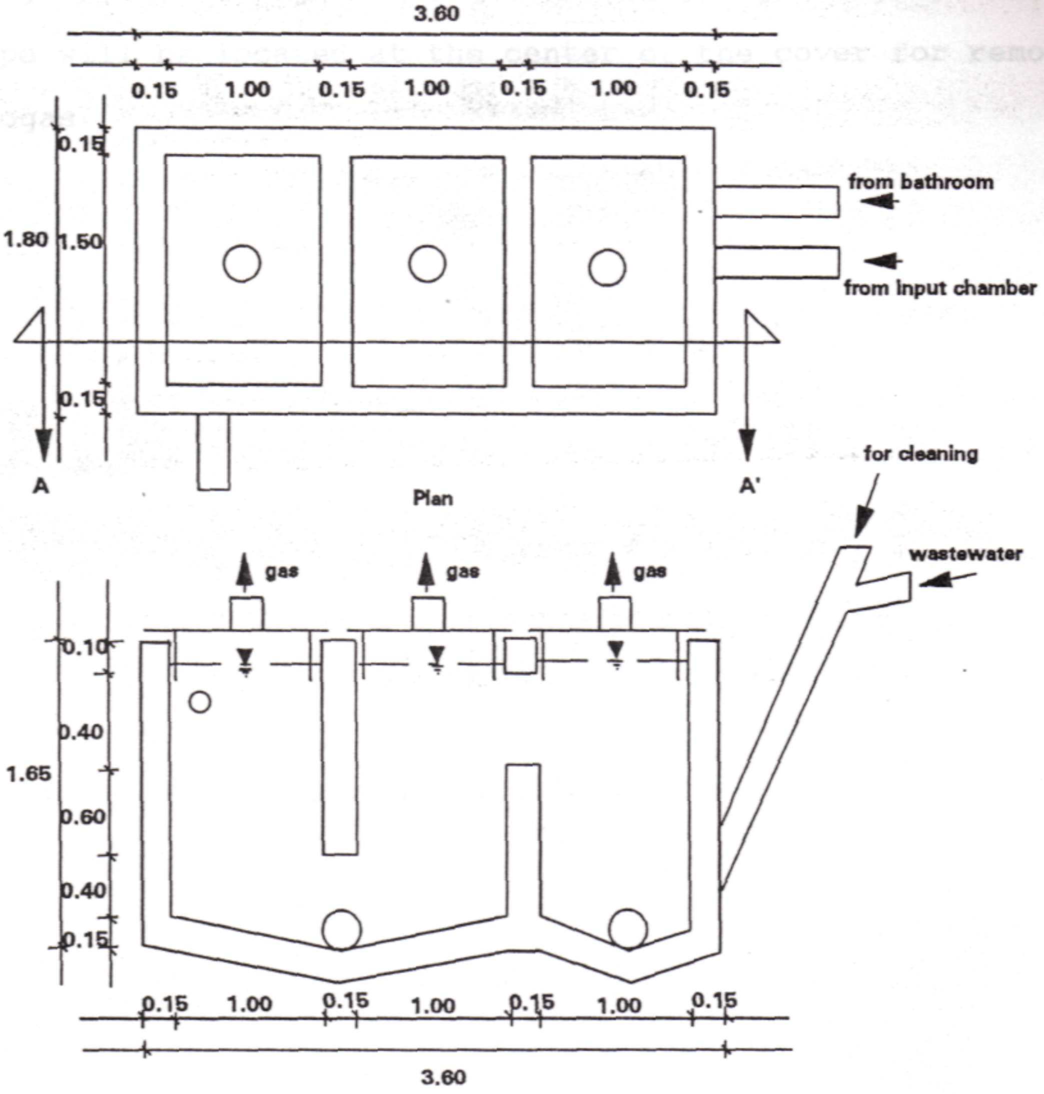
Table 4-2 Main Design Parameters.

Live load	200 kg m^{-2}
Normal working gas pressure inside the digester	<800 mm water pressure
Limit of maximum gas pressure inside the digester	<1200 mm water pressure
Maximum loading amount	90% of the digester volume
Effective volume of the storage gas unit	40% of the daily gas production
Groundwater level under the ground	0.7 m
Permissive bearing-force of the foundation	>5 ton $(m^2)^{-1}$

system could be reduced by approximately 10% of the total cost.

Shakedown and Testing

To check the system for gas tightness, a 40 kg propane liquified commercial gas tank was used. This tank was connected at the end of the gas line instead of the stove. First, the system between the stove and the storage tank was tested. The valve that connects the digester with the gas storage tank was closed. Using a gas regulator at 27 cm of water pressure for the propane tank, all the drums were filled with propane gas up to their equilibrium point of floating (no bubbles through the hydraulic sealing were allowed to go into the atmosphere). The drums were tested for 24 hours. No leaks were detected during this first check. The next step was to open the valve between the gas storage tank and the digester. When testing the digester, the liquid volume was at 30% of its capacity. The complete system was pressurized at 15 cm (water gauge) by using the propane gas. Soapy water was used as an indicator for gas leaks. Leaks were observed between the flat movable concrete covers and the walls. Substitution of the concrete covers with metal covers is suggested for sealing the system (Figure 4-6). A hydraulic seal will be created between the removable steel covers and the liquid of the digester. Three removable covers will be fabricated from sheet steel. The top sheet of each cover will extend across the walls.



Note: Drawing not at scale.
Dimensions are in meters.

Figure 4-6 Modified Digester.

Vertical sheets welded to this cover will extend down (30 cm height) to the digester liquid forming a gas tight seal. A pipe will be located at the center of the cover for removing biogas.

CHAPTER 6
OPERATION AND PERFORMANCE

Start-up and Performance

Inoculum

Next to the construction of the digester, there was a septic tank with a capacity of 5 m^3 that has been in use for two years on the ranch. Two thousand L of this septic tank liquid were poured into the digester. Because a high solids pump was not available anywhere in the town, the liquid was poured manually with buckets. The first chamber was filled to the top of the baffle wall (1 m deep), and the other chambers were filled to a depth of 40 cm. The inoculum had the following characteristics:

total solids content (% of wet weight) = 1.0

volatile solids content (% of wet weight) = 0.7

pH = 7.0 - 7.3

The advantage of having two chambers in the digester was that, during the start-up operation, the first chamber could become acidic without affecting the second chamber. The reason for initially feeding the digester before the covers were in place was to reduce the time of start-up and distribute the feed equally in the chambers. Oxygen inhibition was not a concern because the digester was not mixed.

Feed

The VGF for starting the digester was obtained from a fruit store in the town. This VGF contained a variety of fresh fruits and vegetables with an estimated volatile solids of 30% of the wet weight (Chynoweth, personal observation).

The amount of VGF added to the digester was 70 kg every other day during the start-up operation to allow enough time for microorganisms to stabilize the feed without producing acidic conditions. The feed amount was determined based on the criteria of adding 1 part of volatile solids from the VGF per 1 part of existing volatile solids of the inoculum in the digester. The VS of the inoculum was approximately 0.1% of the wet weight. Therefore, 2,000 L contained 20 kg of VS in the inoculum. To have the same amount of VS from the VGF, the amount of wet weight was:

(20 kg VS) x (kg wet weight / 30 kg VS) = 70 kg wet weight.

The VGF wastes were chopped manually in the feed chamber before being added to the digester. The pH was measured to check stability during each feeding operation. If a drop in the pH was detected (usually less than 7), the feeding operation was suspended until the pH was around neutral again.

Normal Digester Operation

Feed Addition

The wastewater stream coming from the bathroom only included the use of toilets; showers and sinks were excluded from the system. This stream adds directly to the digester 140 L of flushing water and approximately 50 kg wet human feces d^{-1}. According to the projected growth of the ranch another 50 kg wet animal manures will be added per day (Table 4-1). These animal manures will be collected manually from the different units of production (pigpen, henhouse, stable, etc.) and added to the digester via a feed chamber. These animal manures are supposed to be the main source for grit accumulation in the digester. VGF obtained in the ranch and from the town fruit stores will add 70 kg wet weight d^{-1} to the system.

The daily feed characteristics based on information given in Table 4-1 are

Total wet weight = 170 kg

Total flushing water = 140 kg

Estimated total volume = 310 L

Estimated total solids (TS) (% of diluted volume) = 5-15

Estimated volatile solids (VS) (% of wet weight) = 20

The estimated loading rate of the system is about 4.5 kg VS added m^{-3} d^{-1}. The hydraulic retention time (HRT) is estimated to be 24 days. The solids retention time (SRT) is calculated to be 3 to 4 times the HRT, around 85 days (Chynoweth, personal communication).

When adding the VGF, the size should be reduced by smashing and chopping the wastes manually. No dilution will be required for the VGF and animal manure wastes. To overcome any clogging problem in the input pipes of the wastewater stream and the feed chamber to the digester, a stick can be used to push any fecal material, scums or floaters accumulated in the pipes.

Effluent Removal

Once the digester has reached its working capacity (90-95% of the volume), the 10 cm output flexible pipe should be leveled off at the appropriate elevation that allows the digester liquid to stay at the level designed for operation (around 1.50 m liquid depth). In other words, the same volume of liquid that comes into the digester comes out when a steady state has been reached in the digester. A metallic drum will be used for the collection of the effluent liquid.

