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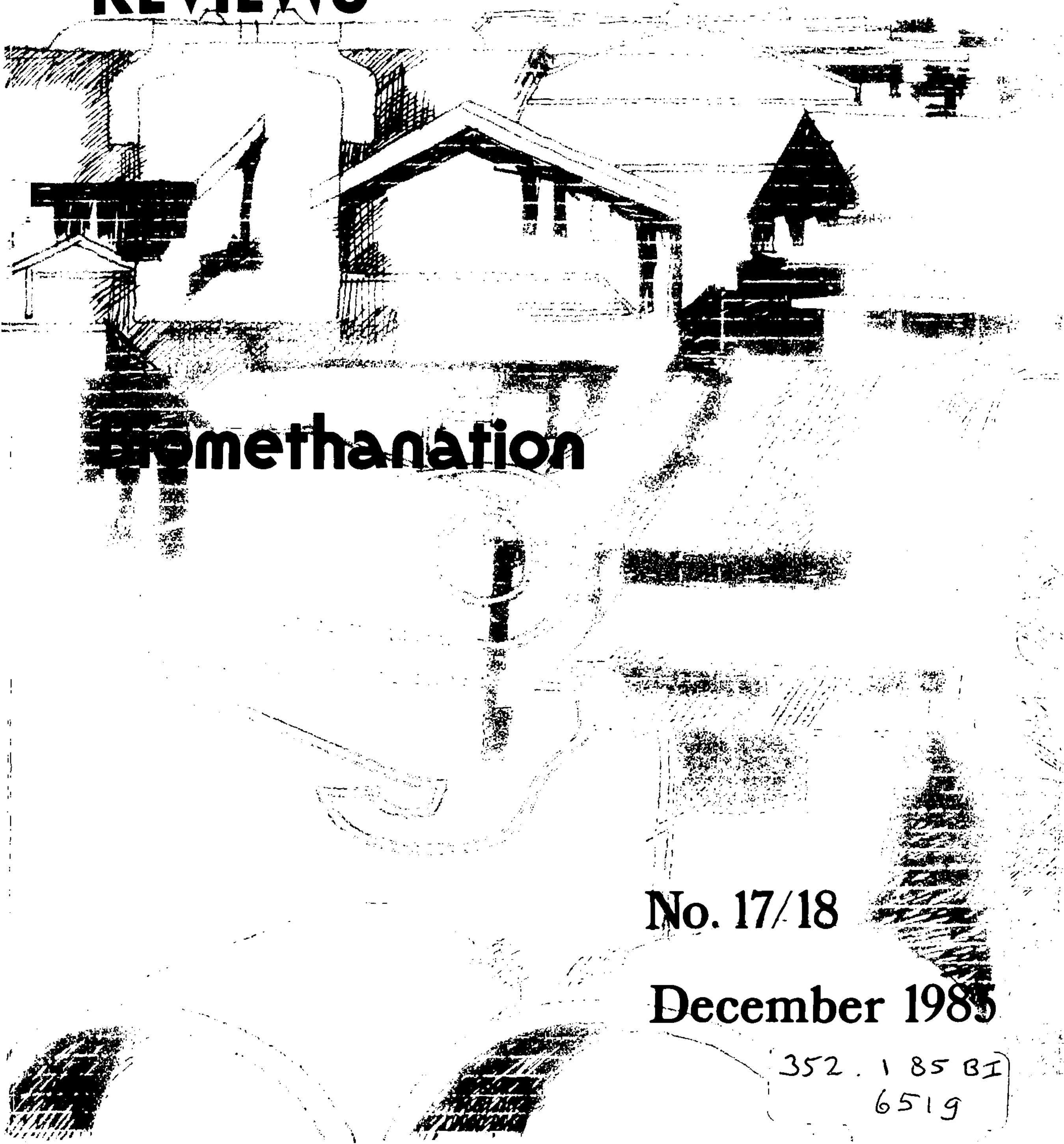

Biomethanation

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BIOMETHANATION

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I. INTRODUCTION

1.1 History

The generation of a flammable gas from organic material rotting in the absence of air (oxygen) has been known for centuries, especially in the form of marsh gas. The fact that manure, decomposing under similar conditions, would produce the same flammable gas has been known at least since 1895. In that year, manure was used in a septic tank designed especially for the purpose, to provide a flammable gas for street lighting in Exeter, England (McCabe & Eckenfelder, Jr., 1957). Several similar installations were subsequently built in England in the next 30-40 years (Lapp et al., 1975). The most widespread use of anaerobic microbiological processes to produce methane (i.e., biomethanation) prior to the burgeoning interest in the last 15-20 years, however, occurred during and shortly after World War II, when methane thus produced was used to power vehicles in France, Germany, and Algeria (National Academy of Sciences, 1977a).

More recently, there has been a rising interest in biomethanation primarily as a source of cooking fuel, although there are situations where it is also used for lighting and to power internal-combustion engines. While international interest in these uses has been most noticeable within the technical and development communities in the last 15-20 years, serious development efforts in this field began about 50 years ago in Asia. In 1930, the Chinese government granted a patent for a biogas production system to an entrepreneur who then established a gas-production company with branches in 13 provinces (Xu, 1983). Soon thereafter, in 1939, Indian agriculturists, concerned over the increased use of dung as cooking fuel and its consequent loss as much-needed fertilizer, began biomethanation experiments at the (then) Imperial Agricultural Research Institute. The purpose of the experiments was to continue to permit the use of dung as a fuel source without destroying its usefulness as a fertilizer (Idnani & Acharāya, 1963). These experiments, which resulted in the development of the prototype of the well known floating-dome biogas plant, began a long series of developmental projects that were expanded and encouraged over the years by the Khadi and Village Industries Commission (Bombay) and the Gobar Gas Research Station (Etawah, Uttar Pradesh), to the point where some 280,000 such plants now exist in India, primarily as small units in rural areas (Anon, 1984).

Interest in biogas in China revived in the 1970s in a concerted effort on the part of the government to provide cooking fuel to an increasing rural population, while at the same time not only conserving fertilizer, but also safeguarding public health, since the materials in question were both pig manure and human excrement. This interest and governmental encouragement were so successful that over 6.5 million family-scale biomethanation plants of the fixed-geometry ("water-pressure") type, 8-10 m^3 capacity are reported to be in existence, serving 30 million villagers. In addition, there are about 700 biogas-based motive-power stations supplying some 9,000 horsepower used to generate 5 MW of electric power and to dry agricultural products (Xu, 1983).

There is no doubt that the pioneering work in India and the massive activity in China in developing small-scale biomethanation systems stimulated the interest in this field that has since developed. Nevertheless, the potential value of this approach to the increasingly serious fuel/fertilizer problem has been recognized by other countries. Taiwan has played a significant role and has been responsible for the development of the flexible-bag ("red mud plastic") digester, beginning about 1955, primarily for use with piggeries of varying size (National Academy of Sciences, 1977a). In Korea, some 29,000 biomethanation systems have been constructed, most between 1969 and 1975 (Stuckey, 1984). It is not certain, however, how many of these are still functioning. Biomethanation systems are being developed and installed in Nepal. Although most activity is limited to the floating-dome digesters, there is an active program to experiment with the introduction of the fixed-geometry Chinese type (World Bank, 1983b). By 1982, the major actor in the biogas program in Nepal, Development and Consulting Services (Butwal), was reporting over 800 plants installed. With a target of 400 more installations in 1983, the total number of functioning biomethanation systems in Nepal has probably passed 1,000 by now (Finlay, 1982).

Thailand reports about 5,000 family-size systems producing 1-2 m^3/d, with 10 community-size systems producing about 20-30 m^3/d. The government has instituted a demonstration and subsidy program, and in fiscal year 1985 is aiming at an additional 30 demonstration units plus 600 promotional (subsidized) systems installed (Chantavorapap, 1984). There has been some biogas activity in Pakistan and Bangladesh, and in Indonesia some experiments have been done using water hyacinth as a feedstock, but no significant numbers of systems seem to have been installed in any of these countries (Soemarwoto, 1983).

The experience in the Philippines is unique, in that the major activity is a private installation that has received no government support. Begun in 1973, the Maya Farms experiment has evolved into a major agro-industrial installation dealing with the manure from approximately 50,000 pigs. The gas generated provides all the energy - electricity, process heat - to operate the piggery, slaughterhouse, and cannery, and to supply the domestic needs of the resident staff. The dried sludge provides 10% of the pig feed, and the liquid effluent, in addition, provides nutrients for crop fertilization and algae as feed for ducks, which are canned and whose droppings provide feed for carp, which are sold fresh. In addition, there are at least 600 other units operating (Maramba, Sr., 1978; 1980 and Orcullo, 1984).

While most of the activity in biomethanation systems using farm wastes seems to have taken place in Asia, there is some history of biomethanation development and use elsewhere. In the Pacific region, a few biomethanation systems have been built and installed in Papua New Guinea and Fiji (World Bank, 1982 & 1983a). While there have been some reports of biogas activity in Africa prior to 1960, expansion of such work seems to have started with experiments in Uganda in 1963 (Jeffries, 1964). By 1973, the number of countries involved included Botswana, Ethiopia, Kenya, Lesotho, Malawi, Tanzania, Zambia, and Zimbabwe (Rugumayo, 1983). That list has now expanded to include Mali, Rwanda, Senegal, Upper Volta, the Gambia, and Seychelles (Associates in Rural Development, Inc., 1984; World Bank, 1983d & 1984c). An organized national development program in Africa seems to have started only in 1975 in Tanzania, where the

Small Industries Development Organization began work designing and installing several digesters of various sizes, based on the Indian (KVIC) floating-dome design (Elhalwagi & Daiem, 1980; Brown & Howe, 1978). Currently, about 300 digesters have been installed, with approximately one-third not operating for technical reasons (World Bank, 1983e). In 1979, however, the Commonwealth Science Council undertook to organize and coordinate a regional Africa Energy Programme that includes biomethanation among its projects. Participants include Botswana, Cyprus, the Gambia, Kenya, Malta, Rwanda, Sierra Leone, Tanzania, Uganda, and Zambia, although it is not clear that all participants are currently engaging in biomethanation projects. In a report to the World Bank, Stuckey gives some details on other projects that have taken place in Sudan, Algeria, Cameroon, Mali, Liberia, and Tunisia, in addition to those in Egypt, Ethiopia, and Tanzania (Stuckey, 1983).

Activity in biomethanation has accelerated recently in Egypt where, under the USAID program, the US National Research Council is cooperating with three Egyptian organizations on a research and development program aimed at expanded village use of biomethanation systems, primarily for cooking and lighting.

Information on the history and current status of biomethanation systems in Latin America is quite sketchy, in contrast to what is known about Asia and Africa. Nevertheless, reports that are available indicate significant activity in Brazil, with more than 2,000 systems installed in three years after the start of the program in 1980 (Stuckey, 1983). Other systems are reported in Central America, Mexico, the Andean countries, Argentina, Uruguay, and Paraguay (Stuckey, 1983). In a program similar in purpose to that of the Commonwealth Science Council in Africa, the Latin American Energy Organization (OLADE) organized a regional program in biomethanation development in Central America in 1979. Participating countries are Guatemala, Honduras, Nicaragua, Haiti, the Dominican Republic, Grenada, Guyana, and Ecuador (Caceres E., 1983).

1.2 Physical and Chemical Characteristics

Biogas, as a product of a biological process, is by no means a pure gas. Its two major constituents, methane and carbon dioxide, are colorless and odorless, but the minor constituents, particularly hydrogen sulfide, contribute to its odor. In this respect, the combination of gases, with the exception of the carbon dioxide, is the naturally occurring counterpart of conventional cooking gas. The latter is essentially methane, but in the United States, to enable it to be detected for safety reasons, a small quantity of a mercaptan is added deliberately. This is a malodorous compound that is as easily detected as hydrogen sulfide, to which it is related chemically.

The composition of biogas is generally 50-70% methane (CH_4), 30-50% carbon dioxide (CO_2), with very small amounts of hydrogen sulfide (H_2S) and traces of other gases. The actual ratio of methane to carbon dioxide varies with the substrate, temperature, and the process conditions. In some experiments, methane concentrations up to 80% have been reported (Jyoti Solar Energy Institute).

Because its flammable constituent is methane, biogas burns the way methane burns, with a blue flame. (H_2S also burns, but its concentration in biogas is so small it does not affect the overall combustion.) The heating value is directly proportional to the methane content. With pure methane releasing 39,487 kJ/m^3 (1,060 Btu/ft^3) on combustion, biogas with a 70% methane content will release 70% of that heat value, or 26,641 kJ/m^3 (742 Btu/ft^3) when burned. (For convenience in calculation, engineers have usually used 1,000 Btu/ft³ for the heating value of methane. There is no similarly convenient number in the metric system, however).

Selected physical and chemical properties of methane are listed in Table 1. The information should be used with the recognition that it applies only to the major constituent of biogas, and not to the biogas itself.

Table 1. Selected physical and chemical properties of methane (National Academy of Sciences, 1977c)

Chemical formula:	CH_4
Molecular weight:	16.042
Boiling point at 760 mm:	-161.49°C
Freezing point at 760 mm:	-182.48°C
Critical pressure:	47.363 kg/cm²
Critical temperature:	-82.5°C
Specific gravity:	
Liquid (at -164°C)	0.415
Gas (at 25°C, 760 mm)	0.00658
Specific volume (at 15.5°C, 760 mm):	1.47 L/g
Calorific value (at 15.5°C, 760 mm):	38,131 kJ/m³ (1,012 Btu/ft³)
Air required for combustion, v/v:	9.53
Flammability limits:	5 to 15 per cent by volume
Octane rating:	130
Ignition temperature:	650°C
Combustion equation:	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
O_2/CH_4 for complete combustion:	3.98 w/w, 2.0 v/v
CO_2/CH_4 from complete combustion:	2.74 w/w, 1.00 v/v

1.3 Use of Biogas

The normal methane concentration in biogas is sufficient to make biogas attractive as a cooking fuel, for lighting in gas-burning lamps, and for gas-burning refrigerators - in short, it is useful in any gas-burning appliance that can use low-pressure gas. It is also useful as fuel for internal-combustion engines, but because of the carbon-dioxide content, a compression ratio of 8:1 or greater is needed (National Academy of Sciences, 1977c). Its usefulness as a transportation fuel would be enormously enhanced if the carbon dioxide were removed and the remaining methane liquified. This would increase the energy density by a factor of almost 600 because about 590 liters of methane gas at standard temperature and pressure would be compressed to 1 liter of liquid. This would make it comparable to current liquid fuels in energy density. Methane, however, can be liquified only at temperatures below its critical temperature (-82.5°C) and must be maintained at pressures above its critical pressure (47.363 kg/cm²). Nevertheless, if removal of the carbon dioxide is feasible (for example, by bubbling the gas through limewater), and suitable pressure containers are available, enough compression can be achieved at ambient temperatures to make the possibility of use as a transportation fuel worth considering. The study by the National Academy of Sciences noted the following:

> "Digester gas may be used as fuel for motor vehicles, but its performance efficiency is dependent on the methane content--that is, the content of carbon dioxide (CO_2) and hydrogen sulfide (H_2S). Furthermore, if enough fuel is to be carried in the vehicle to permit reasonable distances of travel, the gas must be 'concentrated' by being compressed and stored in high-pressure cylinders. (For local travel, low-pressure bag storage can be used.) Thus, the use of digester gas in internal-combustion engines requires special equipment and processes, which further include:
>
> - Reducing the H_2S content of the gas to less than 0.25 percent to prevent corrosive damage to metal surfaces, particularly bearings and other working parts.
> - A scrubbing system to remove CO_2. While carbon dioxide exerts no harmful effects on internal-combustion engines, the presence of this non-combustible gas....reduces the heat content per unit of gas volume and thus lowers the operating efficiency of the engine.
> - A compressor capable of compressing gas to pressures between 2,000 and 3,000 psi (140 and 210 kg/cm²). When digester gas is to be compressed, it is imperative that the carbon dioxide be removed to prevent mechanical damage to the compressor caused by liquefaction of the CO_2.
> - High-pressure cylinders, of the type used for oxygen, that can safely store gas at pressure up to 2,400 psi (170 kg/cm²), to be installed on the vehicle.
> - A set of similar high-pressure storage cylinders equipped with a pressure control panel for filling the vehicle cylinders.
> - Pressure-reducing valves installed on the vehicle to supply the low-pressure gas required by the carburetor. Usually two valves are used, one a high-pressure reduction valve to reduce the tank pressure (2,400 psi, 170 kg/cm²) to an intermediate low-pressure of, say, 50 psi (3.5 kg/cm²), and a second to reduce the pressure below atmospheric pressure so that gas will not escape from the line when the engine is not operating.
> - An automatic gas/air mixing valve installed on the air intake of the carburetor (National Academy of Sciences, 1977c)."

Any consideration of practical use of biogas must deal with consumption rates for various appliances and devices. Typical rates of consumption are given in Table 2. These data represent the average figures obtained by more than one experimenter, in

Table 2. Volume of biogas required for specific applications
(Adapted from National Academy of Sciences, 1977c)

Use	Specification	Gas required m³/hr
Cooking	2" burner	0.33
	4" burner	0.47
	6" burner	0.64
	per person/day	0.34-0.42+
Gas lighting	per lamp of 100 candlepower	0.13
	per mantle	0.07-0.08
	2-mantle lamp	0.14
	3-mantle lamp	0.17
I-C engine (25% eff.)	converted to biogas, per hp	0.45-0.51
Refrigerator	per cubic-foot capacity	0.028-0.034
Incubator	per cubic-foot capacity	0.013-0.020
		m³
Gasoline	1 liter	1.33-1.87
Diesel fuel	1 liter	1.50-2.07
Boiling water	to boil off 1 liter	0.11

most cases. Furthermore, they depend on the actual methane content of the biogas used. Nevertheless, they are useful for evaluating the practicality of any biomethanation system in terms of the intended use of the gas.

1.4 Residue and Its Use

The residue from the anaerobic digestion process has customarily been used as a soil conditioner or fertilizer. Under normal circumstances, it contains about 70% of the weight of the original material, the constituents able to be volatilized having been removed in the gas. These volatilizable constituents do not include any of the mineral content, but consist primarily of carbon from the solid substrate, oxygen from the water, about one percent of the nitrogen (in the form of ammonia), and some sulfur in the form of hydrogen sulfide. Both the nitrogen and the sulfur come from amino acids that may be broken down in the metabolic processes of the microorganisms. The remaining constituents in the residue consist of all the minerals, about 99 percent of the nitrogen of the original material (National Academy of Sciences, 1977b), and the residual fibrous material (primarily lignocellulosics) not broken down chemically during the process. The minerals and the nitrogen are the obvious valuable soil nutrients and the fibrous material improves the tilth of the soil.

The Maya Farms experience has demonstrated vividly the usefulness of the dried residue as a feed supplement, in terms of the accelerated growth of the animals whose feed has been thus supplemented. Part of that acceleration is attributed to "unidentified growth factors" in the residue, probably vitamins produced by the metabolic processes of the bacteria and for which assays have not been performed. The economic advantages of using digested sludge as a feed supplement will be discussed in a later section.

Part of the residue from the biomethanation process is also the liquid fraction, which is often regarded as a nuisance to be removed by evaporation or decantation. Nevertheless, the liquid contains all the nutrients that have been solubilized and dissolved during the process, including much of the ammonia. If it is removed from the sludge by evaporation, all the minerals will be retained in the solid residue, but the ammonia in solution will be lost. Since this represents about 18 percent of the nitrogen originally present in the feedstock (National Academy of Sciences, 1977b), it would be a significant loss. If the liquid fraction is discarded after decantation, even the minerals will be lost, if it is not disposed of on agricultural fields. Thus, the best use of the residue as a fertilizer, if it cannot be stored in a closed container, is immediate application to the soil. Ideally, this should be in a rainy season, so that the liquid soaks into the soil instead of evaporating.

It should be emphasized, in this brief discussion of the uses of the residues of the biomethanation process, that the chief value the residues possess over the input materials is that the minerals present in the residues are more available to plant root systems than they were in their original form. The biomethanation process accomplishes a "mineralization" that produces chemical forms of these minerals that are more soluble than the original forms. Although all of the plant and animal waste materials used for biomethanation would break down over time if applied to the land and would eventually release all their nutrients to the soil, the time required is far longer than usual cropping cycles. Thus, in the time scale characteristic of human cropping patterns, the mineralization accompanying the biomethanation process increases the fertilizer value of these materials significantly.

II RAW MATERIALS (SUBSTRATES)

2.1 Biomass Types

In general, any biomass type that is amenable to microbial degradation can be considered a potential source for the production of biogas. There are some types of materials, however, such as lignin, chitin, bark, feathers, for example, that are not easily degraded by microorganisms and thus are not appropriate feedstocks for the production of biogas. Nevertheless, it is possible to generate biogas from some of the relatively recalcitrant materials by pretreating them to produce substrates that are more readily attacked by the microorganisms.