Gas Collection and Use

The maximum temporary storage capacity of the gas collectors is 40% of the daily biogas production. By cooking early in the morning and late in the afternoon most of the daily gas production of the system will be used (around 80%). The calculated working pressure of the system is between 8 and 10 cm water gauge. Many biogas burners connected to the Gobar and Chinese design digesters work with these water pressures (SPCH, 1985; Bux-Singh, 1971). If more pressure is needed for cooking, adding counterweights on the top of the drums can be used to increase it.

Biogas can not be burned with maximum efficiency on any burner designed for other specific gas uses (i.e., natural gas, propane, etc.). Biogas fed at a lower pressure (8-10 cm water gauge) will stay on the burner, but may not burn efficiently and less heat would be recovered from each cubic foot of gas. The Waston House Laboratory (Bux, 1971) recommended a burner with a flame port-area (i.e., sum of the areas of the individual flame ports) to injector-area ratio of about 300 to 1. Some designs (Bux, 1971) have obtained efficient and stable flames by using a burner with 36 ports of 0.290 cm diameter each (total port area equals 2.37 cm^2) and injectors with orifice diameters of 0.1 cm (area equals 0.008 cm^2); the gas pressure was supplied between 2.5 and 20 cm water gauge with a flame-port area to injector-area ratio of 296 to 1.

If not all the daily biogas production is used for cooking, any excess of biogas will be released to the atmosphere by escape through the hydraulic seal formed by the drum gas collector and the water in the tank. It is recommended that the PVC pipes that guide the vertical movement of the drums be checked periodically to avoid any friction between the drums and also with the walls of the tank.

Residue Use

Residue (slurry from the effluent of the digester) will be applied as fertilizer in the fields. The effluent from the digester has nitrogen in the form of ammonia. If this is stored in the open, the ammonia may be lost by evaporation or drainage. A closed effluent collector drum is therefore recommended to minimize losses of nitrogen. For the application of the residues directly to the fields, it will be necessary to periodically run some analyses to check the level of pathogens because of their potential impact on human health.

Operational Problems

Scum formation in the top of the chambers may be a problem if it is not monitored adequately. Also, the presence of floating solids can clog the gas pipe system. In the top of each cover there is a tee connection to allow cleaning the pipes from outside. By using a stick with a similar diameter as the gas pipe, the scum may be broken from the top of the covers. If many floaters are detected, mainly in the first chamber, and it is not possible to unclog the system from outside, removal of the cover is recommended for cleaning purposes.

If, during the operation of the digester, it is observed that scum travels further into the gas pipe, a scum trap may be constructed between the digester and the gas collectors. A gastight 100 L metallic drum will be installed close to the digester. The gas line coming from the digester is connected at the middle height of the drum. The output gas line is connected to the top of the drum. By gravity all the scum will be accumulated at the bottom of the drum, and a 10 cm pipe with a gastight plug will be installed for periodic drainage of the scum from the drum.

The digester has two 20 cm diameter concrete pipes at the bottom for withdrawal of grit accumulated during the operation of the digester. Most of the grit will be accumulated in the first chamber because of the baffle wall (1 m height above ground) (Figure 4-3). The bottom of the tank has a 3% slope both in the perpendicular and parallel direction of the effluent pipe to facilitate the removal of grit from outside.

Evaluation of Performance

To evaluate the performance of the digester, different indicators have been used for this purpose. Among the most common are gas production and composition, pH, pathogens reduction, solids reduction, and materials balance.

As mentioned before, each drum gas collector has a valve to control gas flow. The gas production can be measured at any time while using these valves. The methane content of the biogas can be indirectly measured by using the Fyrite analyzer previously described. The Fyrite reads the percent of carbon dioxide in the gas. Assuming that methane and carbon dioxide are the only components of biogas, the methane content can be calculated. (The two most significant components of biogas are carbon dioxide and methane which account for around 99.5% of the total gas composition)

Similar to the starting operation, the pH of the digester liquid should be measured periodically to check for stability of the system. Measurements of the pH of the system can be taken in the liquid effluent. An electronic pH meter with an accuracy of around 0.2 pH has been proved to be useful on the ranch and easy to read by local people.

The potential hazards inherent in the anaerobic digestion of wastes include the handling of human feces and animal manures. Fecal coliform bacterial densities may be determined by the Membrane Filter (MF) technique described in Standard Methods (APHA-AWWA-WEF, 1992). Pathogen reduction data can be obtained by applying this technique to the influent and effluent streams of the digester.

Total solids (TS) and volatile solids (VS) analyses will be also performed to the influent and effluent streams of the digester. Because of the diversity of organic matter coming into the digester (human feces, animal manures and VGF wastes), and the lack of adequate lab instruments to perform these analysis, TS reduction and materials balance will be very imprecise if done at the ranch. If it is possible to trace the input and output of organic matter, and the methane yield at any given time, a carbon balance can be done in the digester to evaluate the performance of the system.

Cost Benefit Analysis

The financial viability of the digester will depend on whether outputs in the form of gas, slurry and sludge can substitute for gas propane and fertilizers which have to be purchased at present. If so, the resulting cash savings can be used to repay the capital and maintenance costs, and the digester has a good chance of being financially viable. However, if the outputs do not generate a cash inflow, or reduce cash outflow, the digester loses financial viability.

Other benefits should be incorporated into this economic evaluation. Digesters can generate a variety of social and environmental benefits that are sometimes relevant to financial analysis. To achieve a social and financial analysis to determine the benefit-cost ratio of an anaerobic digester is difficult due to the ambiguity of establishing prices for the different digester products and the other benefits that this process creates, such as, saving cooking time for women, health-related effects, decreasing the rate of deforestation, etc.

A major source behind renewable energy technology research and development, including biogas, has been the need to eliminate deforestation by using substitutes for traditional fuelwood. Presently gas propane and fuelwood are used for cooking. Using methane as a fuel for cooking can decrease the rate of deforestation at the ranch.

The introduction of the digester for treatment of the human wastewater and animal wastes in the ranch should not create any new or additional health hazards. On the contrary, it should reduce the present health hazards significantly.

Current Status and Future Strategy for Evaluation

The movable concrete covers failed to be suitable for the digester because of the leaks found between them and the walls. Also, concrete covers happened to be too heavy for future manipulation (around 250 kg each). Substitution with metal covers was suggested and using an hydraulic seal with the liquid of the digester was recommended to avoid any future gas leaks. The metallic covers should be covered with a tar or other appropriate paint to protect them against corrosion.

The construction of the digester was performed in the Summer of 1993. By the time of writing this thesis (fall, 1993), local people are substituting the covers. Future evaluation of the performance of this digester is planned for the summer of 1994. Detail analyses for pathogen reduction, gas production and composition, residue application, and training people will be done next summer when the digester is expected to be at steady state.

CHAPTER 7
CONCLUSION

For the selection of the 8 m^3 baffled plug-flow digester for the ranch, characteristics such as quantity and quality of the wastes and its composition (TS and VS), site topography, temperature, economics, and material availability for construction were considered during the design phase. This type of digester was selected because of the following reasons: 1) The overall total solid content (TS) of the mixed feed (wastewater stream, animal manures and VGF wastes) was between 5 and 15% of the diluted wet weight, which was considered appropriate for this design; 2) baffles in the design promoted higher conversion efficiencies by increasing the solid retention time (SRT) and the microorganism retention time (MRT) in the digester; 3) the simplicity in the construction procedure reduced the cost of the digester; 4) the digester containing two chambers as a safety factor reduced the probability of the whole digester becoming imbalanced; and 5) the rectangular shape facilitated the construction of flat removable covers for maintenance purposes.

The biggest problem found during the construction phase was that the flat movable concrete covers proved too heavy for future manipulation. Also, at the contact points between the concrete covers and the walls, gas leaks were detected. Light metal sheet covers were suggested as a substitute for the concrete covers. Having a hydraulic seal between the metal covers and the liquid in the digester, the potential of leaking might be null.

The construction of three units (feed chamber, digester, and gas collectors) increased the cost of the system but eases its maintenance. Construction time of the system took approximately two months. Including materials and labor (of all units), the price per m^3 of total volume of digester is about $200 US (Appendix D). Costs might be lowered if the gas storage unit is integrated into the digester.

The equipment used for running the laboratory studies at small scale proved to be adequate for giving an approximate idea of the production of methane for different organic matters (pig, goat, chicken, and liquid septic tank) in the field where precise and sophisticated techniques such as BMP might not be available. The methane yield obtained in the field for the pig sample (250 ml CH_4 (g VS added)$^{-1}$ (Figure C-1)) was lower than another pig sample run in the lab (400 ml CH_4 (g VS added)$^{-1}$ (Figure B-2)). The higher value obtained in the lab using the biochemical methane potential (BMP) assay was attributed to the more ideal conditions in the lab.

The performance and efficiency of this digester on the ranch has to be evaluated and compared with other digester designs. Based on these results, the design can be improved and proposed to other ranches with similar characteristics and for households and small communities. Future work has to be done related to the best use of gas produced by the fermentation process. Gas use for light can be proposed for farms and villages that lack electricity. Slurry and sludge residues from the digester used as fertilizers have to be evaluated based on cost-benefit analysis and the human health risks involved in the application on the field. Studies of the implications that this technology (anaerobic digestion) has on the deforestation rate (by using methane instead of wood for cooking) and rural sanitation have to be done, especially in the highlands of the southern tropics of Mexico.

APPENDIX A
RAW DATA FOR EXPERIMENT IN THE FIELD

Table A-1 Samples for running biogas production.

Sample Number	Content	amount used (g)
1	pig	50.00
2	pig	50.00
3	goat	50.00
4	goat	50.00
5	chicken	50.00
6	chicken	50.00
7	inoculum (septic tank liquid)	750.00
8	inoculum	750.00
9	inoculum	750.00

Table A-2 Calculation of Total Solids (TS) and Volatile Solids (VS).

Sample Number	Content	Tare weight (g)	Tare weight + sample (g)	After 105oC. (24 hrs.) (g)	After 550oC. (1 hr.) (g)	Wet weight (g)	VS (g)	TS (g)	VS wet weight	TS wet weight	VS of TS
1	pig	1.6585	4.1649	2.4716	1.8367	2.5064	0.6349	0.8131	0.2533	0.3244	0.7808
2	pig	1.5753	5.0608	2.6519	1.8322	3.4855	0.8197	1.0766	0.2352	0.3089	0.7614
3	pig	1.5000	5.7542	2.7708	1.8167	4.2542	0.9541	1.2708	0.2243	0.2987	0.7508
avg.		1.5779	4.9933	2.6314	1.8285	3.4154	0.8029	1.0535	0.2376	0.3107	0.7643
4	goat	1.5364	5.9463	3.4887	2.0455	4.4099	1.4432	1.9523	0.3273	0.4427	0.7392
5	goat	1.6475	6.7745	3.8256	2.2334	5.1270	1.5922	2.1781	0.3106	0.4248	0.7310
6	goat	1.6077	6.5575	3.5941	2.1512	4.9498	1.4429	1.9864	0.2915	0.4013	0.7264
avg.		1.5972	6.4261	3.6361	2.1434	4.8289	1.4928	2.0389	0.3098	0.4229	0.7322
7	chicken	1.4795	5.4361	2.4612	1.6887	3.9566	0.7725	0.9817	0.1952	0.2481	0.7869
8	chicken	1.5362	5.3016	2.4353	1.7089	3.7654	0.7264	0.8991	0.1929	0.2388	0.8079
9	chicken	1.5335	5.5094	2.5755	1.7733	3.9759	0.8022	1.0420	0.2018	0.2621	0.7699
avg.		1.5164	5.4157	2.4907	1.7236	3.8993	0.7670	0.9743	0.1966	0.2497	0.7882
10	inoculum	1.5536	33.2354	1.8499	1.6273	31.6818	0.2226	0.2963	0.0070	0.0094	0.7513
11	inoculum	1.5698	45.4243	2.0171	1.6982	43.8545	0.3189	0.4473	0.0073	0.0102	0.7129
12	inoculum	1.6491	47.7471	2.0897	1.7776	46.0980	0.3121	0.4406	0.0068	0.0096	0.7084
avg.		1.5908	42.1356	1.9856	1.7010	40.5448	0.2845	0.3947	0.0070	0.0097	0.7242

Table A-3 Biogas Production.

Sample number	Content	day # 1 6/21/93 vol (ml)	2 6/22 vol (ml)	3 6/23 vol (ml)	4 6/24 vol (ml)	5 6/25 vol (ml)	7 6/27 vol (ml)	8 6/28 vol (ml)	9 6/29 vol (ml)	11 7/1 vol (ml)
1	pig	0	440	380	370	0	320	0	260	300
2	pig	0	280	210	0	360	0	0	480	320
avg		0	360	295	185	180	160	0	370	310
3	goat	0	280	490	440	380	0	480	370	400
4	goat	0	360	330	340	300	0	420	300	360
avg		0	320	410	390	340	0	450	335	380
5	chicken	0	160	0	0	0	0	0	100	40
6	chicken	0	160	0	0	0	0	360	180	260
avg		0	160	0	0	0	0	180	140	150
7	inoculum	0	160	0	0	0	0	0	150	20
8	inoculum	0	200	0	0	0	0	260	0	20
9	inoculum	0	140	0	0	0	0	0	140	0
avg		0	167	0	0	0	0	87	97	13

Table A-3 --continued.

Sample number	Content	12 7/2 vol (ml)	14 7/4 vol (ml)	16 7/6 vol (ml)	18 7/8 vol (ml)	21 7/11 vol (ml)	27 7/17 vol (ml)	37 7/27 vol (ml)	40 7/31 vol (ml)	44 8/4 vol (ml)
1	pig	240	450	0	140	0	470	0	110	0
2	pig	220	460	0	320	0	430	0	80	0
avg		230	455	0	230	0	450	0	95	0
3	goat	260	510	0	440	0	500	0	0	0
4	goat	310	640	300	520	500	480	400	0	0
avg		285	575	150	480	250	490	200	0	0
5	chicken	270	0	0	420	0	580	0	0	0
6	chicken	170	370	0	420	0	360	0	140	20
avg		220	185	0	420	0	470	0	70	10
7	inoculum	20	60	0	0	0	0	0	120	0
8	inoculum	60	70	0	0	0	0	0	110	0
9	inoculum	20	60	0	0	0	0	0	120	0
avg		33	63	0	0	0	0	0	117	0

APPENDIX B
ANALYSIS OF RAW DATA FROM BMP ASSAY

Table B-1 Data for BMP (Serum) bottles.

Sample Number	Content	bottle weight (g)	material added (g)	bottle+manure +medium (g)	medium added (g)
1	cow	232.01	0.98	333.90	100.91
2	cow	230.88	0.98	328.28	96.42
3	cow	236.67	0.98	330.64	92.99
avg.			0.98		96.77
4	pig	235.63	0.80	326.32	89.89
5	pig	232.90	0.80	329.15	95.45
6	pig	231.62	0.80	325.46	93.04
avg.			0.80		92.79
7	cellulose	232.01	0.20	326.43	94.22
8	cellulose	232.67	0.20	326.12	93.25
9	cellulose	231.75	0.20	326.76	94.81
avg.			0.20		94.09
10	control	234.77	0.00	332.04	97.27
11	control	234.37	0.00	326.50	92.13
12	control	234.50	0.00	325.96	91.46
avg.			0.00		93.62

Table B-2 Data for Gas Production.

Sample		day # 1		4		9		18		34		44	
Number	Content	2/22/93		2/25/93		3/2/93		3/11/93		3/27/93		4/5/93	
		vol (ml)	% CH4	vol (ml)	% CH4	vol (ml)	% CH4	vol (ml)	% CH4	vol (ml)	% CH4	vol (ml)	% CH4
1	cow	24.00	4.89	5.50	10.56	21.00	12.27	26.00	18.84	24.00	27.69	8.00	25.33
2	cow	24.00	4.54	4.50	6.74	22.50	11.71	23.00	18.76	24.00	25.58	8.00	27.37
3	cow	26.00	4.58	4.50	6.35	25.00	12.32	23.00	18.98	25.00	25.14	8.50	24.58
avg.		24.67	4.67	4.83	7.88	22.83	12.10	24.00	18.86	24.33	26.14	8.17	25.76
4	pig	70.00	16.42	36.00	23.15	28.00	26.67	12.00	31.66	14.00	33.88	8.50	32.97
5	pig	80.00	17.99	38.00	25.78	34.00	29.96	14.00	34.87	11.00	37.43	8.00	39.59
6	pig	78.00	16.86	37.00	25.29	29.00	29.82	13.00	34.06	14.00	--	8.50	39.63
avg.		76.00	17.09	37.00	24.74	30.33	28.82	13.00	33.53	12.50	35.66	8.33	37.40
7	cellulose	92.00	14.57	45.00	23.31	22.00	25.90	14.00	31.59	12.50	35.24	5.00	28.80
8	cellulose	100.00	15.62	44.00	23.69	25.00	27.00	12.00	31.53	13.00	35.55	5.00	33.30
9	cellulose	87.00	12.97	48.00	23.23	31.00	27.85	14.00	31.95	14.00	36.13	4.50	35.13
avg.		93.00	14.39	45.67	23.41	26.00	26.92	13.33	31.69	13.17	35.64	4.83	32.41
10	control	22.00	3.93	3.00	23.12	5.50	7.22	3.00	31.39	7.00	14.47	7.00	10.80
11	control	25.00	3.89	1.50	11.00	6.00	6.01	3.00	18.86	7.00	11.82	5.00	11.15
12	control	24.50	3.56	--	--	6.00	5.90	1.00	--	8.00	11.03	5.00	12.00
avg.		23.83	3.79	1.50	11.37	5.83	6.38	2.33	16.75	7.33	12.44	5.67	11.32

Table B-3 Calculation of Total Solids (TS) and Volatile Solids (VS).