Table 3. Types of biomass for the production of biogas

Type of biomass	Examples
Animal wastes	Cattleshed wastes (dung, urine, bedding), wastes from poultry, swine, goats, horses, etc.
Human wastes	Feces, urine, refuse, sewage sludge, kitchen waste.
Agricultural wastes	Wheat and rice straw, sugarcane trash, corn cobs and stubble, harvested cotton stalks, banana leaves and stems, peanut hulls, bagasse, rice husks and dust, tobacco wastes, press muds from sugar factories, all types of fruit and vegetable-processing wastes, etc.
Forest and related types of wastes	Twigs, branches and leaves of all types of trees and shrubs, various types of grasses, saw-mill wastes, etc.
Aquatic weeds	Water hyacinth, algae, kelp and other sea weeds.
Industrial wastes	All types of food-processing wastes (bean blanching, pear peeling, potato peeling, sugar-beet and spinach processing, asparagus peels, strawberry wastes, apple peeling, carrot wastes, green-pea slurry, etc.), whey, rum stillage, molasses stillage, brewery wastes, palm-oil mill waste, petrochemical effluent, dairy wastes, confectionary and sugar-refining wastes; wool-processing, rendering, coal-gasification, meat-packing wastes; coffee pulp, vegetable-gum waste; soft-drink bottling waste, soy-processing wastes, etc.

Table 3 lists the types of wastes that can be used for the production of biogas. The literature is replete with studies concerning the production of methane from materials such as animal manure, sewer sludge, and other types of wastes, because of their ubiquitous nature and the necessity to treat them to minimize the risk to the public health and, at the same time, recover methane and fertilizer. Recently, however, studies have been conducted to determine the feasibility of producing biogas from relatively unexploited but abundantly available biomass sources such as Lantana camara, a terrestrial plant that grows wild in tropical and subtropical countries, such as India. Another such source is Leucaena leucocephala (ipil ipil), a tropical leguminous plant (grown commercially in Hawaii, Indonesia, Philippines, Western Australia, Malawi, Mexico, and in the Caribbean), not only because it is a rapidly growing tree but as a source of animal feed. Its leaves are rich in protein but cannot be fully used as animal feed because of the presence of mimosine, a toxic substance. It is interesting to note that this toxicity is reported to have been eliminated by subjecting the leaves to anaerobic digestion; thus the sludge produced can be used as good animal feed since it will have lost essentially only carbon in the process. In addition, its leaves, when subjected to anaerobic fermentation, are reported to yield biogas containing 77 percent methane (Tata Energy Documentation and Information Centre, 1984).

The use of kelp (a sea weed), water hyacinth, and Salvinia molesta for the production of biogas has also been reported (Chynoweth et al., 1984). It is claimed that the digestion of Salvinia, either alone or in combination with other aquatic weeds or animal manures, produces a biogas of high fuel value. Furthermore, the digestion process destroys the spores of this weed, and thus helps in arresting its spread.

Although it is theoretically possible to generate biogas from any readily biodegradable organic material, there are limitations to the full-scale exploitation of such materials. Some of these limitations are summarized for a few categories of wastes in Table 4.

2.2 Alternative Uses

The materials used as feedstock for biomethanation systems are direct or indirect products of agriculture. Thus, they fall somewhere among the five major categories of uses for these products, i.e., food, fuel, fiber, fodder, and fertilizer. It is clear that food can be eliminated as an alternative use except in the most unlikely of imagined circumstances. The other four remain legitimate uses that must be evaluated before a significant investment is made in a biomethanation system. (A discussion of the social and economic issues that concern these choices follows in another section.)

Basically, biomethanation feedstocks consist of crop residues, manure, and in some cases, human excrement. For all of these, other uses exist. Many crop residues are traditionally used as fuel, occasionally to a greater extent than realized by outside observers, as in the case of millet stalks in Upper Volta, when customary fuel is in short supply. Grasses and other plants supply needed fiber for construction, textiles, and household articles. All of these plants/residues can also serve as fertilizer if allowed to rot in the fields or if ploughed under the soil. Manure has traditionally been used as fertilizer, fuel, and construction material, and in many societies human excrement is used as tertilizer.

In most cases, the choices are easy to make. Food will always be the first choice in subsistence situations. Shelter is a logical second priority, but meeting that need

Table 4. Limitations on the use of some biomass in biomethanation

Substrate	Limitations
Woody biomass	1. Quantity and availability 2. Collection efficiency 3. Competition for other uses 4. Complexity of pre-treatment 5. Social factors (e.g., ownership) 6. Environmental damage if not properly used.
Crop residues	1. Soil degradation if collected excessively 2. Quantity and competing uses 3. Seasonal availability 4. Nutritional supplementation and pretreatment possibly required 5. Ownership
Animal manures	1. Availability and collection efficiency 2. Ownership of the minimum number of animals to produce dung for the required quantity of gas. 3. Depletion in soil fertility, if not recycled 4. Current cultural practices of using dung as fuel
Industrial wastes	1. Availability 2. Competing uses, e.g., irrigation 3. Seasonal availability 4. Presence of inhibitors (toxicants) 5. Low concentration of organic matter in some wastes
Human wastes	1. Availability, collection 2. Handling safety (pathogens) 3. Low gas production

generally does not require a constant supply of material. Thus, the use of manure and/or plant materials for construction would not preclude use of subsequent supplies of these continually produced materials as biomethanation feedstocks. The same argument applies to plant fibers used for household articles (e.g., baskets and trays). The traditional use of manure or human excrement as fertilizer may, at first glance, pose a serious choice when biomethanation is proposed as an alternative use. The major questions that must be addressed involve public health, the environment, and the effect on fertilizer value. The first two will be discussed in a later section. The third question, which has been addressed above, may involve an education and demonstration program to convince the justifiably skeptical farmer first, that the fertilizer value of the manure is not diminished by the biomethanation process, and second, that the fertilizer value of the biomethanation residue is sufficiently greater than that of the manure that it will lead to increased agricultural productivity.

2.3 Potential Availability

The potential availability of crop residues and manure in developing countries is not easily established. The amounts of similar types of waste generated under apparently similar conditions may vary widely, even from region to region within a country. There is, in addition, a variability from country to country in total biomass generated for a given crop, even for comparable crop yields or planted areas. Social and economic factors also influence the availability of biomass for biomethanation in any given locale (see Section V: Planning Biomethanation Systems). Among the most important of these are:

- efficiency of collection,
- competing uses for the available waste or biomass,
- seasonality,
- proximity to a community that is the beneficiary of the biogas generated, and
- cultural, sociological, and economic factors that determine the use of the available biomass as a substrate for biomethanation.

A few specific examples of this variability are given in Tables 5, 6, and 7, with a detailed listing of crop residues and their uses given in Table 8. Estimates of human and animal wastes that are available in India and amounts that could be collected for use in biomethanation systems are presented in Table 5. These figures are also compared with the average amounts available in other developing countries. The range of productivity for various aquatic weeds, which can be used as feed materials for biomethanation, is presented in Table 6, while a brief summary of the variation in the quantities of crop residues produced for cereal crops in various developing countries is presented in Table 7.

Table 5. Human and animal wastes: India compared to other developing countries (Tata Energy Documentation and Information Centre, 1984)

Source	Total waste kg/head/d (wet wt.)	Collectible waste kg/head/d (wet wet.)	Other developing countries kg/head/d (average dry wt.)
Cattle	10-15	5-8	2.74
Asses, mules, horses	--	--	2.05
Pigs	1.30	0.30	0.82
Sheep	0.75	0.25	0.41
Man	0.75	0.75	--
Kitchen waste	0.25	0.25	--
Poultry	0.06	0.06	--

Table 6. Yields of aquatic weeds (Tata Energy Documentation and Information Centre, 1984)

Type	Yield, tonnes/ha/y (dry wt., ash free)	
	Mean	Range
Water hyacinth	60	50-60
Algae	40	30-50
Marine macrophytes	29	20-40
Laminaria	40	30-48

Table 7. Summary of variation in production of crop residues for selected cereal crops in developing countries (Hall et.al., 1980)

Crop	Crop Yield (tonnes/ha/y)		Residue Production (tonnes/ha/y)	
	Range	Average	Range	Average
Rice	0.7-5.7	2.5	1.4-11.4	5.0
Wheat	0.6-3.6	1.5	1.1-6.1	2.6
Maize	0.5-3.7	1.7	1.3-9.3	4.3
Sorghum	0.3-3.2	1.0	0.8-8.0	2.5
Barley	0.4-3.1	2.0	0.7-5.4	3.5
Millet	0.5-3.7	0.6	1.0-7.4	1.2

The Food and Agriculture Organization of the United Nations (FAO) periodically conducts a global survey to determine the amount and use of crop residues and related materials (e.g., food processing wastes). Its latest survey includes data from only 41 developing countries out of a total of 53 responses (FAO, 1982). Of these 41, only 23 give any estimates of crop residues -- utilized or unutilized -- and the responses are generally confined to one or two major crops. (This does not include bagasse, which is generally used as fuel by the local sugar mills, and thus would not be a candidate for biomethanation.) The joint UNDP/World Bank Energy Sector Assessment Program reports constitute another possible source of such information, since crop residues represent potential fuel sources. In most cases, however, where biomass resources have been considered, it has been in the context of fuelwood and charcoal for cooking, or bagasse as a source of fuel for sugar mills. Of the 26 surveys that have been printed so far, however, only nine include any other information on crop residues or manure. A summary of the information available from these two sources is presented in Table 8.

Table 8. Summary of estimates of agricultural residues in developing countries

Residue	Quantity (1,000 mt)	Current use (See Notes)	Source (Ref)
Bangladesh:			
Rice straw	21,000	a, b, c	(FAO, 1982)
husk	2,500	d	"
bran	1,000	b	"
Wheat straw	500	b, c, d	"
Jute stems	2,500	c, d	"
Burma:			
Wheat straw	50	b	"
Maize husks	8	e	"
stalks	150	b	"
cobs	80	d	"
Rice straw	10,000	f	"
husks	2,100	g	"
Jute stems	96	g,h	"
Cotton stalks	100	g,h	"
Legumes	1,500	d	"
Groundnut shells	90	d	"
stalks, leaves	150	b	"
Sesame	650	d,h	"
Cameroon:			
Cotton lint	0.15	i	"
husks	0.40	i	"
Groundnut shells	1	i	"

Notes:

a. Food
b. Feed
c. Construction and construction materials
d. Fuel
e. Consumer or industrial products
f. Part feed, part burned, ploughed under, or left in field
g. Small quantity used as fuel, rest burned or decomposed
h. Compost or fertilizer
i. Burned for disposal
j. Dumped in streams
k. Dumped at site
l. Used for biogas
m. Dumped (unspecified)
n. Land fill

Table 8. Summary of estimates of agricultural residues in developing countries (cont'd)

Residue	Quantity (1,000 mt)	Current use (See Notes)	Source (Ref)
Colombia:			
Coffee pulp	1,200	h,j	"
Sorghum chaff and straw	800	c,b	"
Maize stalks	1,500	f	"
Rice husks	290	c,d	"
straw	1,400	f	"
Soy straw and pods	200	i	"
Costa Rica:			
Coffee pulp	470	b,j	(FAO, 1982)
husks	20.5	d	"
Ethiopia:			
Coffee husks	135	g	(FAO, 1982)
pulp	40	j	"
Ghana:			
Cocoa pod husks	500	e,k	"
sweatings	135	e,k	"
Rice husks and straw	517	c	"
Guatemala:			
Poultry manure	1.4	h	"
Coffee pulp	1,000	k	"
Cotton hulls	0.6	b	"

Notes:

a. Food
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d. Fuel
e. Consumer or industrial products
f. Part feed, part burned, ploughed under, or left in field
g. Small quantity used as fuel, rest burned or decomposed
h. Compost or fertilizer
i. Burned for disposal
j. Dumped in streams
k. Dumped at site
l. Used for biogas
m. Dumped (unspecified)
n. Land fill

Table 8. Summary of estimates of agricultural residues in developing countries (cont'd)

Residue	Quantity (1,000 mt)	Current use (See Notes)	Source (Ref)
Guayana:			
Rice husks	60	i	"
India:			
Manure, wet	960,000	h,d(1:1)	"
composted	600,000	biogas	"
Tea wastes	10	(no response)	"
Coffee husks	44.54	" "	"
Rice husk	50,000	f	"
bran	2,500	(no response)	"
Cotton stalks	12,000	" "	"
lint	30	" "	"
Jute stalks	2,500	" "	"
Mango peels, stones	25	" "	"
Citrus peels	400	" "	"
Tamarind leaves	3	" "	"
Indonesia:			
Rice straw	37,500	b,c,e	"
husks	6,800	d	"
Maize stalks and husks	10,000	b,d,h	"
Coconut	6,000	c,d,e	"
Oil palm	2,500	b,d	(FAO, 1982)
Groundnut shells, stems, leaves	330	b,d	"
Soy straw, shells	600	b,d	"

Notes:

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g. Small quantity used as fuel, rest burned or decomposed
h. Compost or fertilizer
i. Burned for disposal
j. Dumped in streams
k. Dumped at site
l. Used for biogas
m. Dumped (unspecified)
n. Land fill

Table 8. Summary of estimates of agricultural residues in developing countries (cont'd)

Residue	Quantity (1,000 mt)	Current use (See Notes)	Source (Ref)
Indonesia: (cont'd)			
Cassava woody stems	7,200	d	"
soft plant parts and leaves	4,800	b,h	"
root peels	2,400	b	"
solid starch-extraction residue	270	a,b	"
Ivory Coast:			
Coffee husks	150	d,h	"
Cocoa pod husks	2,000	h,k	"
Rice straw	400	f	"
husks	26	f	"
Kenya:			
Coffee pulp	600	m	"
husks	25	(no response)	"
Malaysia:			
Cocoa pod husks	270	h,m	"
Rice husks	300	b,m	"
straw	1,620	b,c	"
Pineapple canning	210	m	"
Oil palm cake	9,480	b,d,m	"
sludge	270	l	"

Notes:

a. Food
b. Feed
c. Construction and construction materials
d. Fuel
e. Consumer or industrial products
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g. Small quantity used as fuel, rest burned or decomposed
h. Compost or fertilizer
i. Burned for disposal
j. Dumped in streams
k. Dumped at site
l. Used for biogas
m. Dumped (unspecified)
n. Land fill

Table 8. Summary of estimates of agricultural residues in developing countries (cont'd)

Residue	Quantity (1,000 mt)	Current use (See Notes)	Source (Ref)
Morocco:			
Grains (barley, wheat, maize)	3,960	?	(World Bank, 1984a)
Sugar beets	136	?	"
Nepal:			
Maize stalks	5,000	b,c,d,h	(FAO, 1982)
cobs	1,800	d	"
Nigeria:			
Brewery spent grains	20	b,m	(FAO, 1982)
Cocoa husks	40	m	"
discarded beans	15	i	"
Rice bran	250	b,i	"
Niger:	(79/80: total wastes equivalent to 2.2 million tons of oil)		(World Bank, 1984b)
Philippines:			
Manure	12,700	h,j	(FAO, 1982)
Rice straw	12,000	d,f,h	"
husks	1,000	b,i,n	"
Corn stubble	200,000	f	"
Banana peels	1,500	l,n	"

Notes:

a. Food
b. Feed
c. Construction and construction materials
d. Fuel
e. Consumer or industrial products
f. Part feed, part burned, ploughed under, or left in field
g. Small quantity used as fuel, rest burned or decomposed
h. Compost or fertilizer
i. Burned for disposal
j. Dumped in streams
k. Dumped at site
l. Used for biogas
m. Dumped (unspecified)
n. Land fill

Table 8. Summary of estimates of agricultural residues in developing countries (cont'd)

Residue	Quantity (1,000 mt)	Current use (See Notes)	Source (Ref)
Senegal:			
Rice straw	94	?	(World Bank, 1983c)
husks	22.7	?	"
Groundnut shells	230	d,?	"
Cotton hulls	9.2	?	"
stalks/leaves	107	?	"
Maize stalks	157	?	"
Millet/sorghum straw	1,470	?	"
Cowpeas tops and shells	4.9	?	"
Manure, cattle	50.6/day	?	(World Bank, 1983e)
swine	0.6/day	?	"
sheep/goats	6.3/day	?	"
poultry	1.1/day	?	"
Somalia:			
Maize/sorghum stalks/cobs	450	f	(FAO, 1982)
Banana leaves and stems	800	f	"
Sri Lanka:			
Rice husks	600	d	(FAO, 1982)
straw	2,000	b,c,e	"

Notes:

a. Food
b. Feed
c. Construction and construction materials
d. Fuel
e. Consumer or industrial products
f. Part feed, part burned, ploughed under, or left in field
g. Small quantity used as fuel, rest burned or decomposed
h. Compost or fertilizer
i. Burned for disposal
j. Dumped in streams
k. Dumped at site
l. Used for biogas
m. Dumped (unspecified)
n. Land fill

Table 8. Summary of estimates of agricultural residues in developing countries (cont'd)

Residue	Quantity (1,000 mt)	Current use (See Notes)	Source (Ref)
Sudan:			
Wheat straw	773	f	"
Sorghum straw	4,900	f	"
Rice straw	63	f	"
Groundnut shells	785	b,e,i,m	"
Tunisia:			
Olive cake	100	d	"
pits	100	d	"
Uganda:			
Coffee husks	81	h	"
Tea waste	1.1	m	"

Notes:

a. Food
b. Feed
c. Construction and construction materials
d. Fuel
e. Consumer or industrial products
f. Part feed, part burned, ploughed under, or left in field
g. Small quantity used as fuel, rest burned or decomposed
h. Compost or fertilizer
i. Burned for disposal
j. Dumped in streams
k. Dumped at site
l. Used for biogas
m. Dumped (unspecified)
n. Land fill

Information on the quantities of industrial wastes that are potentially available for biomethanation in developing countries is sparse. The extent of their availability depends on many factors, including the nature and size of the industry, production techniques, feedstocks used, and wastewater treatment practices employed.

In some urban areas of developing countries, where municipal sewage treatment plants exist, the sludge generated from treating sewage is usually digested anaerobically. The biogas thus produced may be used in the sewage treatment plant as an energy source and/or it may be supplied to the neighboring community for its use, as is the case in Bombay, India.

III TECHNOLOGY OF PRODUCTION

3.1 Anaerobic Microbial Processes

The formation of biogas from waste organic matter is a complex process. The conversion of complex organic matter to methane and carbon dioxide is accomplished in general by four groups of bacteria:

Hydrolytic bacteria

- By hydrolyzing many of the organic compounds in the substrate, these bacteria render many of the materials water soluble.

Acetogenic bacteria

- These bacteria form acetic acid.

Acetoclastic methanogens

- These are bacteria that metabolize acetic acid to methane (and carbon dioxide).

Hydrogen-utilizing methanogens

- These bacteria combine hydrogen with carbon dioxide to form methane.

These various groups of bacteria are dependent on the activity of each other and are essential to carry out the biomethanation process. They all perform under anaerobic conditions, *i.e.*, in the absence of molecular oxygen at highly negative redox potential (below 300 mv) (Sleat & Mah, 1984; Ferguson & Mah, 1984).

The current understanding of the microbiology of the biomethanation process is illustrated in Figure 1. The first step in the degradation of biomass consists of the actions of a group of hydrolytic and fermentative bacteria. These organisms act on the complicated organic materials of the substrate and produce simpler organic compounds that are much more soluble in water, such as sugars, alcohols, fatty acids, hydrogen, and carbon dioxide. The fatty acids having more than two carbon atoms in the molecule are converted further to methanogenic substrates, *viz.*, acetic acid, hydrogen, and carbon dioxide, by a group of bacteria called acetogenic bacteria. While some hydrogen-utilizing methanogenic bacteria can convert hydrogen/carbon dioxide to methane, there are other acetogenic bacteria that convert hydrogen and carbon dioxide to acetic acid by acetogenic hydrogenation. About 28 percent of the methane produced comes from the conversion of hydrogen and the remainder is the result of the conversion of acetic acid.

The acetic acid formed in the metabolism of organic matter is decarboxylated to methane by a group of bacteria called acetoclastic bacteria. These bacteria work in symbiosis with the acid-forming bacteria by reducing the concentration of acetic acid formed in a biomethanation system and thereby controlling the pH of the system. The acetoclasts have a longer generation time than the acid formers (2 to 3 days *vs.* 2 to 3 hours at 35°C, under optimum growth conditions). Hence, when biomethanation systems are subjected to surge loads of organic matter, they tend to go "sour," as the acid-forming bacteria produce fatty acids at a rate faster than the rate at which acetoclasts can utilize them.