Sample Number	Content	Tare weight (g)	Tare weight + sample (g)	After 105oC. (24 hrs.) (g)	After 550oC. (2 hrs.) (g)	Wet weight (g)	VS	TS	VS wet weight	TS wet weight	VS of TS
1	cow	1.5880	7.0256	2.7042	1.5972	5.4376	1.1070	1.1162	-	-	-
2	cow	1.5975	6.5123	2.5932	1.5862	4.9148	1.0070	0.9957	-	-	-
3	cow	1.5985	6.6374	2.6393	1.5909	5.0389	1.0484	1.0408	-	-	-
avg.		1.5947	6.7251	2.6456	1.5914	5.1304	1.0541	1.0509	0.204	0.210	0.970
4	pig	1.5994	7.4929	3.2723	1.8146	5.8935	1.4577	1.6729	-	-	-
5	pig	1.6072	6.9479	3.1119	1.7946	5.3407	1.3173	1.5047	-	-	-
6	pig	1.6060	8.6907	3.6626	1.8764	7.0847	1.7862	2.0566	-	-	-
avg.		1.6042	7.7105	3.3489	1.8285	6.1063	1.5204	1.7447	0.249	0.295	0.845
7	cellulose	-	-	-	-	-	-	-	-	-	-
8	cellulose	-	-	-	-	-	-	-	-	-	-
9	cellulose	-	-	-	-	-	-	-	-	-	-
avg.		-	-	-	-	-	-	-	1.000	1.000	1.000
10	inoculum	2.6917	12.6112	2.7628	2.7384	9.9195	0.0244	0.0711	-	-	-
11	inoculum	2.6854	12.6070	2.7567	2.7318	9.9216	0.0249	0.0713	-	-	-
12	inoculum	2.6763	12.4744	2.7472	2.7230	9.7981	0.0242	0.0709	-	-	-
avg.		2.6845	12.5642	2.7556	2.7311	9.8797	0.0245	0.0711	0.002	0.007	0.345

Table B-4 Cow Analysis.

time (day)	vol (ml)	%CH4	volume CH4 (cm3)	cumul. CH4 (cm3)	control CH4 (cm3)	net CH4 (cm3)	mat. added (g)	%VS mat. added	VS added (g)	cumul. data (cm3/g	curve-fit y=Yu(1-exp(-kt) (cm3/gVS)
1	25	4.67	1.17	1.17	7.54	1.80	0.98	20.00	0.20	9.17	10.849
4	5	7.88	0.39	1.56	7.64	7.72	0.98	20.00	0.20	39.40	40.477
9	23	12.10	2.78	4.34	12.53	12.99	0.98	20.00	0.20	66.26	81.395
18	24	18.86	4.53	8.87	12.70	29.18	0.98	20.00	0.20	148.88	134.54
34	24	26.14	6.27	15.14	24.14	36.75	0.98	20.00	0.20	187.48	187.65
47	8	26.00	2.08	17.22	22.28	40.45	0.98	20.00	0.20	206.36	209.19

Table B-5 Pig Analysis.

time (day)	vol (ml)	%CH4	volume CH4 (cm3)	cumul. CH4 (cm3)	control CH4 (cm3)	net CH4 (cm3)	mat. added (g)	%VS mat. added	VS added (g)	cumul. data (cm3/g	curve-fit y=Yu(1-exp(-kt) (cm3/gVS)
1	76	17.09	12.99	12.99	7.54	35.35	0.80	25.00	0.20	176.77	130.99
4	37	24.74	9.15	22.14	7.64	57.80	0.80	25.00	0.20	289.01	315.56
9	30	28.81	8.64	30.79	12.53	68.67	0.80	25.00	0.20	343.35	383.2
18	13	33.53	4.36	35.14	12.70	81.13	0.80	25.00	0.20	405.63	393.23
34	13	36.00	4.68	39.82	24.14	78.69	0.80	25.00	0.20	393.43	393.5
47	8	37.00	2.96	42.78	22.28	85.26	0.80	25.00	0.20	426.28	393.5

Table B-6 Cellulose Analysis.

time (day)	vol (ml)	%CH4	volume CH4 (cm3)	cumul. CH4 (cm3)	control CH4 (cm3)	net CH4 (cm3)	mat. added (g)	%VS mat. added	VS added (g)	cumul. data (cm3/g	curve-fit y=Yu(1-exp(-kt) (cm3/gVS)
1	93	14.40	13.39	13.39	7.54	31.05	0.20	100.00	0.20	155.25	126.58
4	46	23.41	10.77	24.16	7.64	57.49	0.20	100.00	0.20	287.46	302.12
9	26	26.92	7.00	31.16	12.53	65.74	0.20	100.00	0.20	328.68	364.41
18	13	31.69	4.12	35.28	12.70	78.04	0.20	100.00	0.20	390.20	373.18
34	13	35.64	4.63	39.91	24.14	78.15	0.20	100.00	0.20	390.73	373.4
47	5	32.00	1.60	41.51	22.28	75.24	0.20	100.00	0.20	376.18	373.4

Table B-7 Control Analysis.

time (day)	vol (ml)	%CH4	volume CH4 (cm3)	cumul. CH4 (cm3)	mat. added (g)	%VS mat. added	VS added (g)	cumul. data (cm3/gV	curve-fit y=Yu(1-exp(-kt)) (cm3/gVS)
1	24	3.79	0.91	0.91	94.00	0.20	0.19	40.12	8.99
4	2	3.80	0.08	0.99	94.00	0.20	0.19	40.61	32.25
9	6	6.38	0.38	1.37	94.00	0.20	0.19	66.67	61.04
18	2	6.40	0.13	1.50	94.00	0.20	0.19	67.53	92.06
34	7	12.44	0.87	2.37	94.00	0.20	0.19	128.39	114.49
47	6	11.00	0.66	3.03	94.00	0.20	0.19	118.50	120.48

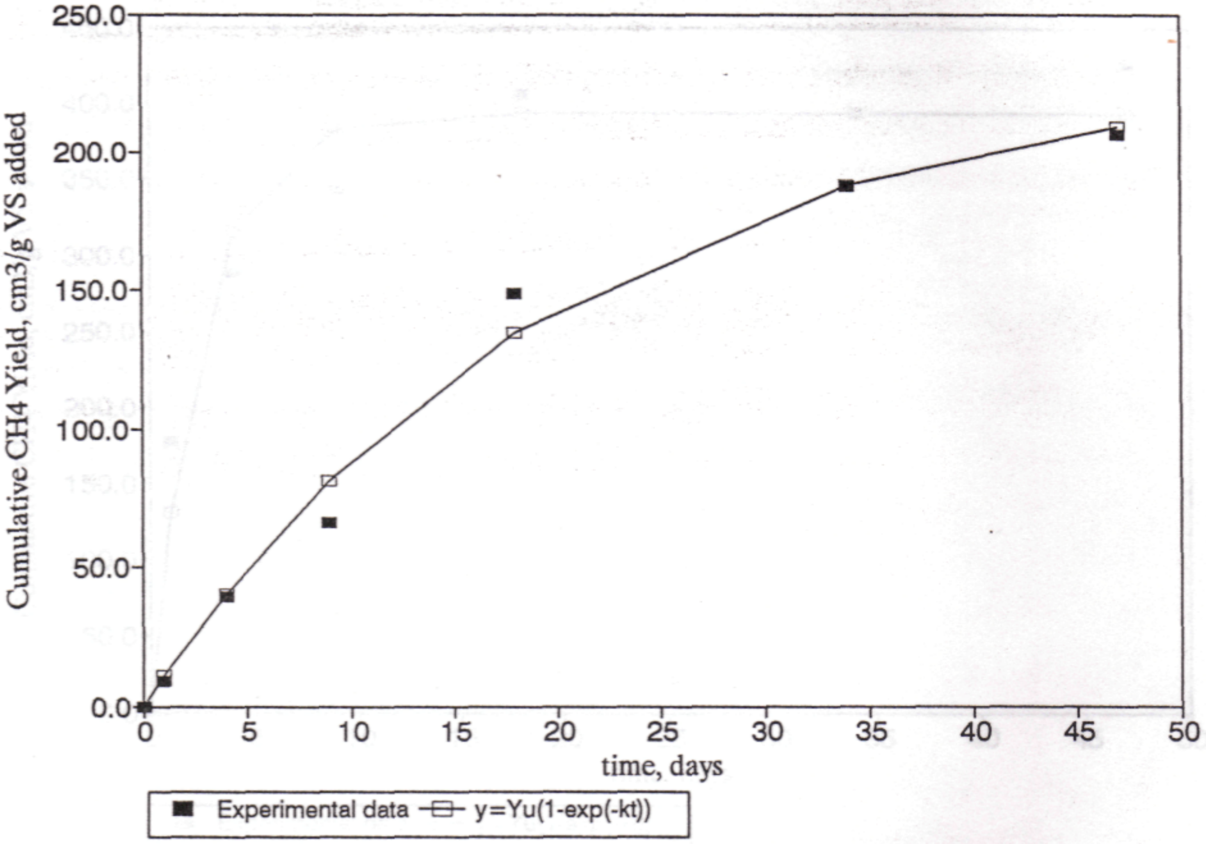


Fig. B-1 Methane Yield for Cow Manure.