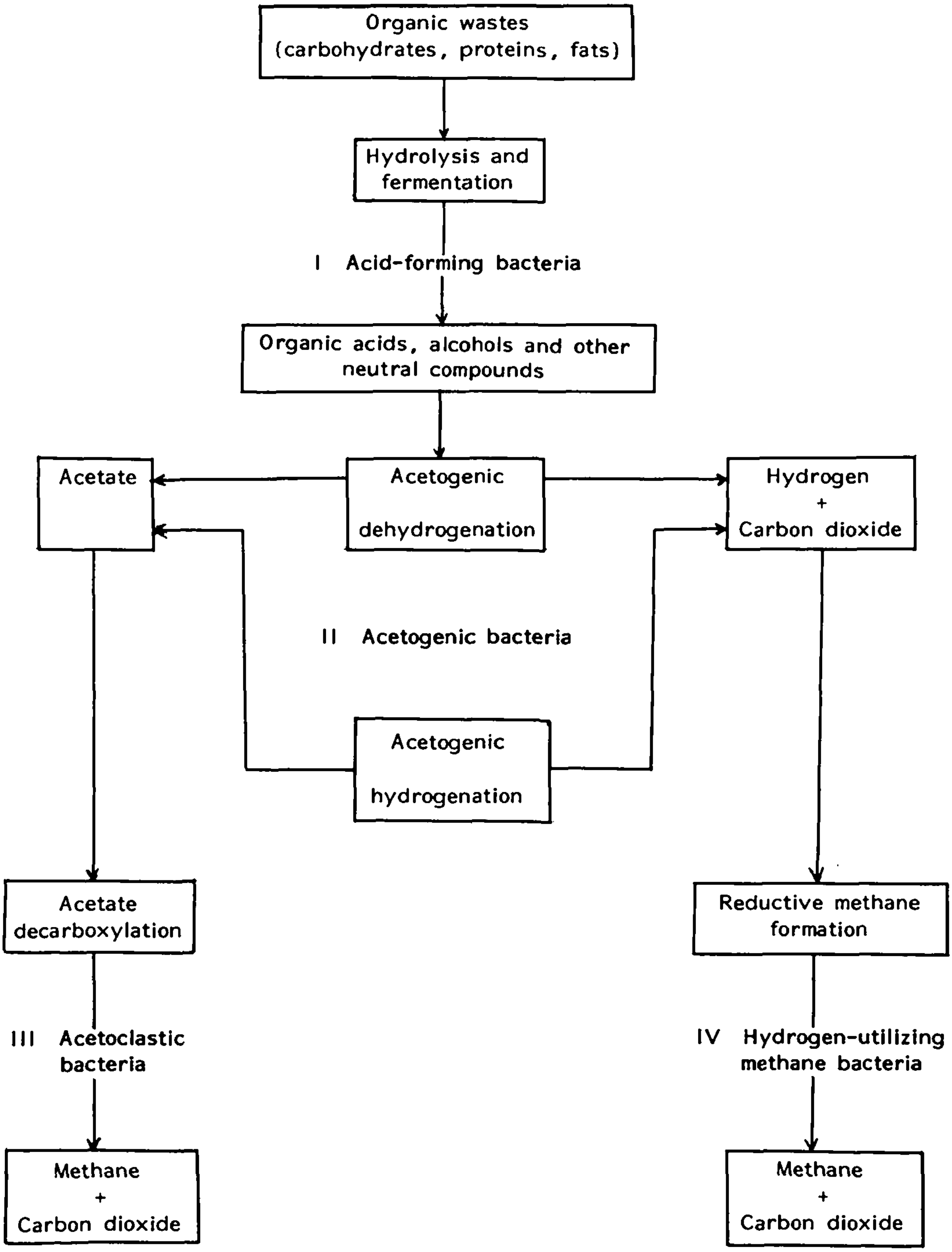


Figure 1. Biomethanation of organic wastes

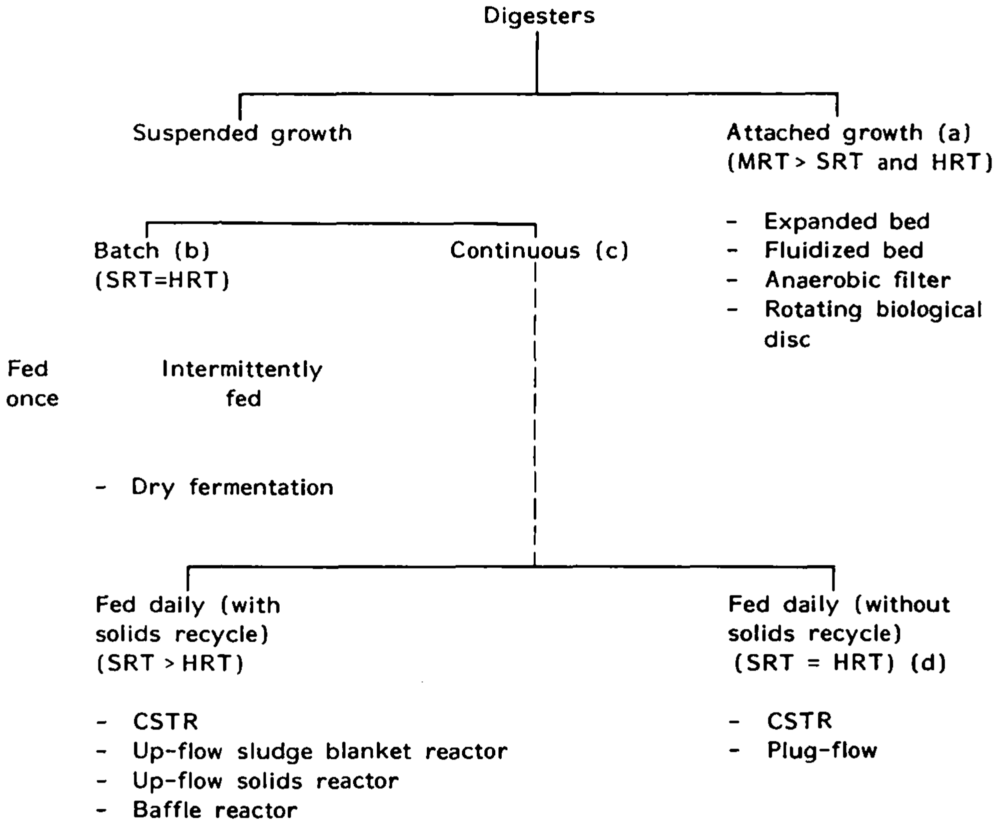
Under normal conditions, the hydrogen produced is easily used by the methane-generating bacteria. When the organic load received in the digesters is excessive, however, an increased quantity of hydrogen is formed. When the concentration of hydrogen is great enough that its partial pressure is above 1/10,000 atm., it promotes the formation of propionic and butyric acids (three- and four-carbon fatty acids) and reduces the chances for the continuing formation of acetic acid (McInerney & Bryant, 1981). However, when conditions for the formation of hydrogen at such high partial pressures are only temporary, the slow-growing acetoclasts will work on the already accumulated acetic acid and return the system to normal conditions, after a temporary set-back in gas production. As the hydrogen concentration is lowered by the hydrogen-utilizing methane bacteria, the propionic and butyric acids will be converted to acetic acid. When feeding rates to a digester are very high, an excessive concentration of hydrogen is continuously formed, and the quick attention of the operator is needed. Otherwise, a "stuck" digester can result, as the slow-growing acetogenic bacteria from the digester may be washed out before the hydrogen-utilizing methane bacteria have had a chance to utilize the hydrogen that has accumulated in excess, and return the digester to normal functioning. Thus, it was pointed out recently that it may be more useful to monitor the partial pressure of hydrogen in a digester with a simple electronic instrument, to control the fermentation, rather than resort to the more complicated chemical determination of volatile fatty acids (Mosey, 1982).

Based on the current knowledge of anaerobic fermentation of organic wastes, it appears that the rate-limiting steps of biomethanation are dependent on the physiological characteristics of the decomposition of the substrate by methanogenic bacteria. These characteristics are related to the nature of the substrate, the temperature, loading rate, pH, and the type of process configuration used. The hydrolysis step is usually the rate-limiting step for substrates such as agricultural crop residues, chitinous materials, and lignin, which are difficult to be digested. However, with wastes that are readily biodegradable, such as the many types of food-processing wastes, the rate-limiting step is the degradation of volatile acids because their rate of degradation is lower than their rate of formation.

3.2 Types of Digesters

Biomethanation digesters can be broadly characterized as suspended- and attached-growth reactors. In the suspended-growth reactors, the biological solids are suspended in the contents of the digester, whereas in the attached-growth reactors they are made to attach themselves to surfaces such as rock, plastic, or ceramic media. For the most part, the digesters that are built in the rural and urban areas of the developing countries fall into the category of suspended-growth reactors, and are similar to those originally developed for municipal sludge digestion. The attached-growth reactor technology is comparatively recent and its dissemination to developing countries has not taken place to any significant extent.

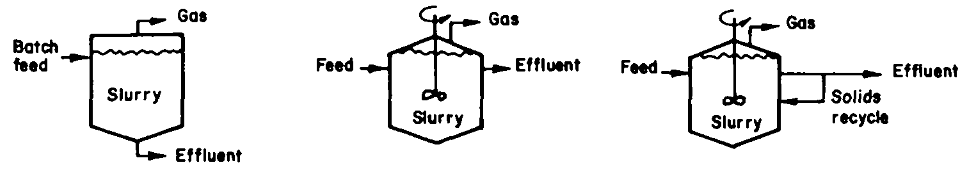
Figure 2 shows a classification of digester designs and their features based on characteristics such as flow patterns, relationship between solids retention time (SRT) and hydraulic retention time (HRT), with typical schematics of these digesters illustrated in Figure 3 (Fannin & Biljetina, 1984). Other design schemes can be developed by a combination of the suspended- and attached-growth systems. The application of such novel schemes to the digestion of biomass and organic waste materials in developing countries, however, needs extensive development work.



Notes: SRT = solids retention time
HRT = hydraulic retention time
MRT = microorganism retention time
CSTR = completely strirred tank reactor

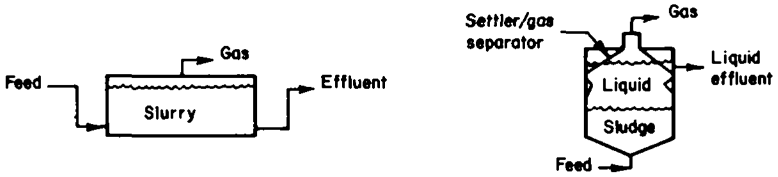
(a) usually continuously fed
(b) can be fed daily, or fed seasonally with irregular frequency
(c) with or without partial mixing
(d) SRT = HRT only when completely mixed

Figure 2. Classification of digester configurations



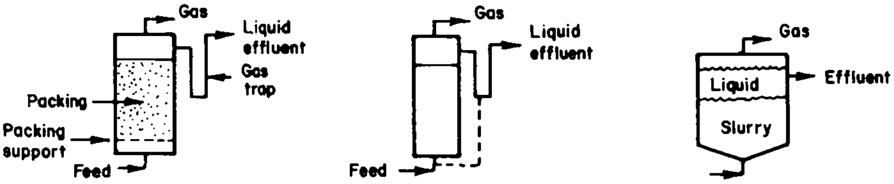
Batch digester

Completely stirred tank reactors



Plug - flow digester

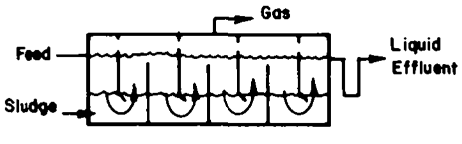
Upflow sludge blanket reactor



Anaerobic filter

Fluidized - bed/ expanded - bed reactor (with or without solids recycle)

Upflow solids reactor



Baffle reactor

Figure 3. Typical digester schematic drawings

Batch Digester

This is the simplest form of digester. A batch of wastes to be treated is generally placed in a large reactor that is then closed after the wastes have been mixed with the needed amount of water and an inoculum of previously digested sludge. Several types of wastes, such as leaves, crop residues, straw, paper and pulp-mill sludges, vegetable wastes, and aquatic weeds, can be digested in these digesters. The volume of biogas liberated from batch digesters depends on the volume and quantity of waste fed to the digester. The production of biogas may last for a few weeks to few months depending on the quantity of organic matter in the batch and the degree of digestion that takes place. During the start-up period, the biogas produced usually contains a large proportion of carbon dioxide, but as the digestion progresses well, the methane content of the biogas will increase and eventually reach a stable level.

Batch digesters can be installed on small farms where certain types of wastes are produced seasonally in large quantities. Many hundreds of batch digesters were reported to have been installed in Europe during the Second World War. Although the routine maintenance is minimal with batch digesters, the cleaning of these digesters at the end of the active gas-production phase can be quite messy and time consuming, depending on the size of the digester.

Recently, experiments have been reported using the dry fermentation process in batch digesters. In this process, agricultural and/or other types of biomass can be fed to the batch digester at a solids concentration as high as about 30 percent, which is much higher than the 6-9 percent customarily used in batch systems. It has been reported that a conversion efficiency of about 90 percent of the biodegradable material fed to the digester was achieved in 200 days in these experiments (Jewell *et al.*, 1982).

Sanitary landfills, which produce biogas actively, can also be considered as batch reactors. Although landfills are not customarily designed for optimizing gas production, several studies have demonstrated the feasibility of tapping biogas from landfills (Zimmerman *et al.*, 1983). Efforts are currently being made to take advantage of the potential for producing biogas from these systems.

Completely Mixed Reactors without Solids Recycle

Almost all of the biogas plants that are currently used in developing countries fall in this category. The floating-cover design of Indian digesters and the fixed-dome design of Chinese digesters, which are built in large numbers, do not generally employ solids recycle. Theoretically, the solids retention time and the hydraulic retention time (the time the liquid portion is retained in the digester) are equal - *i.e.*, the ratio of these parameters is 1. This may not usually be the case in the field, however, as there is likely to be incomplete mixing of the digester contents, which will not provide the homogeneity needed to meet this condition. Even in completely mixed systems, a certain portion of the material fed to the system on a given day will leave the system during the same day. (In a perfectly mixed system, this fraction is equal to the reciprocal of the solids retention time of the digester).

Completely Mixed Reactors with Solids Recycle, or Anaerobic Contact Process

Unlike the reactors described above, the ratio of the solids retention time and the hydraulic retention time can be made greater than one in these reactors. This is accomplished by discharging the liquid/solid mixture into a clarifier and recycling the solids to the system after separation. As the solids retention time is made to increase by recycling the solids, it is possible to process a greater flow rate of waste through this type of reactor than in a batch reactor of a comparable volume because the process efficiency is a function of the solids retention time of the reactor and not the hydraulic retention time. (This is a consequence of the fact that the active microorganisms are in the solid phase.) Because of this factor, higher loadings and more favorable economics are possible with reactors using solids recycle. One of the important considerations in the design of these systems is the settling characteristics of the digester effluent and the performance of the clarifier that follows the digester.

Two-Phase Digesters

In the design of these reactors, selective enrichment of acid formers and methane formers is promoted separately in two reactors that are operated in series. Advantage is taken of the big difference in the growth rates of the acid formers and methane formers, and by proper adjustment of flow rates to the first reactor, fatty acids are made to accumulate in it. The contents of this digester are then fed to the second reactor at a rate to promote and sustain the growth of the methane formers. The size of the first reactor (acid) is smaller than the size of the second reactor because of the difference in the growth rates of the acid- and methane-forming bacteria (Ghosh & Klass, 1977).

The configuration of these reactors can be manipulated in several ways. For example, both reactors can be completely mixed reactors with or without solids recycling; the first reactor can be a completely mixed reactor followed by an attached-growth reactor; or both reactors can be attached-growth reactors. The choice of the reactor type and configuration is primarily dictated by the nature of the substrate to be digested. Attached-growth reactors are generally used for soluble wastes that have a high biochemical oxygen demand (BOD).

Plug-Flow Digesters

In an ideal plug-flow system, the material that is introduced on a given day travels through the system like a piston, without getting mixed with the flows of wastewater introduced on previous days. After travelling through the digester, the material is forced out of the digester at the outlet end, having been subject to the microbial action for the detention time for which the digester was designed. If solids recycle is not practiced in these systems, the hydraulic retention time is equal to the solids retention time, as it is in completely mixed systems without solids recycle. Digesters of this type, which can be used in developing countries, have been designed by Fry (Fry & Merrill, 1973).

Up-Flow Sludge Blanket Reactor

This type of reactor, pioneered in the Netherlands, is conducive to the treatment of high-strength organic waste that is low in solid particles and can be operated with or without solids recycling. The digester has three distinct zones: 1) a densely packed sludge bed at the bottom, 2) a sludge blanket at the middle, and 3) a supernatant layer at the top. Wastewater enters at the bottom and passes through the sludge blanket. As the waste water continues to pass upwards, the solids are separated via an internal gas-solids separator. The solids fall toward the digesting zone, thus creating a long solids retention time and a high concentration of sludge solids in the system. It has been reported that 80 to 90 percent of the decomposition of the organic matter takes place in the sludge-blanket zone, which occupies approximately 30 percent of the total volume of the reactor (Lettinga *et al*., 1980).

Up-Flow Solids Reactor

As in the case of the up-flow sludge-blanket reactor, high solids retention time can also be achieved in this type of reactor. There is no solids-gas separator in this system, however. Unlike the up-flow sludge-blanket reactor, this reactor can be used for the digestion of feedstocks containing a high concentration of suspended solids. Studies with kelp indicate that a high yield and production rate of methane can be achieved with a feed containing 12 percent total solids. The process is reported to be very stable, with the overall reactor performance exceeding that of the completely mixed reactor (Fannin *et al.*, 1982).

Attached-Growth Reactors

This type of reactor is packed with materials such as rocks, charcoal, Pall rings, Raschig rings, sand, and different types of proprietary plastic materials. These packing materials provide support to the bacteria that are responsible for biomethanation of the waste. These reactors are well suited to treatment of very highly biodegradable wastes that contain a very low concentration of suspended solids. Wastes with a very high suspended-solids concentration create plugging problems and enormous head (pressure) losses occur as a consequence. In these reactors, microorganisms can be kept for a long time because of their attachment to the media. Hence, a very high *microbial* solids retention time can be achieved in comparison to the solids and hydraulic retention times. A washout of the microorganisms is less likely to happen even at high hydraulic retention times unlike the case of the completely mixed suspended-growth systems. Anaerobic filters, expanded-bed reactors, fluidized-bed reactors, and rotating biological disc systems are examples of these reactors (Figure 2).

The *anaerobic filter* is a reactor that is essentially a filter column packed with stationary media such as those mentioned above. Columns with media having a larger specific surface area (surface area per unit volume of the medium) will have more attached bacterial mass than those with media having a lower specific surface area. Several proprietary media are available for packing filter columns. Depending on the flow regime, the enrichment of the acid- and methane-forming bacteria takes place at different zones in the filter. For example, if the wastewater flow pattern is downward, there will be an enhancement of the acid formers and methanogens in the top and bottom regions of the column, respectively. For an up-flow column, the pattern of enrichment is exactly the opposite (Young & McCarty, 1969; Olthof & Oleszkiewicz, 1982).

Expanded- and *fluidized-bed* reactors contain media that have a relatively small particle size (about 0.5 to 50 mm) such as sand (Biljethina, 1984). The wastewater flow is in an upward direction in both types of reactors. In the expanded-bed reactor, the flow has a velocity sufficient to expand the bed without necessarily causing vigorous agitation. The velocities are greater in the fluidized-bed reactor and the bed is agitated, which results in a reactor whose contents are completely mixed. While the solid particles and the liquid pass through each of these reactors quickly, the microorganisms attached to the media stay for much longer periods. The increase in the effective surface area of the medium achieved by fluidizing and expanding it in these types of reactors provides an opportunity for higher organic loading rates, greater yields of biogas, and greater resistance to inhibitors than in other types of attached-growth reactors.

A summary of the general hydraulic retention times, loading rates in terms of the chemical oxygen demand (COD) of the waste, and the expected degree of substrate removal for the different types of reactors is given in Table 9.

Table 9. Comparison of hydraulic retention time, loading rate, and expected substrate removal.
(Biljethina, 1984; Van den Berg & Kennedy, 1983)

Digester type	Hydraulic retention time (days)	COD loading rate kg/m³/d	COD removal (%)
Batch	30-90	Variable	Variable
Dry Fermentation	Variable	Variable	Variable
Completely mixed	7-60	1-6	80-95
Two-Phase	3-10	5-35	80-95
Up-flow Anaerobic Filter	1-10	1-10	80-95
Down-flow Anaerobic Filter	1-10	5-15	75-88
Fluidized- and Expanded-Bed	<1	1-20	80-87
Up-flow Sludge Blanket	0.5-6	5-30	85-95

The major advantages and disadvantages of the types of digesters in use in the developing countries are summarized in Table 10.

3.3 Gas-Collection Systems

Gas-collection and -supply systems associated with biomethanation can range from simple to complex. With family-type digesters, it can be a simple plastic delivery tube. In a landfill, it may be a complex system of collection wells, radial gas-collection pipes laid at various depths of the landfill, condensate traps, flame arresters, gas-quality enhancement systems, and other subsystems (Giuliani, 1981).

In developing countries where biogas systems consist mainly of family- and community-size gas plants, the gas-collection system usually consists of the following components: 1) gas holder, 2) main gas-delivery pipe (and lateral lines where needed), 3) gas taps, 4) condensate trap, 5) flame arrester, and 6) a manometer and safety valve as in the case of a fixed-dome digester. Other supporting systems may also be present at larger installations. These may include a gas scrubber to enrich the methane content of the biogas, and bottling equipment to fill gas cylinders for use beyond the piped delivery system.

The Indian designs or their modifications typically use a gas holder as an integral part of the digester. Other designs use a separate gas holder. The gas holders can be made of mild steel, galvanized iron, ferrocement, bamboo cement, or plastic (high-density polyethylene or PVC). The bag-type digesters (Taiwan) and the fixed-dome types (Chinese and Indian Janata) collect the gas and store it within the digester itself. Thus the gas produced is drawn directly from these digesters. Plastic bag gas holders are not recommended for exposure to sun and extremes of climate, however, and they are prone to being punctured by sharp objects.

Table 10. Advantages and disadvantages of various reactor types

Type of reactor	Advantages	Disadvantages
<u>Batch reactor</u>		
- low solids reactor (less than 10%)	- simple in design, operation, and maintenance	- gas-production rates variable and unpredictable
- high solids reactor (more than 20%)	- can be used with seasonal biomass (e.g., crop residues)	- large reactor volume - separate gas holder - labor intensive if a large number of digesters are built for continuous gas production (may be useful)
<u>Continuous reactor</u>		
Suspended-growth reactors		
- floating-cover reactor (Indian type)	- predictable gas yields - uniform gas pressure - scum can be controlled - can be modified for solar heating - performance proved in developing countries	- high cost due to separate gas holder - high heat losses from gas holder - corrosion of gas holder - vertical types not suited for high water table - large dead space, hence lower efficiency - not recommended for dilute wastes
- fixed-dome reactor (Chinese type)	- lower in cost than Indian type - can be constructed with local materials - no gas holder - good insulation because of underground construction - millions constructed	- skilled workmanship needed for construction - variable gas pressure - low kills of helminthic ova because of short-circuiting - not suited to dilute wastes - scum control difficult - large dead space (low efficiency)
- Up-flow sludge-blanket reactor	- simple construction except for solids-gas separator - higher loadings than possible in other types - no mechanical mixing - relatively clearer effluent possible	- wastes with high concentration of suspended solids not suitable - needs efficient distribution of feed at the bottom - effluent recycling needed - no proven record in developing countries - operational skill required

Table 10. Advantages and disadvantages of various reactor types (cont'd)

Type of reactor	Advantages	Disadvantages
- two-phase reactor	- selective enrichment of acid formers and methanogens - possibility of maximizing gas yields because of the possibility of controlling environmental conditions optimal for acid and methane formers in the respective reactors	- complex to operate - benefits may not compensate for the cost incurred for all cases - not in extensive use - virtually no full-scale units in developing countries
- plug-flow reactor	- less dead space than Indian and Chinese type digesters, hence more active digestion volume - high solids loading rate possible, hence high gas yields - greater degree of pathogen destruction - relatively simple construction design to make it able to work in high groundwater table areas (Egyptian design)	- low gas delivery pressure - greater land area required than for Indian and Chinese designs - solids may settle out - formation of thick crust on top
- baffled reactor	- same as above for plug-flow reactor - existing septic tanks can be modified to this design	- same as above for plug-flow reactor
Attached-growth reactor		
- anaerobic filter upflow and down-flow reactor	- low HRT - high loading rates, hence high gas yields - simple construction with available materials - high process stability - can withstand temporary exposure to inhibitors	- applicable to wastes with low solids content only - separate gas storage required - not suited for agricultural residues such as crop residues and manures - no developing-country experience - high heat losses - high cost of growth medium - possibility of plugging

Table 10. Advantages and disadvantages of various reactor types (cont'd)

Type of reactor	Advantages	Disadvantages
- expanded bed and fluidized-bed reactor	- low HRT - high loading rates - high gas yields - high process stability - rapid re-starts after temporary shutdowns - promotes good mixing	- operational skill required - high energy requirements - not suited for wastes with high content of suspended solids - high cost of growth medium and its replacement - possiblity for high head losses and potential for plugging - degasifier may be required to separate gas from liquid - virtually no units in developing countries

The piping used for delivering the gas is made of plastic or galvanized iron. Plastic pipes are less expensive but less durable than galvanized iron pipes. Furthermore, they require proper support to prevent sagging. In addition, when exposed to sun and extremes in temperature, they tend to crack and leak. Care must be taken to lay them deep enough in the ground to avoid damage by heavy vehicular traffic. From a maintenance and durability point of view, therefore, it is desirable to use galvanized iron pipes in developing countries, although they are more expensive than PVC pipes.

In the Indian type of digester, the gas pressure is uniform, being provided by the weight of the gas holder, whereas wide pressure fluctuations occur in the fixed-dome type of digester. With community-scale units where the biogas has to be delivered to neighboring households, care should be taken in designing a delivery system, so that fluctuations in the delivery pressure from the nearest point to the farthest point are minimized. The recommended pipe sizes to be used for a gas distribution system for various flow rates and distances are given in Table 11.

Gas collection from landfills has been demonstrated to be a feasible process, in some circumstances, in developed countries, but has not yet been demonstrated in the developing world. It is not clear whether such a technology would make sense in many developing-country situations, where the solid wastes that would normally be used as biomethanation substrates are usually salvaged for rags and paper. Landfill gas-collection systems, if used, require the same type of equipment--gas taps, flame arresters, condensation traps--as other gas collection systems.

In rural situations where the technological infrastructure can support neither general maintenance services nor general familiarity on the part of the users with the equipment, it is important to employ gas taps that open and close smoothly. To avoid breakage, gas taps with a spring return or gas cocks that open and close with a 1/4 turn should be employed.

Table 11. Suggested pipe diameters (in mm) for varying flow rates and distances between biomethanation plants and points of use (Dhussa, 1983)

Flow Rate m^3/hr	Distance (meters)			
	25	50	100	150
0.50	12.5	19.5 (1st 25 m) 12.5 (2nd 25 m)	19	19
0.75	12.5	19	19	25 (1st 100 m) 19 (2nd 50 m)
1.00	19	19	19	25
2.00	19	19	25 (1st 75 m) 19 (2nd 25 m)	25
4.00	19	25	38 (1st 50 m) 25 (2nd 50 m)	38

Condensate traps come in many different shapes - bottle-shaped, T-shaped, and U-shaped traps being the most common - and they are inserted in the gas line to remove the moisture carried by the gas stream from the head space above the digester contents. These traps should be drained when they are filled with condensate, which should be disposed of properly. (The condensate may contain a significant concentration of hydrogen sulfide, which could be corrosive to some metals and toxic to some plants.) If the trap is installed below ground level, it may be prone to flooding during rain storms. In any event, condensate traps should be emptied before the condensate level rises to the point where it blocks the main gas line.

Flame arresters prevent the flame from an appliance such as a stove or a gas-mantle lantern from traveling back through the supply pipe to the digester and/or gas holder and causing an explosion. Thus, they are important safety devices with which every biogas system should be equipped. A common gas arrester is simply a fine-wire mesh made of nonferrous metals that is rolled into a ball and inserted into the gas pipe, either near the gas holder or near the appliance. In order to avoid excessive friction losses, these devices are generally placed in a section of pipe larger in diameter than the main gas supply line. For example, when a 19-mm gas line is used, a 25-mm diameter pipe is recommended for making the flame arrester (ESCAP, 1980).

A "U"-shaped manometer is used in conjunction with the fixed-dome digester to prevent damage from pressure build up that may result from periods of low gas use. Thus, it also acts as a safety device (Van Buren, 1976).

In some biomethanation installations, biogas is purified to enrich its methane content (see Introduction, Physical and Chemical Characteristics), but in developing countries, it is generally not purified. Various methods are available to enhance the quality of biogas to a higher calorific value, however, by removing the gases other than methane. When biogas is to be used in internal-combustion engines, H_2S should be removed to avoid potential corrosion problems. At Maya Farms in the Philippines, for example, hydrogen sulfide is scrubbed by passing the biogas through the bottom of a 55-gallon oil drum containing two layers (each ca. 30 cm deep) of iron filings. The scrubbed gas, which leaves from the top of the drum, is used to fuel the internal-combustion engines that run water pumps and electricity generators (see Introduction).

Several other methods are used to purify biogas and enrich its methane content. These include: 1) physical absorption into a liquid; 2) chemical absorption into a liquid; 3) physical absorption onto a solid; 4) chemical conversion to another compound; 5) membrane separation; and 6) condensation (Glaub & Diaz, 1981).

The bottling of biogas is neither a practical nor economic proposition for most situations in developing countries. Unlike propane and butane, which can be liquified easily, methane cannot be liquified easily, as noted in the Introduction (Use of Biogas). Hydrogen sulfide and carbon dioxide must be removed because they are corrosive and will damage the cylinders into which the biogas is bottled, if any moisture is present. As noted earlier, however, carbon dioxide should be removed in any event because of the large volume of non-flammable gas it represents. (Furthermore, the presence of CO_2 in such proportions will damage the compressor simply because it can be liquified at ambient temperatures.) Although it is physically possible to compress and store methane in cylinders for use as transportation fuel, the cost of the process, including the removal of impurities from the gas and the requirement for specially made cylinders, make this option impractical and uneconomical in developing countries.

3.4 Collection and Storage of Substrates

The success of generating methane from various feedstocks available in developing countries on a sustained basis depends on the steady supply and input of such feedstocks to the biomethanation system. The collection and storage of feedstocks are important factors in assuring this steady input of feed materials. Assuring a net positive energy balance from a biomethanation system, however, requires that the energy spent from commercial sources in collecting and storing the various feedstocks to be used for biomethanation, should not exceed the energy derived from the biogas that would be generated from these materials.

Collection and storage practices may vary from country to country, and from region to region within a country, because of differences in economy, social customs, and cultural practices. There may be prejudices or social taboos against collecting some substrates, such as nightsoil, in certain areas. While prejudices may be overcome by education in some areas, it may be very difficult to overcome them in other areas. When faced with the proposal to use dung and crop residues for biogas production in a community biomethanation system, villagers may be reluctant to give up age-old traditions and habits of collecting and using these materials. All such factors should be considered in devising a scheme for the collection and storage of biomethanation feedstocks to ensure a steady supply of the required quantity of biogas.

The method of collecting and storing feed materials depends on whether the substrate is solid, semi-solid, or liquid. While feed materials have to be hauled to a biomethanation system by either human or animal labor in some places, at other locations, such as cattle sheds, houses, hostels, and industrial parks, for example, the wastes generated may be led directly to a biomethanation system built on the site where such wastes are generated. A storage pit may be built whose size is equivalent to the volume of material required for loading the digester for a two-day period. In winter, additional material will be required in some places to offset lower gas yields resulting from lower gas-production rates. In this case, the storage pit should be large enough to hold this additional material. Any excess material that is not used for biomethanation should be stored or disposed of safely so as not to cause any environmental or public health hazards. In developing countries, dung from cattle that are not confined to stalls, is usually collected by manual labor. This dung can be transported to a storage pit near a digester, which allows the quantity of the dung needed to be withdrawn, on a regular basis, and made into a slurry before it is fed to the digester.

Dry materials, such as leaves, crop residues, forest litter, grass clippings, paper, etc., may be baled and transported to the digester either manually or by animal carts. Bulky materials may be shredded into small fragments and stored in a bin. Wet materials such as green leaves, aquatic weeds (water hyacinth), flotsam, banana stems and twigs, etc., may be shredded, dried, and stored in a secure place. These dry materials may also be placed in an annular space built around a digester to keep it insulated and, incidentally, to provide a useful source of heating in the winter, from the composting action that will occur. The stored material can be withdrawn as and when needed for feeding the digester and may be replenished when additional materials are available.

Other types of waste materials, such as those mentioned in Table 12, may be transported to the site of the digester and placed in separate bins. They may be mixed in the proportions suggested in Table 13 for feeding the digester to obtain satisfactory yields of biogas.

Table 12. Observed increases in the digestibility of substrates by pretreatment techniques (Tsao, 1984).

Substrate	Pretreatment technique	Observed increase (%)
Corn stalks	Shredding	5-10
Wheat straw	Shredding	5-10
Municipal solid waste	Shredding	300-600
Corn stover	Shredding	0
Hybrid poplar	Milling	ca. 20
Sycamore and aspen	Ball milling	ca. 1000
Water hyacinth	Alkali	10-15
Wheat straw	Alkali	50
Corn stover	Alkali	ca. 100
Rice straw and bagasse	4% alkali at 100°C	ca. 140
Municipal solid waste, lignocellulose activated sludge	175°C for 1 hour	100-800
White fir	Heat	30

Table 13. Recommended proportions of different materials as feed to digesters (United Nations, 1980)

Materials (b)	Ratio
Human waste : Straw (wheat stalks)	1.75 : 1
Human waste : Rice stalks	1.40 : 1
Human waste : Corn stalks	1.13 : 1
Human waste : Fallen leaves	0.85 : 1
Human waste : Soy-bean stalks	0.45 : 1
Human waste : Wild green grasses (c)	1.00 : 1
Pig waste : Straw (wheat stalks)	1.75 : 1
Pig waste : Rice stalks	3.65 : 1
Pig waste : Corn stalks	2.95 : 1
Pig waste : Fallen leaves	2.22 : 1
Pig waste : Soy-bean stalks	1.10 : 1
Pig waste : Wild green grasses (c)	1.00 : 25
Human waste : Pig waste : Rice stalks	1 : 1 : 1
Human waste : Pig waste : Wheat stalks	1 : 2 : 1
Human waste : Pig waste : Corn stalks	3 : 4 : 4
Human waste : Pig waste : Green leaves (c)	1 : 10 : 180

Notes:

a. Cow, horse, and sheep dung can be digested alone or with the mixtures shown in any ratio.

b. All human and pig wastes are assumed to be fresh, and plant wastes assumed to be dry.

c. Includes aquatic weeds. Grasses and aquatic weeds are assumed to be fresh.

It should be noted that prolonged storage of animal dung and other putrescible organic matter is counter-productive to the purpose of biomethanation. Not only will such storage result in the loss of much of the methane, it will also contribute to a significant loss of valuable nutrients, such as ammonia nitrogen, from the feed materials.

The effluent from the digesters should also be collected, stored, and/or disposed of in an environmentally acceptable way to avoid contamination of water supplies and public health hazards to workers. Appropriate equipment, such as gloves or rubber boots, for example, should be used by workers in handling not only biomethanation feedstocks but also the spent slurry, both of which may contain pathogenic organisms.

3.5 Pretreatment of Substrates

Several techniques are available for pretreating substrates that are not readily useful for biomethanation because of their resistance to microbial degradation. These techniques include physical, chemical, and biological methods.

Size reduction of cellulosic materials by processes such as ball milling and wet extrusion milling will enhance their rate of hydrolysis. One can expect higher rates of biogas production with cellulosic substrates of smaller particle sizes than with larger particle sizes, although the overall quantity of biogas produced may not be changed significantly. The physical forces exerted on cellulosic materials by milling may distort the structure of cellulose, thereby making it susceptible to greater penetration of macromolecular enzymes on the expossed surfaces, which would lead to more rapid hydrolysis (Tsao, 1984). Some results obtained in studies of the enhancement of biodegradation by size reduction are presented in Table 12.

Techniques such as treating wood residues with steam (steam explosion) and by liquid anhydrous ammonia (freeze explosion) have been reported to break up the structure of cellulose and lignin in woody materials (Tsao & Chiang, 1983). The removal of lignin from woody biomass can be achieved by solubilizing the lignin in alcohols such as butanol, ethanol, and ethylene glycol (Tsao, 1984). The lignin removed by this type of solvent-extraction pretreatment may be a valuable by-product since it may have a market of its own.

Irradiation by gamma rays has also been reported as a possible means of achieving the degradation of biopolymers, complex carbohydrates, and the crystallinity of cellulose. The irradiated material is more susceptible to alkaline or acid hydrolysis and enzyme activity (Gottschall et al., 1978).

Heat treatment of biomass can increase its digestibility because simpler organic compounds are formed. The temperature that can be used may be as high as 225°C. As heating causes loss of oxygen in the form of water and production of less carbon dioxide, the biogas formed from utilizing heat-treated substrates will have a higher methane content than those that are not treated by heat. Substrates such as sludge, wheat straw, white fir, and other types of hardwood have been reported to undergo autohydrolysis, when they are subjected to heat treatment, thereby enabling a greater rate of digestion of the products formed (Jerger et al., 1983; Colleran et al., 1982). A rotating biological disc and an anaerobic filter performed stably and produced methane at a detention time of one day using products formed by heat treatment of wheat and corn stover (Colberg et al., 1981).

In the heat treatment of biomethanation feedstocks, the incoming feed to a digester may be preheated through a heat exchanger by the heat exhausted from an internal-combustion engine run on the methane generated from the digester itself. Although the preheating of feedstocks may be considered as a pretreatment, it is usually part of a process to maintain digester temperatures in the design range. Most municipal and industrial organic sludge digesters are designed with preheating of sludge to either mesophilic or thermophilic temperatures as an integral unit process to sustain stable gas production.

The chemical methods for pretreating biomass materials may include: 1) acid hydrolysis; 2) alkaline hydrolysis; and 3) sulfur dioxide application (Tsao, 1984; Tsao & Chiang, 1983; Connor, 1980). Hydrolysis of cellulosic material with dilute acid under ambient conditions and at temperatures of 80 to 100°C yields simpler organic compounds such as sugars and uronic acid (Tsao, 1984). The heat treatment of biomass at temperatures in the range of 175 to 225°C for about 1 to 2 hours, has been reported to produce organic acids. These acids in turn hydrolyze cellulose and hemicellulosic materials to simpler substrates. Hydrolysis by sulfuric acid will add sulfate to the system and it can inhibit methane production by acting as an electron acceptor in preference to carbon dioxide.

Treatment by alkalies, such as NaOH, is the best known method to pretreat biomass for achieving enhanced biodegradation of cellulose and removal of lignin. Enhanced rates of methane production were reported with hybrid poplar, cotton wood, and sycamore, wheat straw, and water hyacinth (Chynoweth et al., 1983; Ghosh et al., 1980).

Pretreatment of biomass by fungi has been suggested for degrading lignin at a fast rate without rapid depolymerization of cellulose. Such fungi are reported to be Lentinus edodes, Phanerochaete, Chrysosporium, and Polyporus adustus (Tsao & Chiang, 1983; Brooks et al., 1978; Ander & Eriksson, 1978).

Enzymatic treatment of cellulose has been the subject of numerous investigations for the production of simple organic compounds. Saccharification of cellulose is the primary objective of these investigators and the principles involved in this process should be applicable for methane generation (Tsao, 1984).

The results of a recent review of different pretreatment techniques are summarized in Table 12. Although some of the pretreatment methods show promise for enhanced rates of biomethanation with some complex biomass substrates, their application has not yet found a wide application even in developed countries. Thus, it is unlikely that these techniques and the degree of operational control needed to achieve the desired end products may preclude their use in developing countries.

3.6 Integrated Biomethanation Systems

Anaerobic digestion systems can be integrated with other unit processes to accomplish more than the production of biogas and fertilizer and the stabilization of waste. The most important integrated resource-recovery options for biomethanation systems and associated unit processes are illustrated in Figure 4, while Figure 5 illustrates schematically the processing and uses of biogas.

The benefits and advantages, both technical and socio-economical, that are associated with community-size integrated biomethanation systems over family-size units can be considerable in developing countries. The size of the operation permits the employment of trained personnel to control plant operation, which has the following advantages:

- Gas-production rates and yields can be optimized by incorporating a good mixing and heating system in the digester, with proper operator control.
- Resource recovery can be enhanced by the use of solid and liquid effluents as feed supplements for livestock, fish, and water fowl.
- Generation of electricity becomes possible.
- Proper operation and maintenance means improved control of pathogens.
- Environmental protection can be enhanced with trained personnel by controlled storage and handling of feedstocks and effluents.