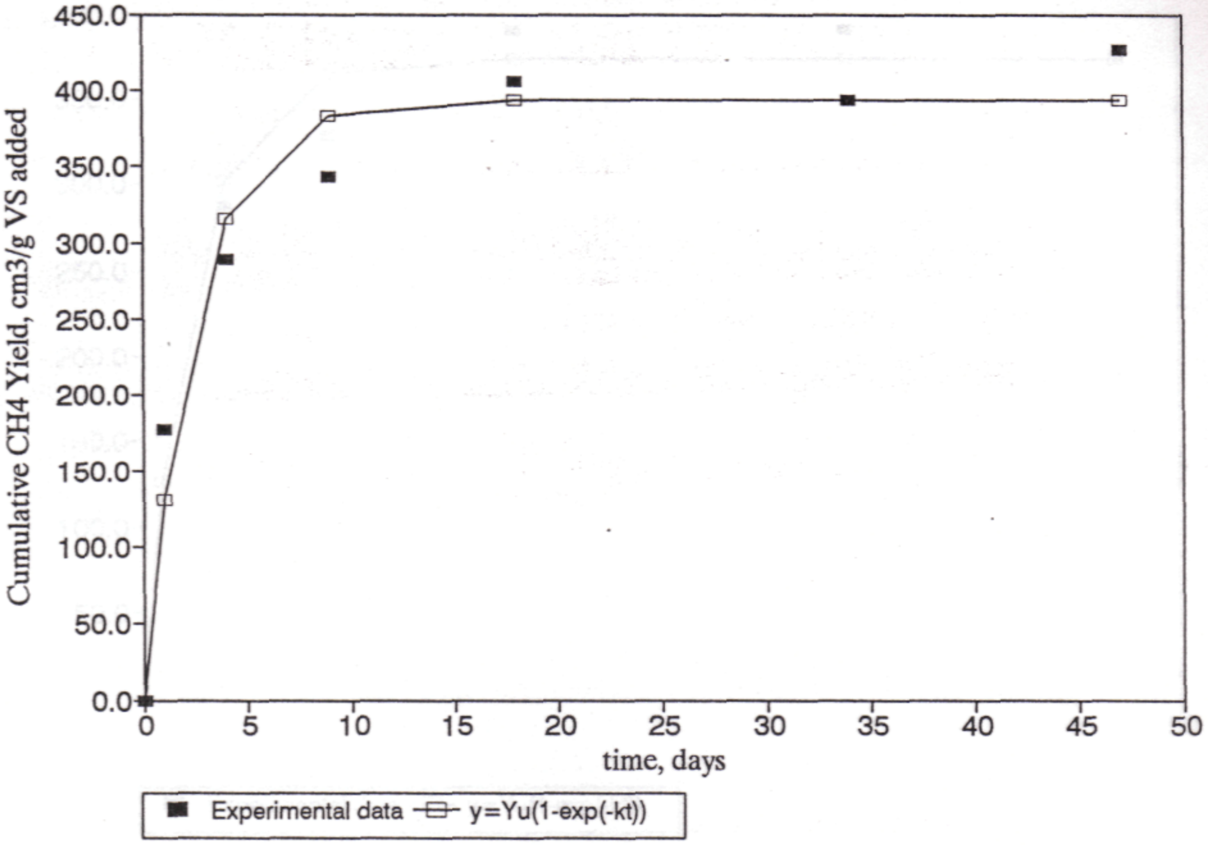


Fig. B-2 Methane Yield for Pig Manure.

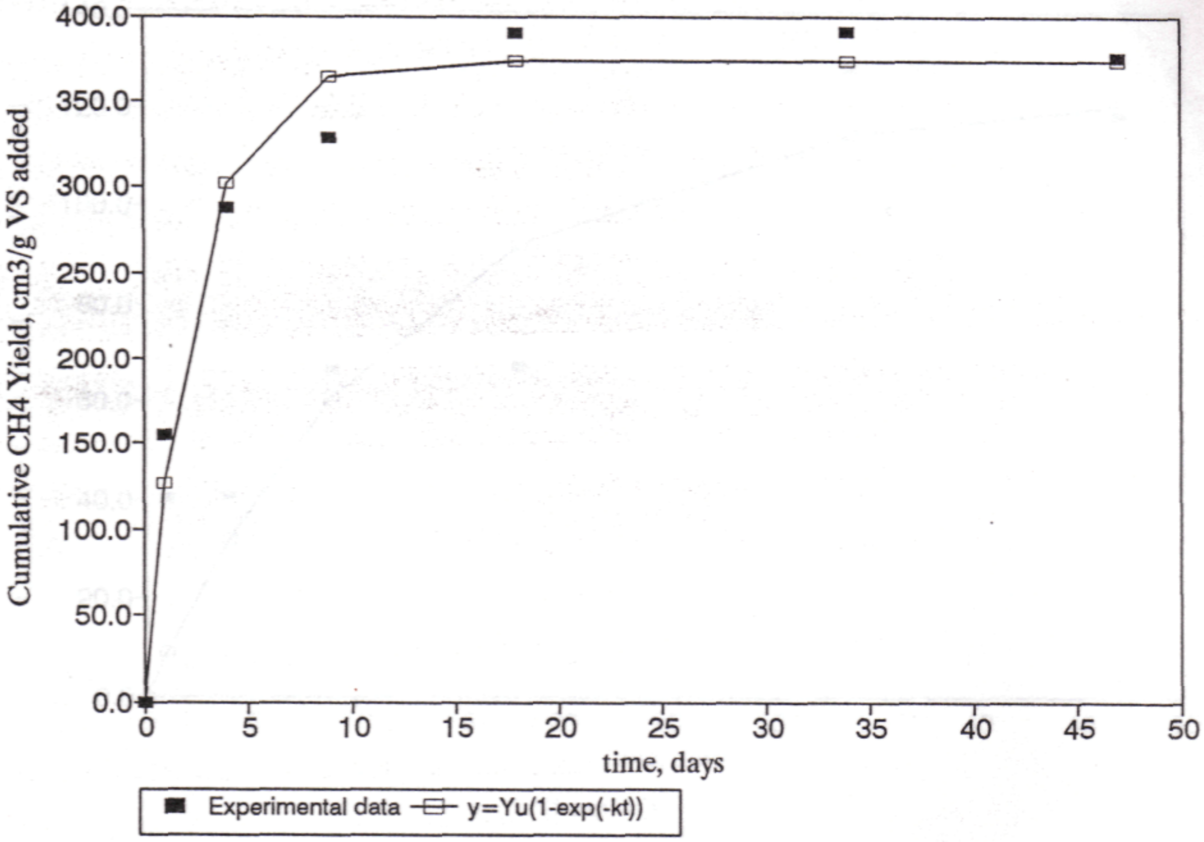


Fig. B-3 Methane Yield for Cellulose.

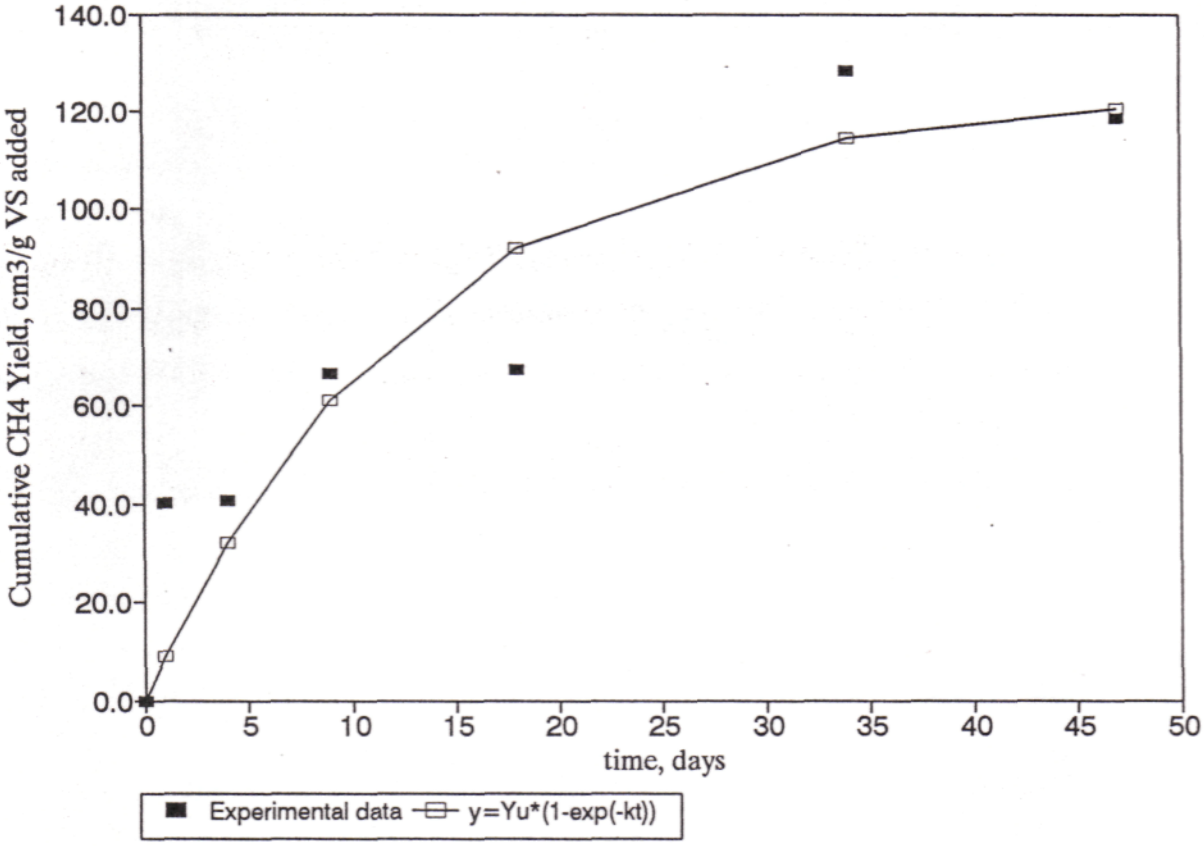


Fig. B-4 Methane Yield for Control.

APPENDIX C
ANALYSIS OF RAW DATA FROM FIELD EXPERIMENT

Table C-1 Pig Analysis.

time (day)	vol (ml)	temp. (oC.)	vol (35oC) (ml)	%CH4	volume CH4 (cm3)	cumul. CH4 (cm3)	head CH4 (cm3)	total CH4 (cm3)
1	0	24	0	60	0	0	0	0
2	360	26	485	60	291	290	210	500
3	295	22	469	60	282	570	210	780
4	185	24	270	60	162	730	210	940
5	180	22	286	60	172	900	210	1110
7	160	25	224	60	134	1030	210	1240
8	0	22	0	60	0	1030	210	1240
9	370	24	540	60	324	1350	210	1560
11	310	23	472	60	283	1630	210	1840
12	230	24	335	60	201	1830	210	2040
14	455	29	549	60	329	2160	210	2370
16	0	23	0	60	0	2160	210	2370
18	230	24	335	60	201	2360	210	2570
21	0	22	0	60	0	2360	210	2570
27	450	26	606	60	363	2720	210	2930
37	0	25	0	60	0	2720	210	2930
40	95	24	139	60	83	2800	210	3010
44	0	24	0	60	0	2800	210	3010

Table C-1 --continued.

time (day)	control CH4 (cm3)	net CH4 (cm3)	mat. added (g)	%VS mat. added	VS added (g)	cumul. data (cm3/gVS)	curve-fit y=Yu(1-exp(-kt)) (cm3/gVS)
1	0	0	50	24	12	0	0
2	57	440	50	24	12	37	38
3	57	720	50	24	12	60	55
4	57	880	50	24	12	73	70
5	57	1050	50	24	12	88	85
7	57	1180	50	24	12	98	110
8	71	1170	50	24	12	98	122
9	85	1470	50	24	12	123	132
11	87	1750	50	24	12	146	151
12	92	1950	50	24	12	163	159
14	100	2270	50	24	12	189	173
16	100	2270	50	24	12	189	186
18	100	2470	50	24	12	206	196
21	100	2470	50	24	12	206	209
27	100	2830	50	24	12	236	228
37	100	2830	50	24	12	236	244
40	117	2890	50	24	12	241	247
44	117	2890	50	24	12	241	250

Table C-2 Goat Analysis.

time (day)	vol (ml)	temp. (oC.)	vol (35oC) (ml)	%CH4	volume CH4 (cm3)	cumul. CH4 (cm3)	head CH4 (cm3)	total CH4 (cm3)
1	0	24	0	60	0	0	0	0
2	320	26	431	60	258	260	210	470
3	410	22	652	60	391	650	210	860
4	390	24	569	60	341	990	210	1200
5	340	22	541	60	325	1310	210	1520
7	0	25	0	60	0	1310	210	1520
8	450	22	716	60	430	1740	210	1950
9	335	24	489	60	293	2030	210	2240
11	380	23	578	60	347	2380	210	2590
12	285	24	416	60	249	2630	210	2840
14	575	29	694	60	416	3050	210	3260
16	150	23	228	60	137	3190	210	3400
18	480	24	700	60	420	3610	210	3820
21	250	22	398	60	239	3850	210	4060
27	490	26	660	60	396	4250	210	4460
37	200	25	280	60	168	4420	210	4630
40	0	24	0	60	0	4420	210	4630
44	0	24	0	60	0	4420	210	4630

Table C-2 --continued.

time (day)	control CH4 (cm3)	net CH4 (cm3)	mat. added (g)	%VS mat. added	VS added (g)	cumul. data (cm3/g	curve-fit y=Yu(1-exp(-kt)) (cm3/gVS)
1	0	0	50	31	16	0	0
2	57	410	50	31	16	26	40
3	57	800	50	31	16	52	58
4	57	1140	50	31	16	74	75
5	57	1460	50	31	16	94	90
7	57	1460	50	31	16	94	119
8	71	1880	50	31	16	121	132
9	85	2150	50	31	16	139	144
11	87	2500	50	31	16	161	166
12	92	2750	50	31	16	177	176
14	100	3160	50	31	16	204	194
16	100	3300	50	31	16	213	210
18	100	3720	50	31	16	240	224
21	100	3960	50	31	16	255	241
27	100	4360	50	31	16	281	267
37	100	4530	50	31	16	292	293
40	117	4510	50	31	16	291	298
44	117	4510	50	31	16	291	304

Table C-3 Chicken Analysis.

time (day)	vol (ml)	temp (oC.)	vol (35oC) (ml)	%CH4	volume CH4 (cm3)	cumul. CH4 (cm3)	head CH4 (cm3)	total CH4 (cm3)
1	0	24	0	60	0	0	0	0
2	160	26	215	60	129	130	210	340
3	0	22	0	60	0	130	210	340
4	0	24	0	60	0	130	210	340
5	0	22	0	60	0	130	210	340
7	0	25	0	60	0	130	210	340
8	180	22	286	60	172	300	210	510
9	140	24	204	60	123	420	210	630
11	150	23	228	60	137	560	210	770
12	220	24	321	60	193	750	210	960
14	185	29	223	60	134	880	210	1090
16	0	23	0	60	0	880	210	1090
18	420	24	613	60	368	1250	210	1460
21	0	22	0	60	0	1250	210	1460
27	470	26	633	60	380	1630	210	1840
37	0	25	0	60	0	1630	210	1840
40	70	24	102	60	61	1690	210	1900
44	10	24	15	60	9	1700	210	1910

Table C-3 --continued.

time (day)	control CH4 (cm3)	net CH4 (cm3)	mat. added (g)	%VS mat. added	VS added (g)	cumul. data (cm3/gVS)	curve-fit y=Yu(1-exp(-kt)) (cm3/gVS)
1	0	0	50	20	10	0	0
2	57	280	50	20	10	28	16
3	57	280	50	20	10	28	24
4	57	280	50	20	10	28	32
5	57	280	50	20	10	28	39
7	57	280	50	20	10	28	53
8	71	440	50	20	10	44	60
9	85	540	50	20	10	54	66
11	87	680	50	20	10	68	78
12	92	870	50	20	10	87	84
14	100	990	50	20	10	99	95
16	100	990	50	20	10	99	105
18	100	1360	50	20	10	136	114
21	100	1360	50	20	10	136	127
27	100	1740	50	20	10	174	149
37	100	1740	50	20	10	174	177
40	117	1780	50	20	10	178	184
44	117	1790	50	20	10	179	192

Table C-4 Inoculum Analysis.

time (day)	vol (ml)	temp (oC.)	vol (35oC) (ml)	%CH4	volume CH4 (cm3)	cumul. CH4 (cm3)	head CH4 (cm3)
1	0	24	0	10	0	0	0
2	167	26	225	10	22	22	35
3	0	22	0	10	0	22	35
4	0	24	0	10	0	22	35
5	0	22	0	10	0	22	35
7	0	25	0	10	0	22	35
8	87	22	138	10	14	36	35
9	97	24	141	10	14	50	35
11	13	23	20	10	2	52	35
12	33	24	48	10	5	57	35
14	63	29	76	10	8	65	35
16	0	23	0	10	0	65	35
18	0	24	0	10	0	65	35
21	0	22	0	10	0	65	35
27	0	26	0	10	0	65	35
37	0	25	0	10	0	65	35
40	117	24	171	10	17	82	35
44	0	24	0	10	0	82	35

Table C-4 --continued.

time (day)	total CH4 (cm3)	mat. added (g)	%VS mat. added	VS added (g)	cumul. data (cm3/gVS)	curve-fit y=Yu(1-exp(-kt)) (cm3/gVS)
1	0	750	1	5	0	0
2	57	750	1	5	11	6
3	57	750	1	5	11	8
4	57	750	1	5	11	10
5	57	750	1	5	11	12
7	57	750	1	5	11	14
8	71	750	1	5	14	15
9	85	750	1	5	16	16
11	87	750	1	5	17	17
12	92	750	1	5	18	18
14	100	750	1	5	19	18
16	100	750	1	5	19	19
18	100	750	1	5	19	19
21	100	750	1	5	19	20
27	100	750	1	5	19	20
37	100	750	1	5	19	20
40	117	750	1	5	22	20
44	117	750	1	5	22	20