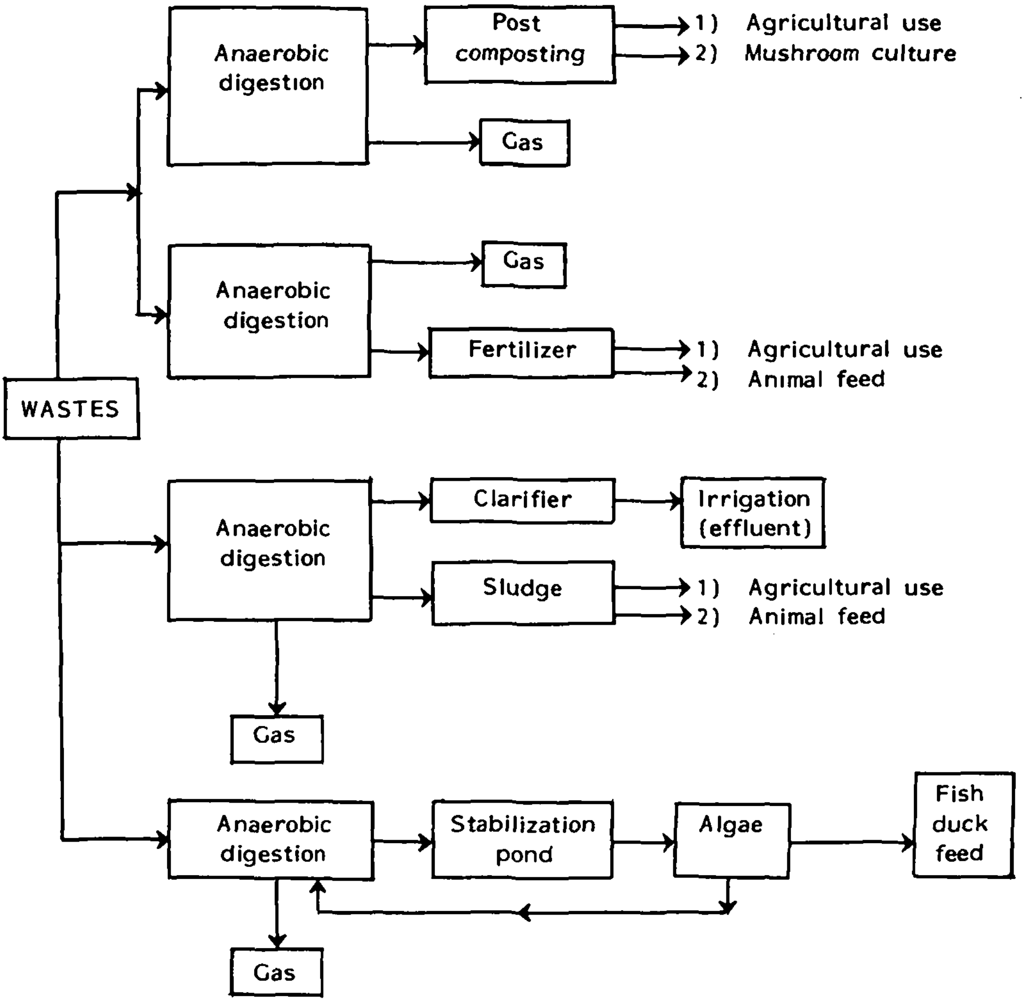


Figure 4. *Integrated resource recovery options utilizing* anaerobic digestion of wastes (Barnet, 1978)

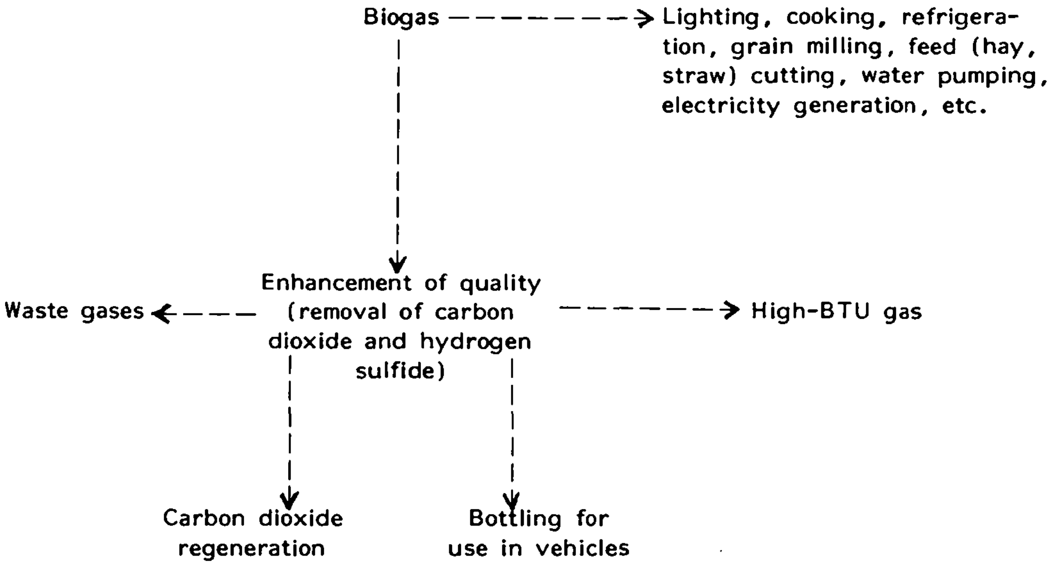


Figure 5. Processing and uses of biogas

Stemming from the technical advantages of community-scale integrated systems over family-size units are social and economic benefits, many of which might not otherwise be available to the community, even on an individual basis. These include the following:

- Clean fuel for cooking reduces the incidence of respiratory and ophthalmic diseases chiefly among the women and girls responsible for cooking.
- Availability of biogas cooking fuel will reduce deforestation pressures.
- The availability of electricity in areas where it is not otherwise provided can mean improved rural development options:
    - irrigation of fields
    - lighting
    - lighting and operation of audio-visual equipment in schools
    - operation of agricultural machinery
    - lighting and preservation of biologicals in rural health clinics
    - operation of submersible pumps to provide safe drinking water from protected wells.
- The growth and use of algae as a feed or feed supplement can increase the availability of protein (from fish and/or water fowl).
- The use of digested slurry as fertilizer will improve crop yields without the need to purchase chemical fertilizers.

- Employment opportunities in rural areas can be increased by:
  - operation and maintenance of biomethanation system
  - distribution of system products
  - jobs created by introduction of electrical machinery (small industry) and new agricultural equipment
  - jobs associated with raising and processing new sources of protein.
- Economies of scale mean lower unit capital requirements for construction of biomethanation system and distribution facilities.

In spite of the advantages of integrated resource-recovery systems based on biomethanation, which have been demonstrated by the Maya Farms experience, for example (Maramba, 1978), these systems have not yet gained popularity in many developing countries. Although the technology is available, social and institutional factors, and their impact on economics, appear to be primarily responsible for limiting their application. These issues will be discussed in the section on Planning Biomethanation Systems.

3.7 Factors That Influence Performance

The rate and extent of biomethanation of organic matter is affected mainly by three things:

- the nature of the substrate
- the environment under which the various microorganisms perform
- the design features of the biomethanation system.

Substrates that cannot be degraded biologically are obviously not appropriate feedstocks for biomethanation. Those that are degraded slowly may also be inappropriate feedstocks if they do not respond favorably to one or more of the pretreatment techniques described above.

Biomass that is readily biodegradable on the other hand, can be digested under anaerobic conditions to produce biogas. The composition of the organic matter in the biomass determines the methane yield (quantity of methane produced per kg of biomass fed to the digester). Reduced compounds, such as fats and proteins, produce more methane than substrates more relatively oxidized (in the sense of having a smaller proportion of hydrogen atoms in the molecule), such as sugars. The ultimate yield of methane depends on both the extent of biodegradability and the initial energy content of the substrate. Thus, although the energy content of coal and petroleum is high, the methane yield from these substrates is negligible, as they cannot be degraded easily biologically. Animal dung, municipal sludge, and industrial wastes such as food and vegetable processing wastes are amenable to biodegradation easily and thus are more readily suited to being used as feedstocks for biomethanation systems than are chitinous materials, crop residues, and woody biomass, all of which are not easily degraded. For example, vegetable matter from older plants has been observed to yield less biogas than the same material taken from younger plants (Sathianathan, 1975). Presumably, this may be due to lignification of the biomass in older plants. Also, dry vegetable matter produces more gas per unit weight than fresh vegetation, so it is useful to dry green bush and foliage before they are fed to the digester.

The carbon-to-nitrogen ratio (C:N) of a substrate is considered to be an important factor in the biodegradation of organic matter and is often referred to as a parameter of digestibility. Hence, a C:N ratio of 30 in a substrate is usually considered to achieve an optimum rate of biogas production in biomethanation systems, especially in systems using cow dung as substrate (National Academy of Sciences, 1977a). It should be noted, however, that substrates with C:N ratios higher or lower than 30 can also be degraded, depending on the availability of nitrogen from the substrate. For substrates rich in carbon (high C:N ratio), the addition of materials that are rich in nitrogen, such as shredded wild leguminous plant material or poultry manure, will provide a C:N ratio more conducive to digestion (National Academy of Sciences, 1977a). It is important, of course, that both the carbon and nitrogen contained in a substrate be available for the growth of the microorganisms to achieve successful biomethanation. The recommended proportions of various materials for feeding the digesters are presented in Table 13.

The quantity of methane produced from different types of wastes under different operating conditions is shown in Table 14. The amount of biogas produced from the same type of substrate may vary considerably from system to system, or even within the same system, because of seasonal or geographical variations in the composition of the substrate and/or differences in environmental or operating conditions of the digesters.

The composition of animal manure is strongly dependent on the type of feed given to the animals. For this reason, it is not unusual to find differences in gas production rates from animal manures of the same type from one country to another. Similarly, wastes from the same type of industry may vary in quality because of differences in production techniques, water consumption, or other conditions.

Methanogenesis can be initiated quickly in anaerobic systems if they are initially seeded with a good inoculum, such as digested sludge. During start-up, the seed material should have at least twice the volume of the feed slurry. The seed volume can then be progressively reduced while increasing the proportion of the feed over a three-week period. At the end of this period, the feed slurry alone can be fed to sustain active biomethanation. Digesters that are "stuck" may also be rejuvenated by stopping the feed input to the digester, removing a portion of the slurry daily (about 10 percent of the volume of the digester contents), and replenishing it with the same volume of a well digested slurry obtained from a sewage treatment plant or another biogas plant that is operating satisfactorily. The key to starting and maintaining a successful biomethanation system lies in providing a balanced distribution of the acid formers and methane formers. As long as there is an adequate population of methane bacteria in the digester to utilize the volatile acids produced by the acid formers, the biomethanation process can be maintained when proper environmental conditions are provided for the organisms.

Successful production of biogas depends on providing a favorable environment for all groups of microorganisms responsible for biomethanation. Methanogens have unique nutritional and environmental requirements and these should be met in order to initiate and sustain methanogenesis in a digester. Aside from maintaining anaerobic conditions, the major environmental factors that influence the production of biogas are pH, temperature, toxic inhibitors, mixing, and nutrient mix.

Table 14. Biogas production from different substrates - variation with loading rate and retention time

Substrate	Temp. °C	Loading rate kg VS/m^3/d	Retention time (days)	Gas yield m^3/kg VS added	Reference
Dairy manure:					
	32.5	15.21	5	0.07	(Morris, 1976)
		7.60	10	0.16	"
		3.80	20	0.23	"
		2.55	30	0.23	"
		1.92	10	0.30(a)	(Gramms et al.,1971)
			15	0.32(a)	"
		3.85	10	0.39(a)	"
			15	0.55(a)	"
	35	5.10	10	0.12	(Pigg, 1977)
		3.90	15	0.16	"
		3.00	20	0.18	"
		2.20	30	0.21	"
		11.05	10	0.12	(Jewell et al.,1980)
		7.50	15	0.15	"
		3.19	30	0.18	"
		6.22	10.4	0.15	(Converse et al., 1977)
		10.00	11	0.12	(Martin & Lichtenberger,1981)
	60	10.51	6.2	0.14	(Converse et al., 1977)
Cattle manure:					
	35	1.35	10	0.32	(Loehr & Agnew,1967)
		2.71	10	0.31	"
		3.51	10	0.38	"
		4.80	10	0.37	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m³/d	Retention time (days)	Gas yield m³/kg VS added	Reference
Cattle manure: (cont'd)					
	35	6.3	8	0.25	(Hashimoto et al., 1978)
			10	0.29	"
	55	14.88	4	0.21	"
		11.45	6	0.23	"
		5.15	12	0.31	"
		3.42	20	0.22	(Hashimoto, 1983)
		6.3	8	0.37	"
			10	0.32	"
Cattle manure + Straw:					
(1:9)	35	6.5	15	0.02	(Hashimoto, 1983)
	55	6.5	10	0.09	"
(1:3)	35	6.1	8	0.03	"
			10	0.02	"
	55	6.1	6	0.11	"
			8	0.20	"
(1:1)	35	6.6	8	0.13	"
			10	0.11	"
			8	0.24	"
			10	0.19	"
Cattle manure + Molasses:					
(1:1)	55	11.3	6	0.30	(Hashimoto, 1981)

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m^3/d	Retention time (days)	Gas yield m^3/kg VS added	Reference
Cattle manure (two-stage):					
	53	11.3	6	0.30	(Hashimoto & Robinson, 1982)
Pig manure:					
	24	0.53	6	0.58	(Brumm & Nye, 1982)
		0.92	3	0.48	"
		1.57	2	0.42	"
	25	2.5	22	0.32	(cited by Fannin *et al.*, 1981)
	30	1.8	20	0.25	"
		2.2	-	0.24	"
		3.1	-	0.22	"
		2.7	-	0.23	"
		2.6	15	0.35	"
	32	3.1	15	0.28	"
	32.5	1.9	10	0.15	(Gramms *et al.*,1971)
			15	0.25	"
		3.8	10	0.26	"
			15	0.25	"
	34	1.25	8.5	0.54	(Thomas & Evinson, 1978)
	34	5.6	2.65	0.25	"
	34	5.6	2.65	0.25	"
	35	1.0	30	0.51	(Loehr & Agnew, 1967)
		2.1	15	0.44	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m³/d	Retention time (days)	Gas yield m³/kg VS added	Reference
Pig manure: (cont'd)					
	35	4.0	15	0.34	(Fischer, 1979)
		1.3	10	0.35	(Ianotti et al.,1979)
		3.8	15	0.35	"
	55	2.7	20	0.26	(Van Velsen, 1979)
Broiler (poultry) litter + Feed:					
	32.5	1.92	10	0.17	(Gramms et al., 1971)
			15	0.21	"
		3.84	10	0.13	"
			15	0.15	"
	35	1.6	70	0.19	(Morrison et al., 1981)
		2.21	70	0.21	"
		3.18	70	0.17	"
		2.71	25	0.25	"
		3.12	25	0.22	"
		3.05	15	0.33	"
		3.77	15	0.29	"
		4.38	15	0.29	"
		2.72	10	0.28	"
		3.81	10	0.34	"
		4.6	10	0.37	"
		1.95	50	0.27	(Converse et al., 1980)
	50	7.5	8	0.3	(Huang et al., 1982)
		10.0	4	0.29	"
		15.0	4	0.23	"
		20	4	0.17	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m^3/d	Retention time (days)	Gas yield m^3/kg VS added	Reference
Broiler (poultry) litter + Feed: (cont'd)					
%VS:					
3	60	6.1	5	0.03	(Shih & Huang,1980)
5		10.0	5	0.03	"
7		22.9	3	0.01	"
		14.0	5	0.02	"
		10.0	7	0.02	"
		7.7	10	0.03	"
9	60	18.4	5	0.15	"
Primary sludge:					
	35	3.2	8.5	0.47	(Chynoweth et al., 1982b)
		1.6	15	0.52	"
Activated sludge + Primary sludge (9:1):					
	35	2.08	17	0.21	(Chynoweth et al., 1982b)
	54	3.20	11.3	0.26	(Rimkus et al.,1982)
Municipal solid waste:					
	35	-	-	0.17	(Fry & Merrill,1973)
		-	-	0.12	"
		-	-	0.11	"
	37	3.2	8.5	0.47	(Stenstrom et al., 1983)
	60	-	10.0	0.35	(Walter, 1983)

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m³/d	Retention time (days)	Gas yield m³/kg VS added	Reference
<u>Municipal landfill effluent</u>:					
	29-38	0.25	5	0.27(b)	(Cameron & Koch, 1980)
		0.25	10	0.27(b)	"
		0.08	20	0.28(b)	"
<u>Thermal sludge conditioning liquor</u>:					
Anaerobic filter:	35	20.6(b)	0.6	0.16(b)	(Hall & Jovanovic, 1983)
Down-flow filter:	35	19.1(b)	0.6	0.12(b)	"
Up-flow sludge blanket:	35	5.9(b)	2.0	0.18(b)	"
Fluidized bed:	35	21.7(b)	0.6	0.11(b)	"
<u>Bean blanching waste</u>:					
	55	11.2	3.5	0.84(c)	(McCabe & Eckenfelder, 1957)
		19.2	2.0	0.66(c)	"
<u>Green pea blanching waste</u>:					
	35	2.7(b)	5.5	0.25(b)	(Chambelhac *et al.*, 1982)

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m³/d	Retention time (days)	Gas yield m³/kg VS added	Reference
Green pea slurry:					
	33	0.87-1.25	32	0.28-0.34	(Knol *et al.*,1978)
French bean waste:					
	33	0.96-1.15	32	0.33-0.35	"
Spinach:					
	33	0.83-1.18	32	0.31-0.32	"
Asparagus peels:					
	33	0.74-1.06	32	0.19-0.25	"
Strawberry:					
	33	1.02-1.15	32	0.24-0.25	"
Apple pulp:					
	33	1.02-1.60	32	0.25-0.37	"
Apple slurry:					
	33	0.83-1.15	32	0.27-0.29	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m^3/d	Retention time (days)	Gas yield m^3/kg VS added	Reference
Carrot waste:					
	33	0.80-0.90	32	0.41-0.42	(Chambelhac *et al.*, 1982)
Carrot peelings:					
	35	2.7(b)	5.5	0.25(b)	"
Pear blanching waste:					
	35	3.5(b)	6	0.29(b)	"
Tomato solids:					
	35	1.0	35	0.24	(Hills & Dystra,1980)
		3.0	35	0.11	"
		5.0	35	0.07	"
		1.0	25	0.23	"
		3.0	25	0.10	"
		5.0	25	0.07	"
		1.0	15	0.14	"
		3.0	15	0.09	"
		5.0	15	0.07	"
Sugar beet waste:					
	30	3.5(d)	0.12	0.61(e)	(Heertjes & Van der Meer, 1978)
		4.5(d)	0.13	0.80(e)	"
		5.5(d)	0.18	0.79(e)	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m³/d	Retention time (days)	Gas yield m³/kg VS added	Reference
<u>Confectionary waste</u>:					
	35	6.0(b)	-	0.34(b)	(Anderson *et al.*, 1983)
	20-25	5.0-15.0(b)	1.0-1.3	0.3-0.5(b)	(Wheatley & Cassell, 1983)
<u>Sugar-refining waste</u>:					
	35	1.5(b)	5.1	0.76(b)	(Tesch *et al.*,1983)
		10.7(b)	0.7	0.3(b)	"
<u>Cheese waste</u>:					
	37	1.28(f)	40	0.81(f)	(Harishchandra & Saxena, 1969)
		3.04(f)	15	0.67(f)	"
<u>Whey</u>:					
	22-25	1.90(b)	-	0.45-0.5(b)	(cited by Chynoweth *et al.*, 1983)
	35	85.00(b)	7.4	0.3(b)	(Sutton *et al.*,1983)
<u>Molasses stillage</u>:					
	35	-	-	0.35(b)	(Anderson *et al.*, 1983)
	37	2.2(b)	10	0.12(b)	(Chao, 1983)
		5.4(b)	4.1	0.04(b)	"
		7.5(b)	3.0	0.02(b)	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m³/d	Retention time (days)	Gas yield m³/kg VS added	Reference
Rum distillery waste:					
	35	10.4(b)	12-15	0.28-0.29(b)	(Szendrey, 1983)
		8.8	8-10	0.27-0.29	(Biljethina,1984; Abeles *et al.*,1979)
Brewery byproducts:					
	37	6.0	10	0.3	(Keenan & Kormi, 1981)
Water hyacinth (WH):					
	35	1.3	12	0.23	(Chin & Goh, 1978)
		1.6	15	0.19	(Chynoweth *et al.*, 1982a)
		3.4	8.5	0.17	(Chynoweth *et al.*, 1982b)
	37	3.16	20	0.25	(Chin & Goh, 1978)
		6.31	10	0.2	"
WH + Bermuda grass (BG) + Waste blend feed (W):					
	35	1.6	12	0.22	(Chin & Goh, 1978)
Caustic pretreated blend feed (WH+BG+W):					
	35	1.6	12	0.26	(Chin & Goh, 1978)

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m^3/d	Retention time (days)	Gas yield m^3/kg VS added	Reference
WH + BG + MSW sludge blend:					
	35	1.3	12	0.26	(Chynoweth *et al.*, 1982a)
WH + Sludge:					
	35	1.6	15	0.28	"
		3.7	8.5	0.25	"
Sea kelp:					
	35	1.6	18	0.28	(Chynoweth, 1978)
		1.6	18	0.30	(Fannin *et al.*, 1982)
		1.6	40	0.26	(Chynoweth, 1978)
		1.6	50	0.37	(Yang, 1981)
Sea kelp (g):					
	35	2.4	27	0.20	(Fannin *et al.*,1982)
Sea kelp (h):					
	35	1.6	-	0.37	"
Sea kelp (i):					
	35	1.6	50	0.35	"
		2.4	27	0.16	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m³/d	Retention time (days)	Gas yield m³/kg VS added	Reference
S. maxima:					
	35	2.0	20	0.25	(Samson & Le Duy, 1983b)
S. maxima + 9% sewage sludge:					
	35	2.2	20	0.31	(Samson & Le Duy, 1983a)
S. maxima + 49% sewage sludge:					
	35	3.8	20	0.36	"
Tetraselmis. air-dried (marine alga):					
	35	1.0-1.9	14-20	0.21-0.23	(Asinari Di San Maizano *et al.*, 1981)
Tetraselmis. fresh:					
	35	1.0	20	0.33	"
Tetraselmis. air-dried - Two-step methanation:					
	20-35	1.95-4.05	14	0.19-0.21	"
Hydrodictyon (fresh-water alga):					
	35	0.9-11.36	1.6	0.22	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m³/d	Retention time (days)	Gas yield m³/kg VS added	Reference
<u>Scenedesmus</u>:					
	35	1.0	20	0.20	(Aninari Di San Maizano <u>et al</u>., 1981
<u>Bermuda grass</u>:					
	35	1.3	12	0.14	(Ghosh <u>et al</u>.,1980)
<u>Bermuda grass with nitrogen addition</u>:					
C:N=6.3	35	1.3	12	0.27	"
C:N=12.3	35	1.3	12	0.21	"
<u>Hybrid poplar</u>:					
	35	0.03	60	0.32	(Jerger <u>et al</u>.,1982)
<u>Sycamore</u>:					
	35	0.03	60	0.24	"
<u>Black alder</u>:					
	35	0.03	60	0.24	(Jerger <u>et al</u>., 1982)
<u>Cottonwood</u>:					
	35	0.03	60	0.22	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

Table 14. Biogas production from different substrates - variation with loading rate and retention time (cont'd)

Substrate	Temp. °C	Loading rate kg VS/m^3/d	Retention time (days)	Gas yield m^3/kg VS added	Reference
Eucalyptus:					
	35	0.03	60	0.014	(Jerger, et al., 1982)
Loblolly pine:					
	35	0.03	60	0.063	"

Notes:

a. Volatile solids destroyed
b. COD basis (loading is per kg; gas production is per kg of COD added)
c. Biogas/kg VS destroyed (not methane)
d. Total organic carbon basis
e. Biogas/kg total organic carbon added
f. BOD basis
g. Up-flow solids reactor
h. Baffle-flow reactor
i. Stirred-task reactor

pH

The effect of hydrogen-ion concentration in the digester is a very important environmental factor. Although acid-forming bacteria can tolerate a pH as low as 5.5, the methane formers are inhibited at such low pH values. Biomethanation can proceed well within a pH range of 6.6 to 7.6, with the optimum range being 7 to 7.2 (McCarty, 1966). The pH of the digester may drop to 6 and below if there is an excessive accumulation of volatile acids. Such an accumulation may occur when the organic loading rates are excessively high and/or when toxic factors are introduced into the digester.