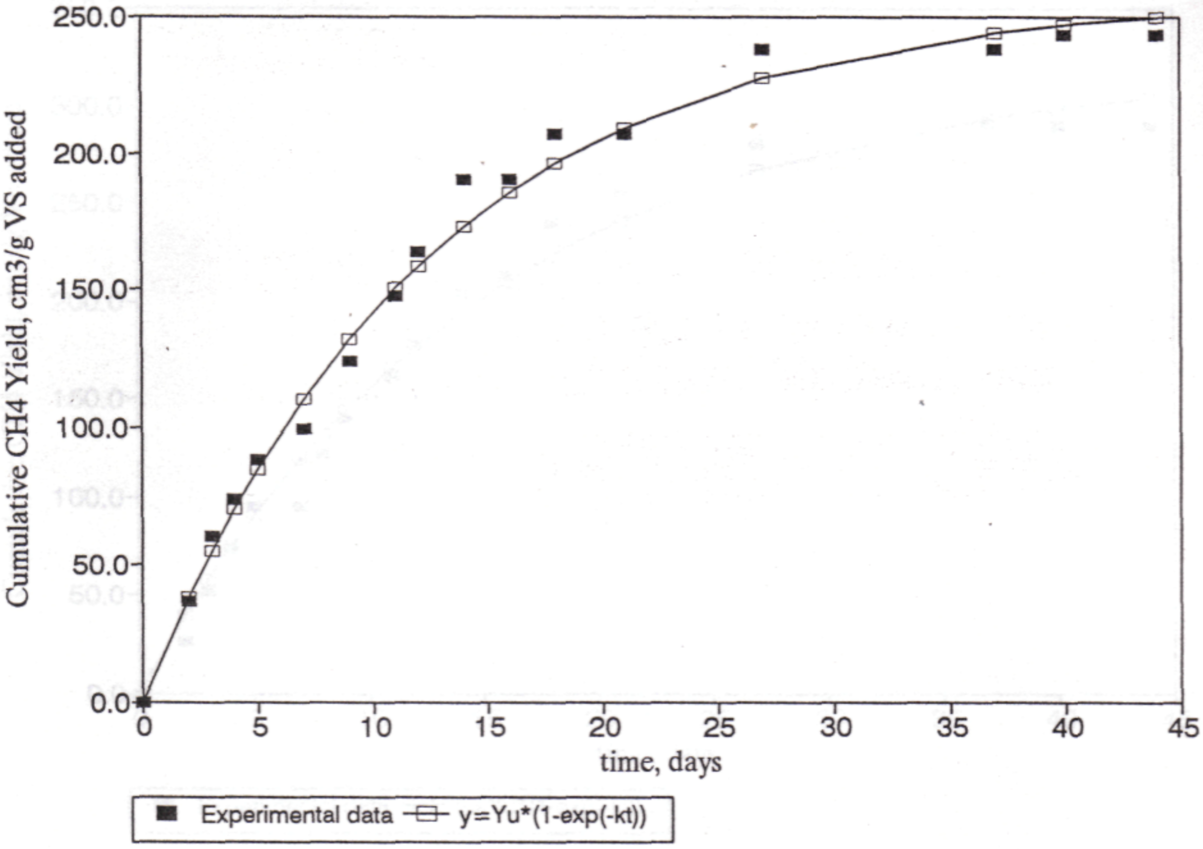


Fig. C-1. Methane Yield Pig Manure.

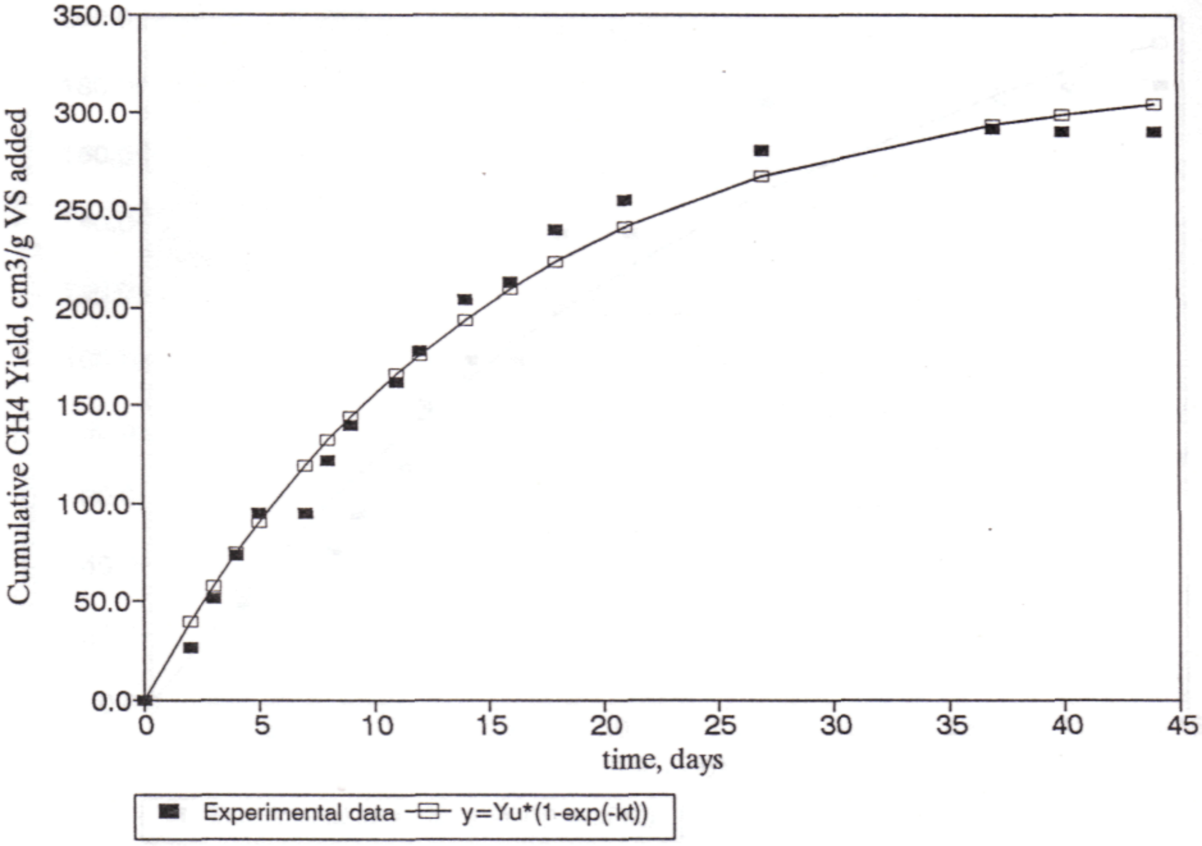


Fig. C-2. Methane Yield Goat Manure.

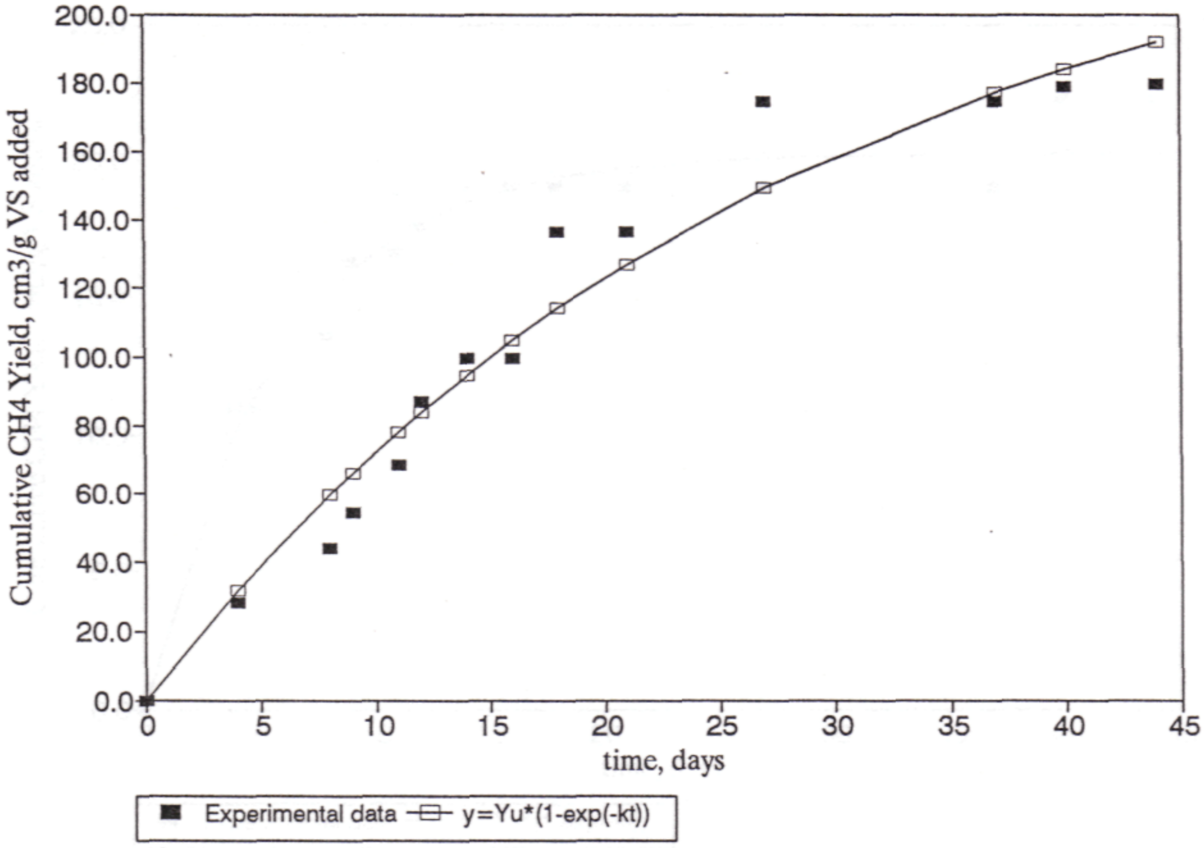


Fig. C-3 Methane Yield Chicken Manure.

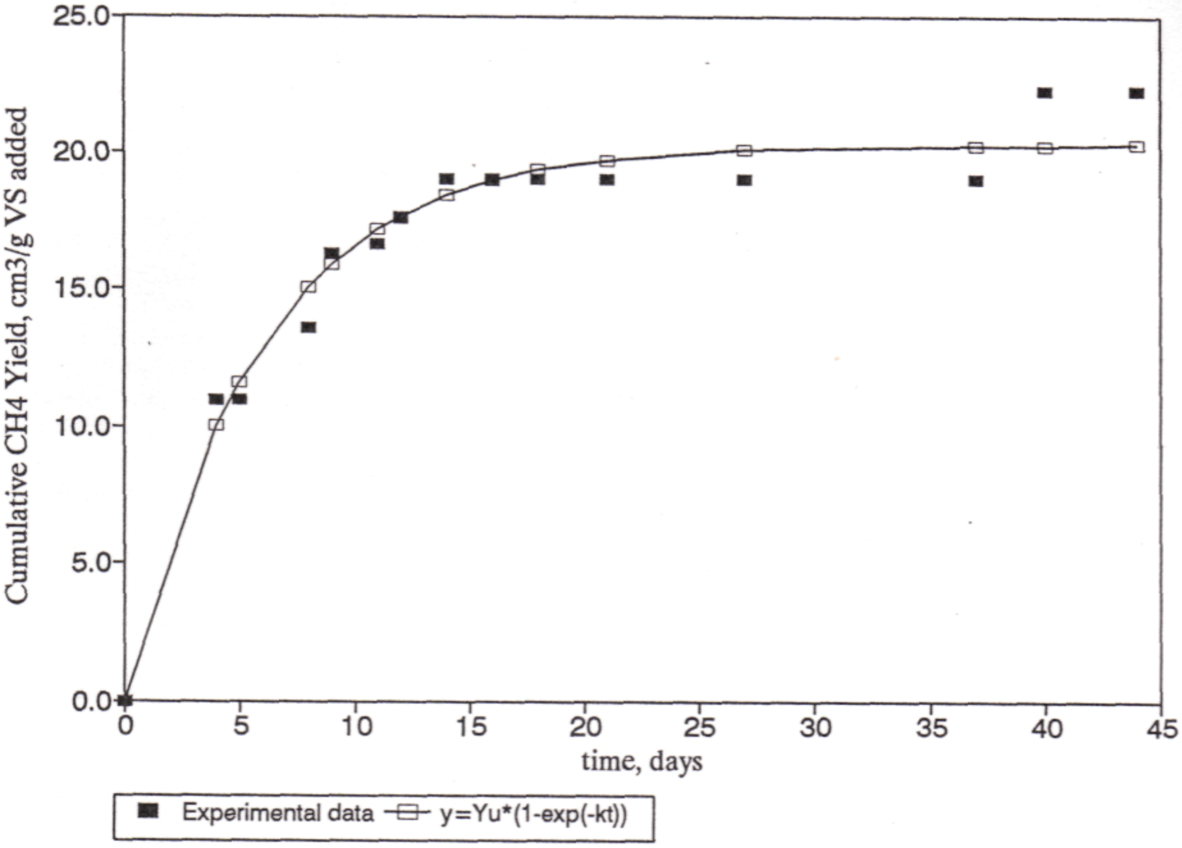


Figure C-4 Methane Yield for Control.

APPENDIX D
COST OF DIGESTER

Table D-1 Cost of the Digester.

Description	Amount	Unit	Unit price (Mex $)	Amount (Mex $)	Amount (US $)	Week of work
I. Digester						
Excavation (labor)	6	day	$15.00	$90.00	$29.51	06/06/93
Cement	1000	kg	$0.41	$410.00	$134.43	06/12/93
Gravel	1.84	m3	$75.00	$138.00	$45.25	
Sand	0.78	m3	$75.00	$58.50	$19.18	
Armex(steel bars)	32.5	m	$4.50	$146.25	$47.95	
Concrete blocks	180	piece	$1.30	$234.00	$76.72	
8" concrete pipes	8	piece	$9.40	$75.20	$24.66	
Steel sheet mesh (10x10 cm)	14	m2	$8.00	$112.00	$36.72	
Nails	0.5	kg	$3.50	$1.75	$0.57	
Alambrito	3	kg	$2.80	$8.40	$2.75	
1/4" structural metal (for covers)	1.5	m2	$67.00	$100.50	$32.95	
Labor for structural covers	2	day	$40.00	$80.00	$26.23	
Masonry labor (mason and helper)	12.5	day	$40.00	$500.00	$163.93	
8" flexible industrial pipe	1.5	m	$80.00	$120.00	$39.34	07/11/93
Silicon cement	8	piece	$18.00	$144.00	$47.21	07/19/93
2" PVC pipe	6	m	$4.50	$27.00	$8.85	
coples 2" PVC	3	piece	$3.50	$10.50	$3.44	
tapon 2" PVC	3	piece	$1.40	$4.20	$1.38	
Subtotal				$2,260.30	$741.08	
II. Gas storage tank						
Excavation (labor)	1	day	$40.00	$40.00	$13.11	06/17/93
Cement	625	kg	$0.41	$256.25	$84.02	
Gravel	0.504	m3	$75.00	$37.80	$12.39	
Sand	0.882	m3	$75.00	$66.15	$21.69	
Concrete blocks	122	piece	$1.30	$158.60	$52.00	
Steel sheet mesh (10x10 cm)	7.5	m2	$8.00	$60.00	$19.67	
2" PVC pipes	31	m	$4.50	$139.50	$45.74	
Masonry labor (mason and helper)	6	day	$40.00	$240.00	$78.69	
Metalic drum	6	piece	$70.00	$420.00	$137.70	
3/4" spheric valve	1	piece	$16.00	$16.00	$5.25	
Subtotal				$1,434.30	$470.26	

Table D-1 --continued.

Description	Amount	Unit	Unit price (Mex $)	Amount (Mex $)	Amount (US $)	Week of work
III. Input chamber						
Excavation (labor)	4	day	$40.00	$160.00	$52.46	07/09/93
Cement	150	kg	$0.41	$61.50	$20.16	
Gravel	0.144	m3	$75.00	$10.80	$3.54	
Sand	0.252	m3	$75.00	$18.90	$6.20	
Concrete blocks	61	piece	$1.30	$79.30	$26.00	
8" concrete pipes	2	piece	$9.40	$18.80	$6.16	
Clay brick	18	piece	$0.40	$7.20	$2.36	07/12/93
Subtotal				$356.50	$116.89	
IV. Gas conections						
Labor	3	day	$50.00	$150.00	$49.18	07/27/93
3/4" spheric valve	9	piece	$16.00	$144.00	$47.21	
sand paper	3	piece	$2.00	$6.00	$1.97	
1/2" spheric conector	9	piece	$11.00	$99.00	$32.46	
3/4" external rosca conector	3	piece	$5.00	$15.00	$4.92	
3/4" copper tee	1	piece	$3.80	$3.80	$1.25	
3/8" flexible pipe	15	m	$12.00	$180.00	$59.02	
teflon	5	piece	$3.60	$18.00	$5.90	
tuerca conica 3/8"	9	piece	$3.00	$27.00	$8.85	
conector rosca ext.1/2"	22	piece	$1.50	$33.00	$10.82	
3/4" copper pipe	2	m	$10.00	$20.00	$6.56	
1/2" copper pipe	5	m	$6.00	$30.00	$9.84	
PVC pegament	2	piece	$10.00	$20.00	$6.56	
plastiacero	2	piece	$10.50	$21.00	$6.89	
2" flexible pipe	2	m	$50.00	$100.00	$32.79	
Subtotal				$866.80	$284.20	
Grand Total				$4,917.90	$1,612.43	

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Engineering.

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