If an increase in volatile-acid concentration occurs and methane formation decreases due to a lowering in the pH of the system, the situation can be corrected in two ways. First, the feeding of the digester can be stopped to permit the methanogens to utilize the accumulated volatile acids at their pace. When optimal gas production rates are reestablished, the normal loading of the digesters can be resumed. Second, the pH may be adjusted to neutrality by the addition of lime or other basic materials. If the alkalinity of the digesting medium is maintained within the range of 2,500 to 5,000 mg/L, a good buffering capacity is generally insured in the digester.

Temperature

It is generally agreed that two optimal temperature ranges exist for biogas production. These are the mesophilic (30 to 45°C) and thermophilic (50 to 60°C) ranges, with many design engineers accepting 35°C and 55°C as the optimum mesophilic and thermophilic temperatures for biogas production.

During winter months, gas-production rates in unheated digesters will be lower than those observed during summer months. Hence, at comparable loading rates, the yield or the volume of biogas produced in a given time will be lower in winter months than in summer months. For maintaining biogas yields in winter at the same level as in summer months, the loading rate of the digester should either be increased or more microbial solids should be retained in the system by recycling the digester sludge or by immobilizing the biological solids. The drop in biogas yield during winter months may create problems in communities of developing countries, if they are dependent on the biogas as the sole energy source. The temperature of the digester can be maintained in the mesophilic range by preheating the feed slurry through a heat exchanger. The heat exchanger in turn may receive the waste heat of a generator operated on the biogas produced by the same digester.

As a rule of thumb, for every 10°C in the digestion temperature, one can expect a doubling of gas-production rates in the mesophilic and thermophilic ranges. In the designing of biogas systems for application in cold regions, one should make allowance for lower gas-production rates in the colder months. The heating requirements of a digester are dependent on the materials used for construction, ambient temperature, and heat losses occurring from the digester. The heating of a digester can be accomplished by heating the feed slurry through a heat exchanger and pumping it into the digester or by recirculating hot water through coils of pipe installed inside the digester. The heating of a digester can also be accomplished by the following means:

- Housing the digester in an enclosure lined with a thick transparent plastic film; (The heat within the enclosure can be 5 to 15°C higher than the ambient temperature).

- Designing the digester in such a way that water can be held on the roof of the gas holder and heated by solar radiation; (Heat losses from the gas holder can be minimized by such an approach. The warm water from the bermed area can be used for making up the daily feed slurry).

- Insulating the digester with suitable materials available locally or by placing compostable material like leaves in an annular space built around the digester.

The Khadi and Village Industries Commission of India feels that feeding cold slurry to the digester in the winter months is the cause of more heat loss than the fall in ambient temperatures. Thus, they recommend feeding the digester with a slurry made with hot water in cold weather (Sathianathan, 1975). Singh has reported that a feedback principle can be used to heat the digester slurry. This involves heating and recirculating the digester contents by using a part of the biogas produced. The increased quantity of the gas produced by using this principle would be more than sufficient to compensate for the biogas used in heating and recirculating the digester contents (Singh, 1971).

Toxic Factors

Toxicity to biomethanation systems may result from a number of sources. Accumulation of volatile fatty acids and undissociated ammonia are commonly associated with digester failures. Molecular oxygen also inhibits biogas generation. A list of the more commonly encountered inhibitors of biomethanation is given in Table 15.

Inhibition caused by excess concentrations of certain ions can be counteracted by some other ions (antagonistic ions), while it can also be exacerbated by others (synergistic ions). Ions that are known to exhibit such interactions are listed in Table 16. Guidelines for diluting animal manures as feed to digesters to alleviate potential ammonia and volatile acid toxicity are presented in Table 17.

Table 15. Inhibitors of biomethanation (EPA, 1979)

Parameter	Inhibiting concentration (mg/L)
Volatile acids	>2,000 (as acetic acid) (a)
Ammonia nitrogen	1,500 - 3,000 (at pH>7.6)
Sulfide (soluble) (b)	>200; >3,000 toxic
Calcium	2,500 - 4,500; 8,000 strongly inhibitory
Magnesium	1,000 - 1,500; 3,000 strongly inhibitory
Potassium	2,500 - 4,500; 12,000 strongly inhibitory
Sodium	3,500 - 5,500; 8,000 strongly inhibitory
Copper	0.5 (soluble metal)
Cadmium	150 (c)
Iron	1,710 (c)
$Chromium^{+6}$	3
$Chromium^{+3}$	500
Nickel	2

Notes:
- a) Within the pH range of 6.6 to 7.4 and with adequate buffering capacity, volatile acids concentrations of 6,000 to 8,000 mg/L may be tolerated.
- b) Off-gas concentration of 6% is toxic (Speece, 1984).
- c) Millimoles of metal per kg of dry solids.
- d) Nickel promotes methane formation at low concentrations. It is required by methanogens.

Table 16. Synergistic and antagonistic cations in anaerobic digestion systems (EPA, 1979)

Toxic cations	Synergistic cations	Antagonistic cations
Ammonium-N	Ca, Mg, K	Na
Ca	Ammonium-N, Mg	K, Na
Mg	Ammonium-N, Ca	K, Na
K	--	K, Na
Na	Ammonium-N, Ca, Mg	K

Table 17. Suggested dilution requirements for animal wastes (National Academy of Sciences, 1977d)

Animal type	Dilution manure; (manure+water)
Swine (growing/finishing)	1:2.9 (a)
Dairy cattle	Undiluted
Beef cattle (*ca.* 320 kg)	1:2.5 (b)
Poultry (layer)	1:8.3 (a)
Poultry (broiler)	1:10.2 (b)

a. Based on ammonia toxicity criteria.
b. Based on volatile acids criteria.

The potential toxicity of the materials listed in Table 16 may also be diluted with water, while other compounds may be diluted with nontoxic wastes. The various materials that are available as feed inputs to biomethanation systems in the rural areas of developing countries, however, are generally free of these toxicants. The inhibition of methanogenesis caused by ammonia and volatile acids in manure digesters can be corrected by proper management and operation of such systems. Where biomethanation of industrial wastes is being considered, however, the toxicity of such substrates should be evaluated before one embarks on such a project.

Nutrients

Biomethanation systems may be plagued with problems in spite of careful supervision and operation because of a deficiency or imbalance in the nutrients required by the microorganisms. As a result of the growing interest in the use of different types of biomass to produce biogas it is important to recognize that supplementation of the required nutrients may be needed to achieve optimum rates of digestion and yields of biogas.

Nitrogen and phosphorus are by far the major nutrients that are required for biomethanation. Stoichiometric calculations show that the requirement for nitrogen in the anaerobic digestion of wastes is 6 kg N per 1,000 kg of COD (chemical oxygen demand) removed (1 kg N/60 m^3 methane produced). The corresponding phosphorus (P) requirement is approximately 1/7th that of the nitrogen. Systems operated at higher solids retention times have lower nitrogen requirements than those operating at lower solids retention times (Speece, 1984). It should be emphasized that the concentration of available N and P actually determines the nutrient-limiting condition of a system.

It is reported that a concentration of about 12 mg of unionized hydrogen sulfide per liter (equivalent to about 0.5% hydrogen sulfide in the digester gas) are required for optimum methanogenesis (Speece, 1984). Other nutrients such as Fe, Mg, K, Na, Ca, Co, Ni, Se, W, and S are all reported to stimulate methanogenesis. Some of these micronutrients are detrimental to anaerobic digestion when present in high concentrations, as described previously. Although Ni is considered to be a nonessential nutrient for bacteria, it plays an important role in the physiology of methane bacteria with an estimated required concentration for various methanogens in the range of 250 to 1,100 micromoles/g of cells (dry weight) (Diekert et al., 1981).

Finally, it should be emphasized that a preliminary assessment of the nutrient requirements must be made before industrial wastes are used for biomethanation, to avoid potential difficulties. For example, wastes from vegetable-processing plants may be relatively low in nitrogen content and therefore may require supplementation with manure or leguminous plant material to lower the C:N ratio to the optimum level, to avoid the production of excessive proportions of carbon dioxide. Similarly, wastes high in nitrogen may have to be mixed with cellulosic materials to avoid the loss of nitrogen as ammonia (see Table 13).

Mixing

Mixing reduces the settling of solids and the separation of supernatant. It provides an intimate contact between the bacterial populations and their substrates. Hence, higher rates of gas production can be realized with mixing than without it. The simplest types of reactor are unstirred, of course, but they are inefficient in performance, as evidenced by their low gas-production rates, low loading rates (less than 1.6 kg VS/m^3/day) and high detention times (more than 30 days) (Barnett, 1978). Mixing also reduces the potential for scum formation. It can be accomplished manually in small-scale digesters, as in the case of some of the Chinese and Indian types. In community-scale digesters and other large-scale digesters, it can be achieved mechanically by stirring and recirculation of the gas and/or the digester contents. (An interesting system using another source of renewable energy, in the form of a wind-driven device, to mix a digester has been reported to be in use in Ecuador) (Xu, 1983).

3.8 New Technologies - Prospects and Problems

In contrast to the suspended-growth digesters, which are widely used in some of the developing countries, attached-growth systems have not made their debut to any significant extent in the developing countries. The anaerobic filter, expanded-bed, and fluidized-bed designs are of relatively recent origin and have not gained wide acceptance even in the developed countries. They are potentially very useful, however, particularly for high-strength organic wastes that do not contain a high concentration of particulate matter. Thus, their application in rural areas of developing countries, where such wastes are not usually generated, is limited. In areas where the generation of such wastes from different types of industries is possible, however, these systems may be used, but skilled personnel are required to operate them. This technology could be of great benefit to industries that generate liquid wastes with high concentrations of dissolved organic material because of its potential for energy recovery and water reuse. This might not only offset some production costs but it would also be environmentally beneficial by improving the quality of the discharged water.

Digester designs such as the up-flow sludge-blanket reactor, upflow solids reactor, and the two-phase digester have been demonstrated to perform well in experimental situations in developed countries. While these designs also offer opportunities for application in developing countries, their performance has yet to be field tested and demonstrated.

In view of the relative complexity of operation and maintenance of the above types of digesters, in comparison to the floating- and fixed-dome types, it is not likely that they would gain popularity in developing countries in the near future, with the exception, perhaps, of adaptation to specific industrial use.

IV LESSONS FROM EXPERIENCE

4.1 Technical and Socio-Economic Issues

Learning from the experience of others in the field of practical (*i.e.*, field) use of biomethanation systems is not easy. In most fields of technology, benefitting from the experience of others on a technical level is a relatively straightforward process, particularly in laboratory or experimental situations where decisions can generally be based on the results of physical measurements or chemical analyses. Where practical applications of technology are involved, however, technical evaluations are less straightforward in that technological issues cannot be separated from their social and economic implications.

In the case of conventional energy resources and technologies, decision making has traditionally been based on what most economists and businesspeople would consider straightforward ("hardheaded") economic analysis. However, these analytical techniques were developed in an era when concern for environmental impact, resource depletion, foreign exchange, foreign relations, and that most intangible of all, quality of life, did not play as important a role as they do today. The rising concern for these issues has made these analyses less straightforward, and often controversial, as disagreements arise as to the extent to which a given evaluation has taken them into account.

In spite of the fact that many renewable-energy technologies predate conventional energy systems, by centuries in some cases (*e.g.*, windmills, water wheels, wood stoves), evaluation of these systems by traditional analytical techniques seems to be more difficult than for conventional systems for several reasons. In addition to the social, political, environmental, and economic issues already mentioned, renewable-energy systems raise issues of the scale of operation and local control, and the weight attached to the renewable nature of the energy resource. The analytical problem is further complicated, when these systems are used in developing countries, particularly in rural areas where the scale and modular nature of systems such as biomethanation make them seem most appropriate, by consideration of country-specific goals of economic and social development.

Finally, learning from past experience where biomethanation systems are concerned has been made additionally difficult by the lack of uniformity in reporting even the basic technical data such as physical measurements and chemical analyses. This difficulty has been stated clearly:

> "Although biomethanation systems have been in use for many years in many parts of the world, the lack of a systematic way of reporting the results of experimentation with, and use of, such systems has made comparisons among them, and their relative evaluation, extremely difficult. This problem arises from the lack of agreement on parameters and variables to be measured, the conditions of measurement, and even the units of measurement."
>
> "Compounding this confusion is the fact that there exists no basis for cost comparisons because different direct costs are usually reported, and many important indirect costs, such as taxes and subsidies, are frequently not taken into account. The situation has reached a point where there are even disagreements over whether or not a given system 'works'." (Equity Policy Center, 1983)

Nevertheless, serious attempts at evaluating biomethanation systems, while taking into account the tangible complications and devising approaches to account for some of the less tangible issues, have been made for several years. The chief difference between these techniques and the "traditional" economic analyses is that the newer approaches to renewable-energy systems can better be described as social and economic benefit-cost analysis.

One of the earlier such attempts at a comprehensive social and economic benefit-cost analysis was made by Parikh in a study of biogas plants in India (Parikh, 1963). Most subsequent studies and major reviews of biomethanation systems (and other renewable-energy technologies) used in developing countries similarly have been based on social and economic benefit-cost analyses, with some reviews emphasizing methodologies for this approach. These include the analysis by Bhatia in 1977 (Bhatia, 1977) (based on essentially the same source of technical information as used by Parikh). Other studies and reviews include the analysis of a community biogas plant by Bhatia and Niamir (1979), the assessments by Barnett (1978), Sanghi (1979), and Stuckey (1983), and the reviews by deLucia and Bhatia (1980), ESCAP (1981), and Meta Systems Inc. (1980).

In summary, benefitting from the experience of others continues to be hampered by two major obstacles:

1. Until the community of technologists concerned with biomethanation systems agrees on what data will be reported, and how, there will continue to be serious disagreements between different evaluations of the same system--not only in the technical evaluations, which would be expected, but also in the social and economic evaluations that depend on them. [An interesting illustration of the latter is the comparison of the conflicting technical data used by Parikh (1963) and Bhatia (1977), based on the same source, which led to different conclusions in the economic analysis. See Stuckey (1983) for a discussion of this comparison].

2. The second major obstacle is that "the most difficult aspect of social cost analysis in the renewable energy field is the quantification and valuation of direct and indirect benefits and costs."(Meta Systems Inc., 1980)

This second point is particularly important because it is less easily taken into account. Resources (e.g., capital, cement, dung, water, labor) allocated to biomethanation systems have alternative uses. Thus, to justify this particular use, three things must be demonstrated by the social and economic benefit-cost analysis. First, it must be shown that the aggregate benefits to society are greater than the aggregate costs. Second, the benefits per unit capital cost must be greater than for an alternative use. Third, evaluating the aggregate benefits and costs to society must take into account the "total welfare of the society" in such a way that it is not diminished by this use of resources (Meta Systems Inc., 1980).

V PLANNING BIOMETHANATION SYSTEMS

Biomethanation systems are of little interest unless they are accepted and used. Too often the importance of the frequently intangible and generally unquantifiable social and ecological impacts has been overlooked in planning systems. The result is dissatisfaction on the part of the user and eventual abandonment of the system. Thus, conventional benefit-cost analyses must be broadened to the type of social and economic benefit-cost analysis discussed in the previous section.

Methodologies for performing such analyses are available from many of the sources already cited. The approach used by deLucia and Bhatia (1980) and by Meta Systems Inc.(1980) is particularly comprehensive and the reader involved in planning a biomethanation program is urged to refer to those or similar works. The approach suggested is summarized as consisting of the following steps:

"(i) calculating the financial viability of the project when benefits and costs are valued at market prices and market interest rate is used for the opportunity cost of capital;

(ii) making corrections in financial costs and benefits by eliminating taxes and subsidies which are treated as transfer payments and do not reflect real resource costs;

(iii) recognizing the distortions in market prices on account of price and quantity controls, minimum wage regulations, imperfect capital markets, and regulations of trade and foreign exchange by the government; and, hence, replacing the market prices by "accounting prices" or "shadow prices" which reflect the real values of inputs and outputs of each project;

(iv) incorporating considerations of income distribution, regional development and employment through explicit weights on these objectives; and

(v) calculating the social profitability of the project by using appropriate values of social rate of discount and shadow price of investment to estimate Net Present Value, Benefit Cost Ratio, and the Internal Rate of Return." (Meta Systems Inc., 1980)

When such an approach is applied to specific circumstances for planning purposes, a host of specific items must be taken into account. The check-list approach used by the Bangkok workshop is helpful in this regard, and is shown in Table 18. It should be noted, however, that each table of issues in a particular area is a companion to a table of technical parameters and variables in the same area, which must be reported in some recognized standard manner as the basis for rational and useful social and economic cost comparisons (Equity Policy Center, 1983). (The Bangkok workshop report recommends such a standardized manner of reporting technical details of biomethanation systems).

One of the major controversies associated with the introduction of biomethanation systems concerns alternative agricultural uses for the raw-material feedstocks (manure and other agricultural wastes). Evaluation of these alternative uses is meaningful only in comparison with use of the residues of biomethanation, and a comprehensive list of these uses is given in Tables 19 and 20, which are adapted from the report of the Bangkok workshop.

Table 18. Use of energy from biomethanation: socio-economic issues check list (Equity Policy Center, 1983)

Quantifiable aspects	Non- (or not easily) quantifiable aspects
Fuels or systems displaced (relative calorific value vs. cost) + Firewood + Charcoal + Crop residues + Dung + Other biomass systems - Gasification - Ethanol - Methanol + Fossil fuels - Kerosene - Gasoline - Diesel oil - LPG + Electricity - Grid - Local generator + Water power (mechanical) + Solar energy - Cooking - Drying - Photovoltaics + Wind Labor costs + Construction + Operation and maintenance Capital costs + Digester + Gas storage and distribution Cost of end-use appliances/equipment	Impact on: + Food preservation (from cooking smoke and heat) + Insect repelling (from cooking smoke and heat) + Space heating (side effects from cooking) + Deforestation - Erosion - Water control - Water tables + Alternative use of limited labor pool + Employment generation - Construction - Collection of feedstock - Operation and maintenance - New jobs created by increased availability of energy + Employment displaced - Jobs associated with previous uses of substrate - Jobs displaced by new energy source + Human resources/skills - Availability of manpower for technical assistance, maintenance - Skills training needed - Education + Communication (public education required to encourage acceptance)

Table 19. Agricultural uses of biomethanation residues used as fertilizer/soil conditioner - socio-economic issues check list (Adapted from Equity Policy Center, 1983)

Quantifiable aspects	Non- (or not easily) quantifiable aspect
Fertilizer/soil conditioner (relative value vs. cost) + Dung + Crop residues + Forest residues + Chemical fertilizer + Night Soil Effects on crop yields Labor costs + Transportation + Storage + Application Income generation from sale of residues Energy costs + Transportation + Processing + Application + Manufacture (of displaced fertilizer) Relative concentration of toxic substances	Impact on: + Self sufficiency + Human resources/skills - Availability of manpower for technical assistance, maintenance - Skills training needed - Education + Communication (education needed for acceptance and use) + Pollution - Air - Water - Soil + Habitat for pests + Soil fertility and land value + Land carrying capacity + Employment generation - Handling, processing, storing residues + Employment displaced - Jobs associated with previous uses of feedstock + Safety (sanitation)

In discussions of the use of biomethanation residues as fertilizer, the issue of nitrogen availability (see section on Raw Material) seems to be of particular concern, especially to economists. There are two major reasons why it remains an issue. First, the chemical analytical data available are inadequate - inaccurate analyses, estimates only or no information, and no uniformity in handling and use of residues. The second reason is that in addition to the recycling of nutrients, a major value of application of biomethanation residues to the land comes from the humic materials they contain; that is, the value of the residue as a soil conditioner - its contribution to the tilth of the soil - must be considered.

In Table 20 are listed the issues to be considered that are related to the use of biomethanation residues as feed supplements.

Finally, those aspects of the impact on health and sanitation that should be considered are listed in Table 21.

Table 20. Agricultural uses of biomethanation residues as feed supplement - socio-economic issues check list (Adapted from Equity Policy Center, 1983)

Quantifiable aspects	Non- (or not easily) quantifiable aspects
<u>Feed/fodder supplemented or displaced</u>: + Crop residues + Commercial feeds + Fodder/forage <u>Effect on yield/productivity</u> <u>Labor costs</u> + Transportation + Packaging/handling + Storage + Use <u>Equipment costs</u> + Transportation + Storage <u>Income generation from sale</u> <u>Energy costs</u> + Processing + Transportation + Manufacture (displaced feed, if any) <u>Toxic substances</u>	<u>Impact on</u>: + Self sufficiency + Human resources/skills - Availability of manpower for technical assistance, maintenance - Skills training needed - Education + Communication (education needed for acceptance and use) + Pollution - Air - Water + Employment generation - handling, processing, storage + Safety (sanitation) + Land carrying capacity

Table 21. Public health/sanitation - socio-economic issues check List (Equity Policy Center, 1983)

Quantifiable aspects	Non- (or not easily) quantifiable aspects
Capital costs (equipment)*	Human resources
	+ Availability of manpower for technical assistance, maintenance + Skills training needs
Use of outputs + Cost of use + Income generated	Communication (education needed for acceptance and use)
	Social organization needed for successful use of systems + Latrines + Night soil/dung collection

* Allocation of these costs must be shared among other uses for biomethanation systems, because these systems would not be constructed solely for public health/sanitation purposes.

VI RESEARCH ISSUES AND PRIORITIES

Considerable progress has been made in the development of biomethanation technology. Nevertheless, it is apparent from the foregoing discussion that there are many problems yet to be solved -- technological and social and economic -- before there is likely to be more widespread local dissemination of these systems in developing countries. The more serious of these problems will be discussed in this section, with some attempt to list them in order of descending priority.

1. Without a doubt, the cost of digesters is one of the most important issues facing governments, communities, and individuals. The research effort to bring down the cost of family-size and community-size digesters should continue. The possibilities of using locally available and cheaper construction materials for both digesters and gas holders, without risking either their durability or their performance, should be a matter for continual serious investigation.

2. Community-scale digesters appear to present a favorable opportunity for biogas production in areas where individual families cannot afford biogas systems. Research and demonstration in this area is a definite priority and the objective should be to produce digesters that are not only cheaper but are more efficient than those previously tested. This effort should be coupled, however, with an effort to delineate procedures for making these digesters acceptable to the community for their sustained, reliable performance.

3. A large gap in knowledge exists on the role that women can play to make biomethanation schemes successful. If women in the communities of developing countries are really convinced of the benefits of biomethanation systems, chances are that these systems will be more readily accepted. The role of women in the successful dissemination of biogas technology in developing countries should be investigated and documented.

4. Gas yields are enhanced by heating and mixing digester contents. The few successful attempts to use the waste heat generated from an engine run on biogas for heating the digester and its contents should be followed by further research and development. More economical heat exchangers could be developed and the use of waste heat from biogas-fueled engines to heat digesters should be clearly demonstrated. It would be useful if controlled studies were performed on community-size digesters to determine whether there will be a net benefit if a portion of the biogas generated is used to effect good mixing and heating. This information can be used in the proper design of community- and industrial-scale units. Also, the possibility of heating digesters by solar radiation should be more fully explored.

5. In the developing countries where biogas systems are currently used, wastes of human and animal origin are the primary inputs to the digesters, although other types of biomass are also used to some extent. There is an immense potential, however, for the use of other types of biomass that are available. Such feedstocks should be identified and their potential explored by experimental studies. Some of these feedstocks may not be suitable, as collected, as substrates for biomethanation because of their slow rate of biodegradability. Hence, cheap and effective methods of pretreatment should be developed to render them more readily biodegradable in biomethanation systems.

6. One of the major problems in the biomethanation of biological wastes is the lack of uniformity in reporting basic technical data concerning design criteria and results. Hence, it is very difficult for researchers and planners alike to compare and evaluate various systems used not only in other parts of the world but even in other regions of their own countries. An attempt has been made to solve this problem and recommendations have been made in the workshop held in Bangkok. The suggested procedures should be tested in a few developing countries, improved and modified as necessary, and the resulting approach used to compare the performances of various types of biomethanation systems. The results of such a study would provide a reliable basis, for planners and technologists to use in judging the performance characteristics -- cost, yield, efficiency -- of various possible digesters.

7. Biomethanation systems by themselves may not appeal to many communities living in developing countries. On the other hand, integrated resource-recovery systems, in which biomethanation is a central unit process, may appeal to the communities or small industries, because tangible benefits such as production of fish, electric energy (e.g., chopping hay, milling grain, pumping for irrigation or drinking water), and biofertilizer should be very appealing. Areas where such integrated biomethanation systems would be applicable should be identified. Appropriate designs for achieving the needed benefits should be developed and demonstrated clearly, for demonstration is the key to acceptability.

8. Some of the recently developed digester designs, such as the up-flow sludge-blanket reactor, plug-flow digester, and some types of attached-growth systems, could well be applied in some specific situations in developing countries, particularly in the industrial sector. Research in this field and demonstration of such digester designs at appropriate locations in developing countries is likely to pay dividends not only to industry, in helping to offset energy costs, but also to the community by helping to solve pollution problems in the urban environment.

9. Although many studies have been published that show the value of digested slurry as fertilizer, systematic studies are lacking that quantify and compare the fertilizer value of digested slurries obtained from various feedstocks. Also, additional field data that document yields of various crops grown with the application of digested slurry from biomethanation systems would be valuable. The collection of such information would be useful in identifying the effects of different types of digested slurries on crop yields.

10. Research should be continued to develop cheap and efficient biogas appliances such as stoves, burners, lamps, and engines.

11. The dissemination of pathogens and helminthic ova is a serious problem in developing countries. A properly designed and operated biomethanation system, as an anaerobic process, is a major barrier to such dissemination and thus promotes public health. However, quantifiable data are not available on the public health impact of these systems. Systematic controlled studies should be conducted to determine the impact of biomethanation systems on public health.

12. While biomethanation systems have yielded tangible benefits in some areas, they have not in others, although similar types of designs have been constructed. Often, it is not the technology that is at fault, but more likely the socio-economic factors that are responsible for such dismal results. A careful cataloguing and evaluation of such factors is required.

13. Even though the members of a community may appreciate the benefits that can be derived from biogas systems, there is seldom sufficient motivation to operate the biogas systems in a prescribed way. This lack of motivation is generally rooted in traditional social and cultural customs and practices to which such systems are foreign. This problem should be studied seriously with the information developed shared among technicians and planners of biomethanation schemes.

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PREFACE

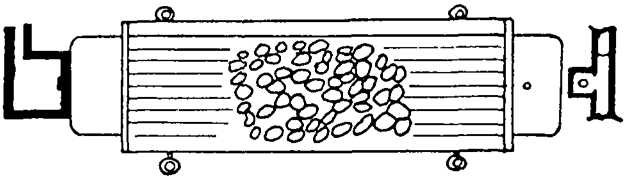
The widespread interest in biogas over the years, has brought about the development and design, by various institutions and agencies, of different types of biogas digesters to suit local conditions. Some of the representative plant and experimental models are presented in this appendix as a supplement to the main text, written by Mr. N.L. Brown and Mr. P.B.S. Tata. These models have been designed for particulate slurry which includes slurry prepared from input materials like human wastes, livestock wastes, agricultural crop residues, aquatic plants, etc. Digester models for soluble wastewaters are deliberately excluded because some of these are already described in the main text.

Details of construction methods and materials have been omitted so as to reduce the length of the entries. However, some of the special features of the model are briefly outlined. If available the addresses of the institutions or agencies which developed a particular biogas digester are given so as to enable the reader obtain access to more complete details.

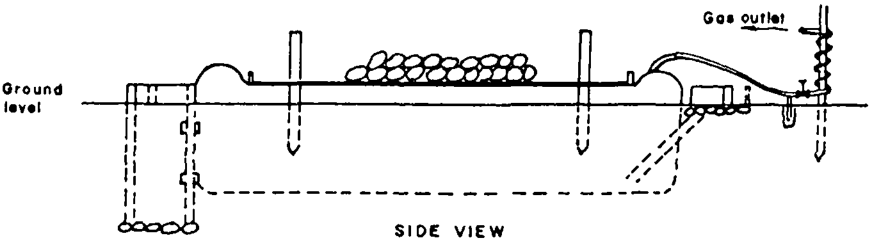
ENSIC accepts the responsibility for any errors which may have crept in, even though every effort has been made to ensure accuracy. Suggestions and comments on the presentation of additional information of this sort would be welcome.

The Editors

PLANT MODELS FOR PARTICULATE SLURRY



TOP VIEW



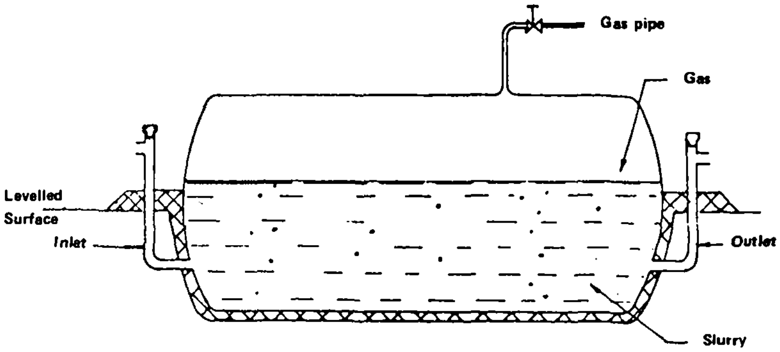
SIDE VIEW

The RMP Model (1)

A variation of the flexible bag type design, developed by the Union Industrial Research Laboratories in Taiwan.

For details, contact:

Dr. Tsu-Fu Wang
Head of Development Department
Union Industrial Research Laboratories
Industrial Technology Research Institute
1021 Kuang Fu Road
Ksiuchu, Taiwan
Republic of China

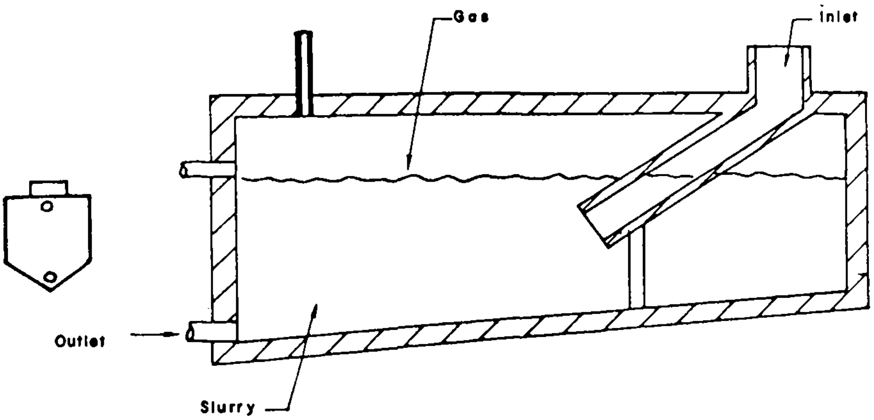


The Neoprene Bag Model (1)

Essentially made of a cylindrical neoprene rubber bag, developed by Dr. Chung Po of Taiwan.

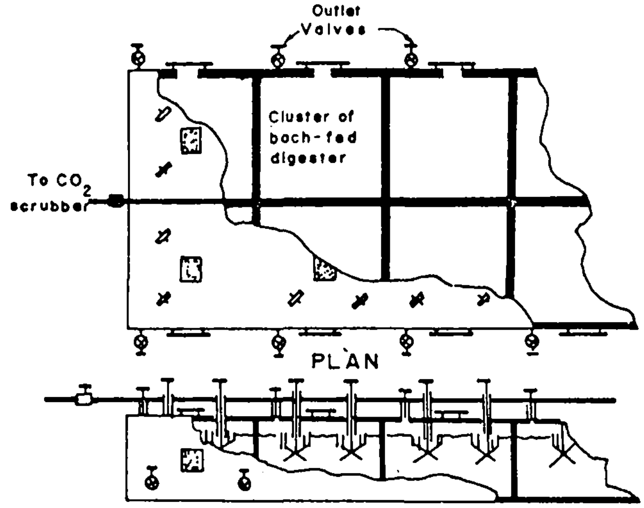
For details, contact:

Dr. Chung Po
37, Nan Hai Road
Taiwan, Republic of China



The Xochically-Mexico Model (1)

A continuous-fed model developed by Proyecto Xochically AC in Mexico.

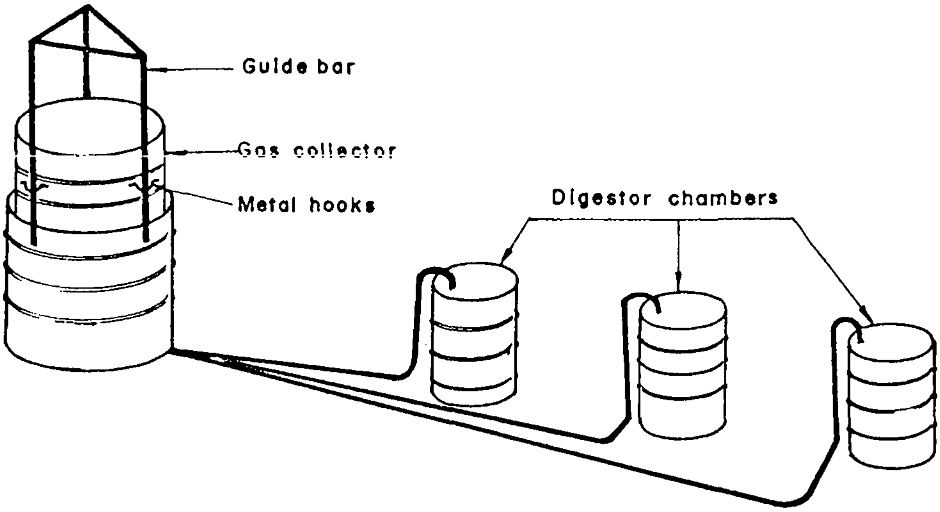


The Maya Farms Model (1)

Basically a separate gasholder design modified to suit large scale operation - designed by Dr. F.D. Maramba, Sr. in the Philippines.

For details, contact:

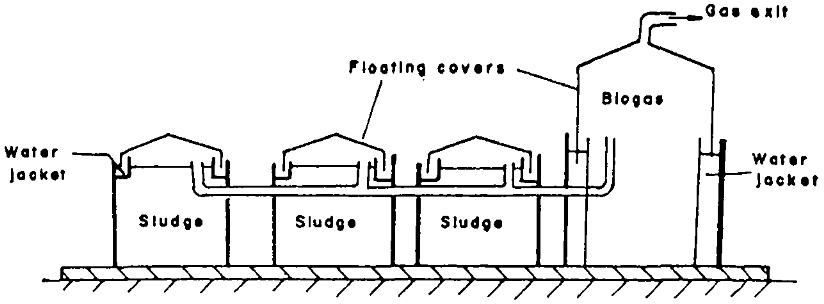
Dr. Felix D. Maramba
Maya Farms Division
Liberty Flour Mills, Inc.,
Liberty Building
Pasay Road, Makati
Metro Manila, Philippines



The Botswana Model

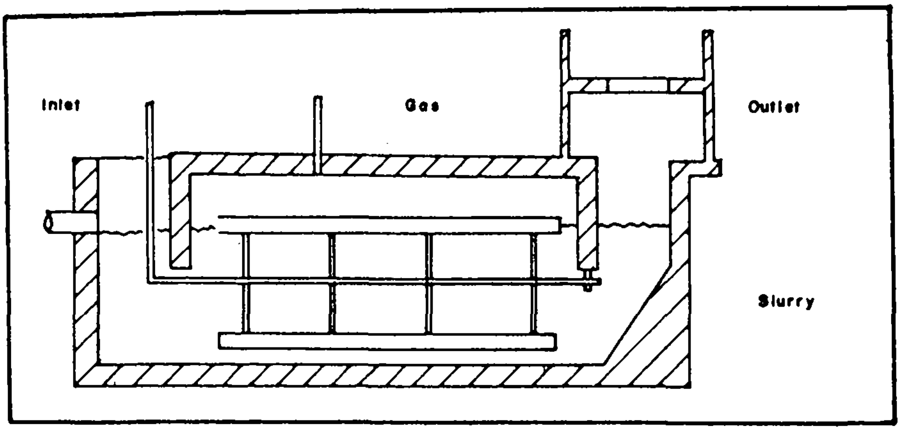
Designed by the Rural Industries Innovation Center in Botswana - the biogas produced from several scaled steel drums functioning of the digestion compartment is connected with a pipe to a gas collector storage tank.

For details, contact: Rural Industries Innovation Center
Botswana



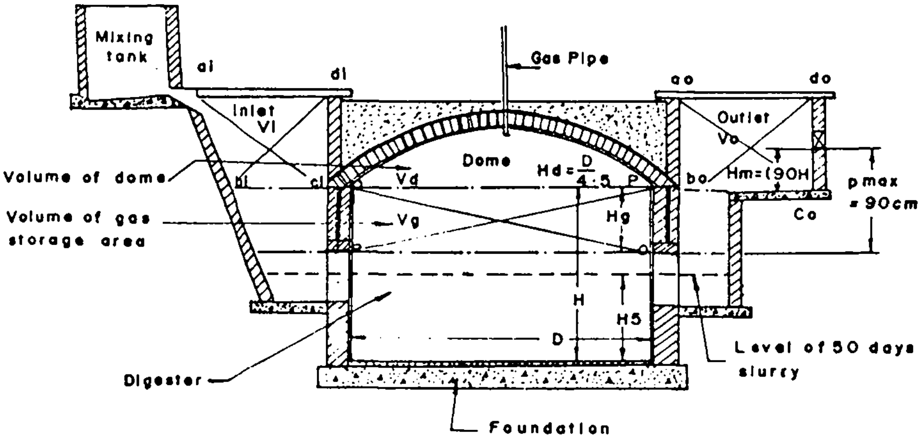
The Guatemala-Olade Model (1)

A batch-fed plant based on the separate gasholder design.



The CETA Model (1)

A continuous-fed model developed by the Experimentation Center on appropriate technology of the Engineering Colleges University of San Canlose, Guatemala.

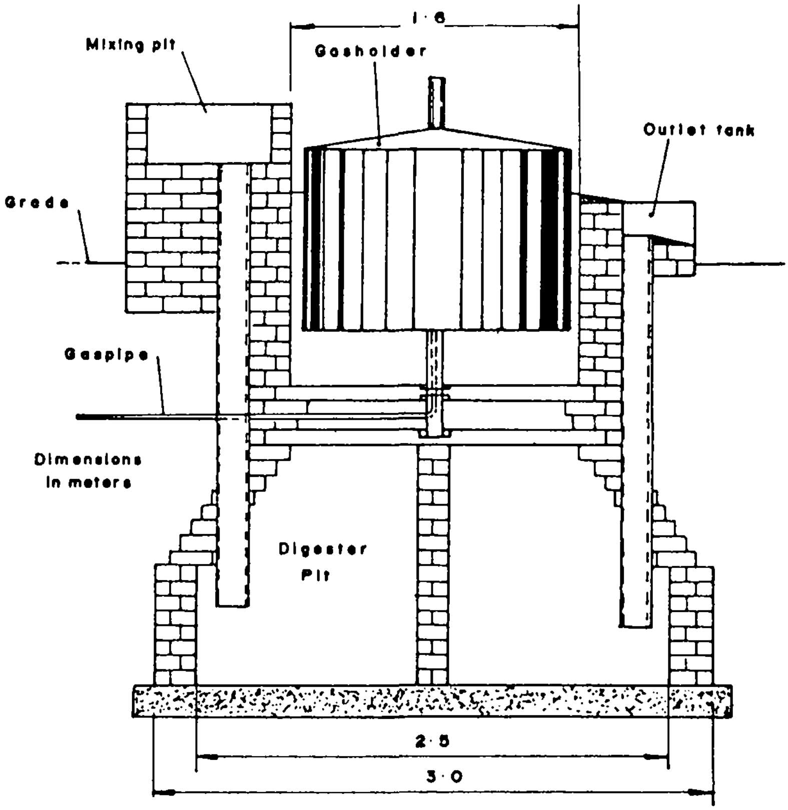


The Janata Biogas Plant Model (1)

A modification of the Chinese fixed-dome model, designed by the Uttar Pradesh State Planning Research Institute, Gobar Gas Research Station, Ajitmal, India, in 1997.

For details, contact:

Uttar Pradesh State Planning Institute
Planning Research and Action Division
Kalakankar Bhavan
Lucknow, India

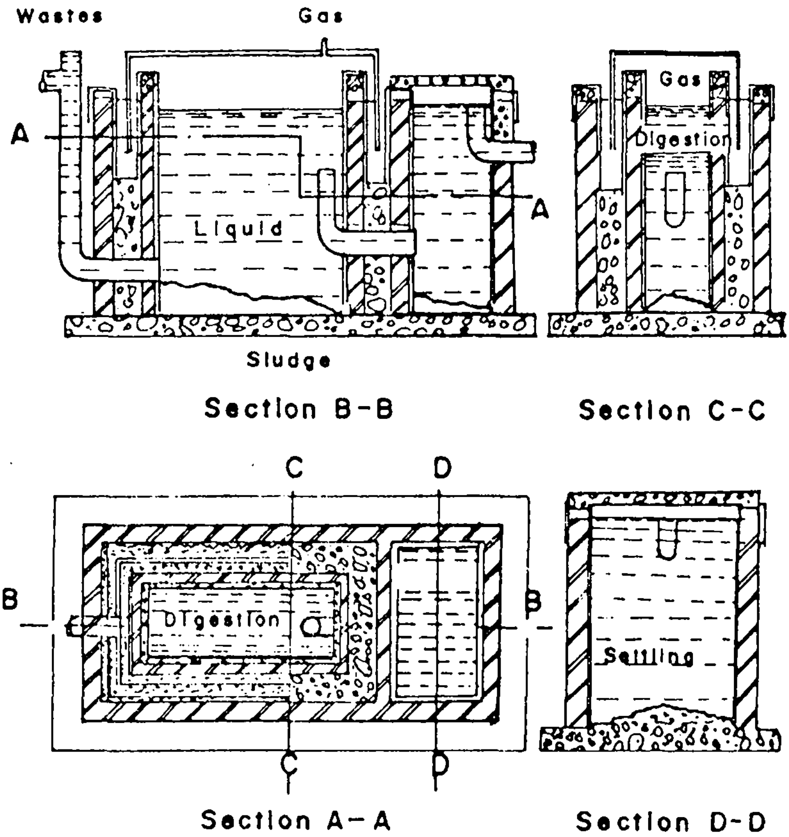


The DCS, Nepal Model (1)

A modification of the flexible gasholder design in which the biogas produced is piped through an underground fixed-pipe rather than through the flexible hose at the roof of the gasholder.

For details, contact:

Mr. D.J. Fulford
Development and Consulting Services
Butwal, Nepal

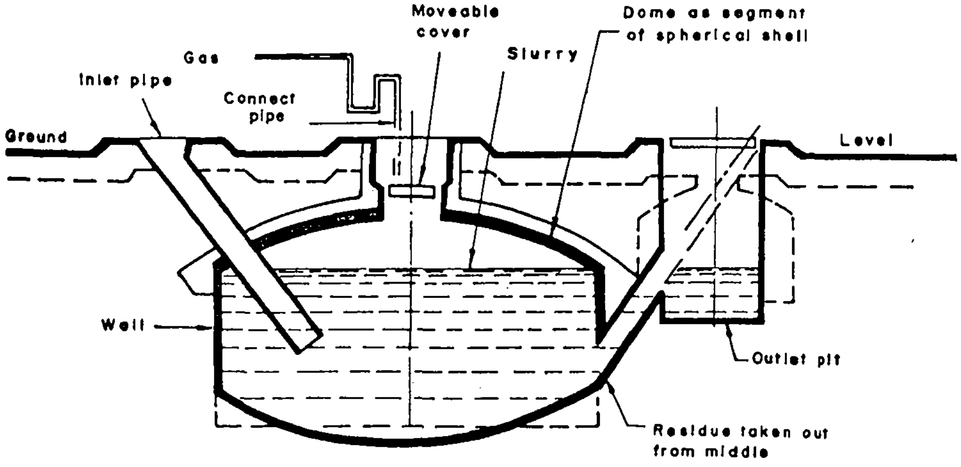


The Taiwanese Model (1)

A variation of the flexible gasholder design consisting of a double-walled digestion chamber and a settling chamber - developed based on the principle of integrated biogas system.

For details, contact:

Mr. George L. Chen
P.O. Box 151, CHRB
Saipan, Mariana Islands
CM 96950, U.S.A.

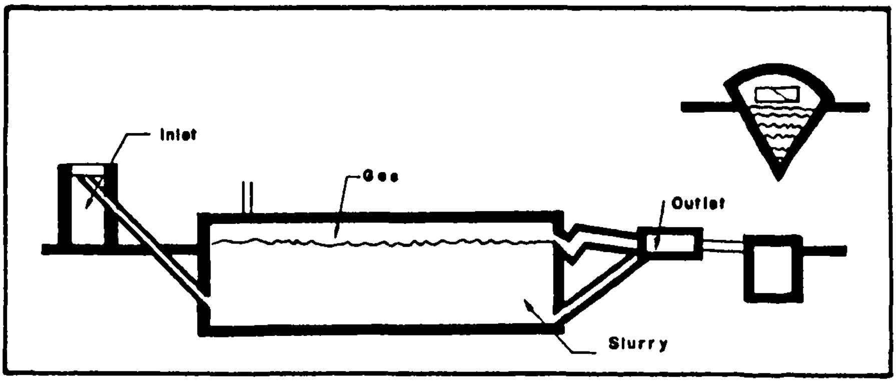


The Chinese Biogas Plant Model (1)

The first fixed-dome model to be developed with digester and gas holder combined in one unit and built underground.

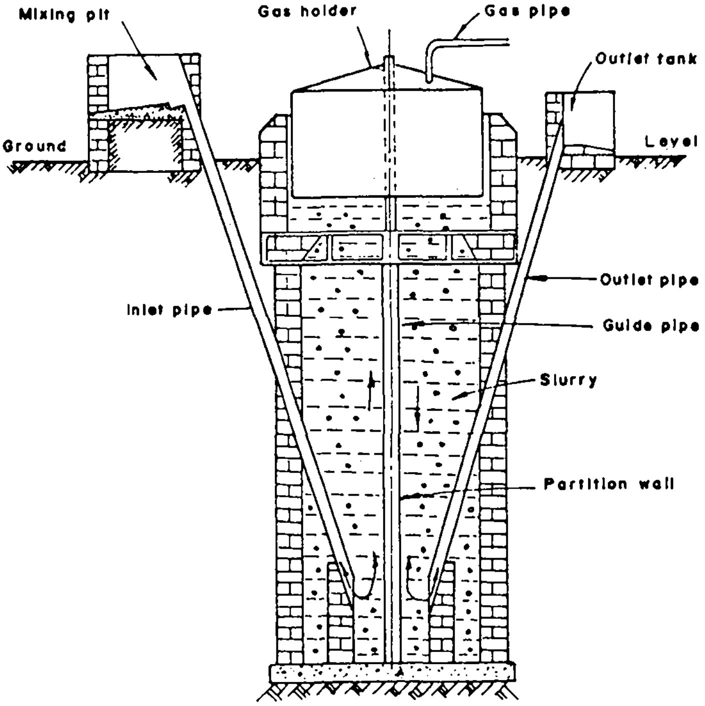
For details, contact:

Sechuan Provincial Office of Biogas Development
Chengdu, Sechuan
People's Republic of China



The IIE Model (1)

Developed by the Institute de Investigaccones Electricas, Mexico, the model is being installed for demonstration in Latin America and the Carribbean.



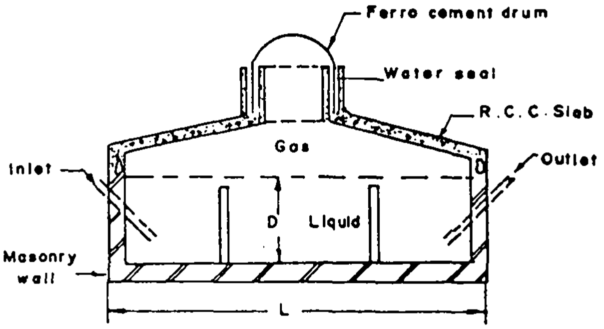
The KVIC or Indian Biogas Plant Model (1)

The pioneer of the floating drum gasholder designed by the Khadi and Village Industries Commission, India, and based on a model originally designed by J.J. Patel, 1951.

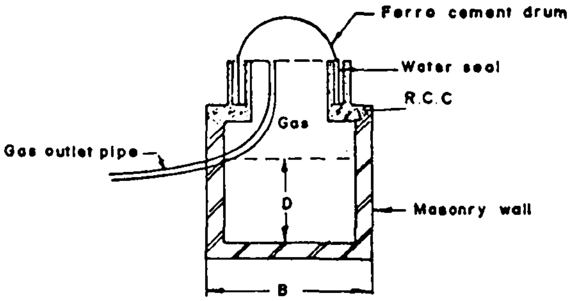
For details, contact:

The Director
Gobar Gas Scheme
Khadi and Village Commission
3, Irla Road, Vile Parle (West)
Bombay 400 056, India

SOME EXPERIMENTAL PLANT MODELS



LONGITUDINAL SECTION



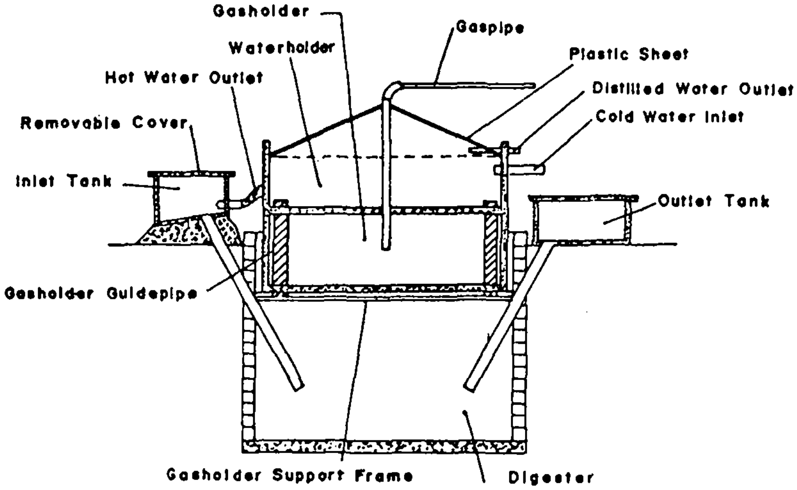
CROSS SECTION

The Manipal Model (1)

A blend of the Indian and Chinese models, the digester is in the form of a rectangular tank built of masonry, with a flat but sloping RCC roof.

For details, contact:

G.R. Raghunath Rai
Professor of Civil Engineering
Manipal Institute of Technology
Manipal - 576119, India

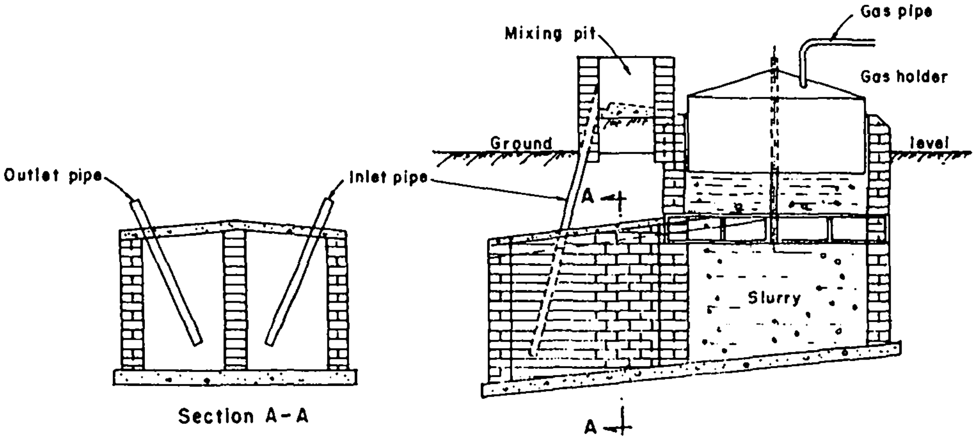


The Astra Model (1)

Basically, a variation of the floating gasholder design incorporating a solar water heater and a solar still.

For details, contact:

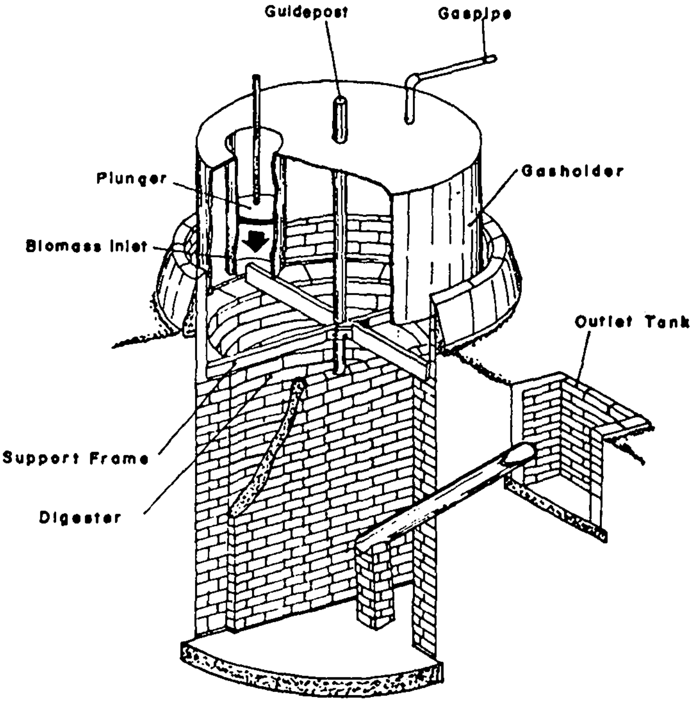
Dr. A.K.N. Reddy
Covener, ASTRA
Indian Institute of Science
Bangalore 560 012, India



Section A-A

Horizontal Flow Digester with Floating Gas Holder (India) (2)

A modification of the floating gas holder design to suit high water-table areas.

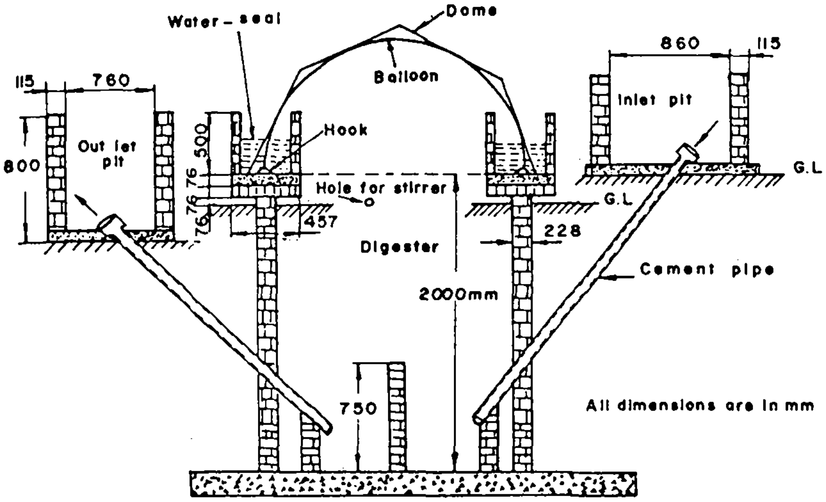


The Jyoti Top Loaded Digester (1)

A modified KVIC model designed by the Jyoti Solar Energy Institute, India and suited specifically for the digestion of agricultural and forestry residues.

For details, contact:

Mr. J.H. Patel
Jyoti Solar Energy Institute
Birla Vishva Karma Mahavidyalaya
Vallabh Vidyanagar, India

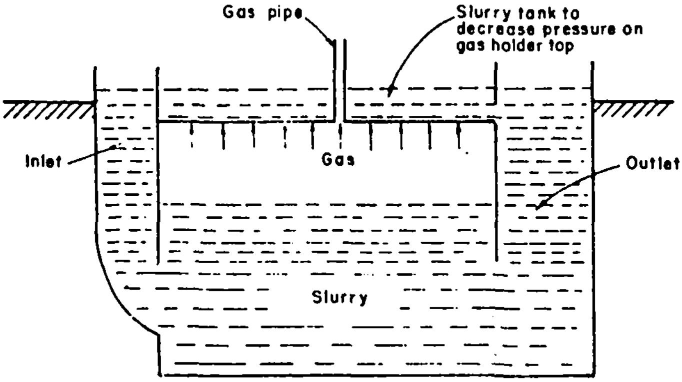


The Jwala Biogas Plant (1)

A variation of the floating gasholder design wherein the digester is of the KVIC type and the gasholder constitutes a low density polyethylene (LDPE) sheet together with a geodesic balloon.

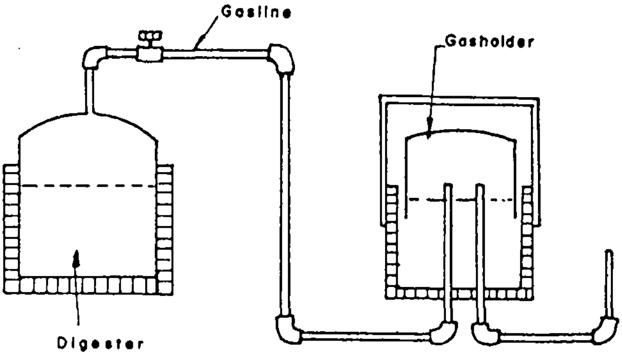
For details, contact:

The Director
AMM Murugappa Chettiar Research Center
Photosynthesis and Energy Division
Tharamani, Madras 600 042
India



Square Fixed-Dome Digester (China) (2)

A square fixed-dome digester which allows the flow of displaced slurry onto the top of the gas holder when gas collection starts.

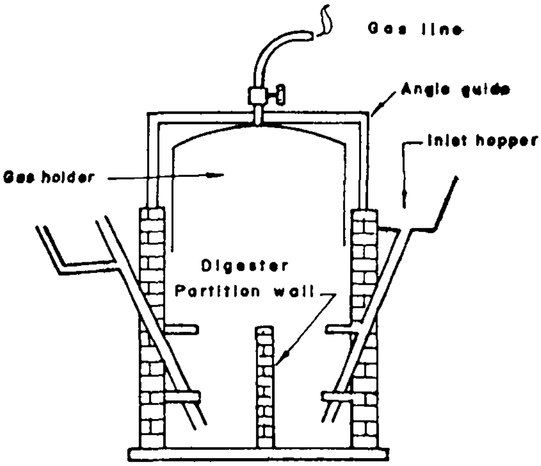


The Belur Math Model (1)

Based on the separate gasholder design consisting of a digester, a simple pit dug into the earth, and a gasholder, made of two cylindrical tanks, one inverted over the other.

For details, contact:

Ramakrishna Mission Saradapitha
Belur Math, Howrah
West Bengal, India

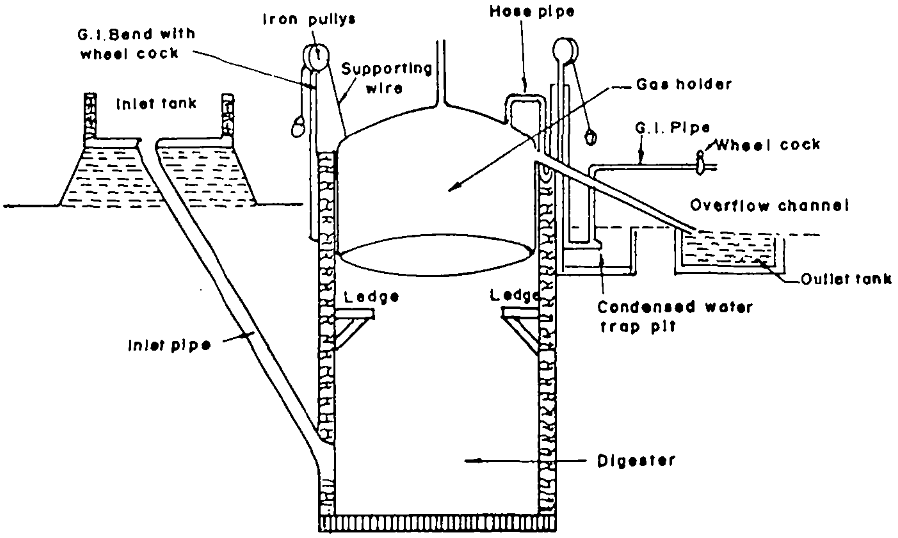


The NEERI Night-Soil Biogas Plant (1)

A variation of the floating drum gasholder design and developed by the National Environmental Engineering Research Institute in India.

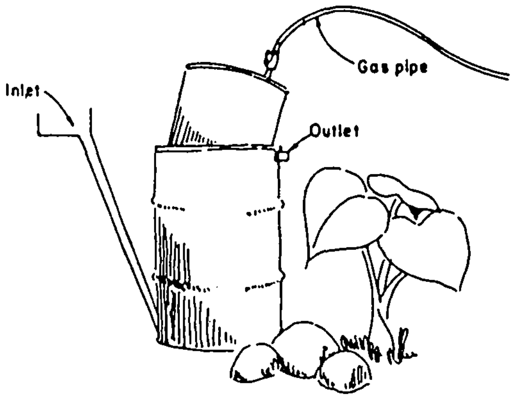
For details, contact:

The Director
National Environmental Engineering Research Institute
Nehru Marg
Nagpur - 440 202, India



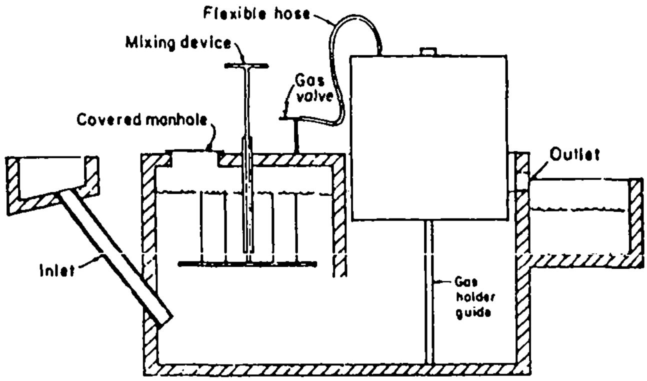
The IARI Biogas Plant (1)

The first biogas plant model to be designed in India which consists of a floating drum gasholder introduced upside down into the digester.

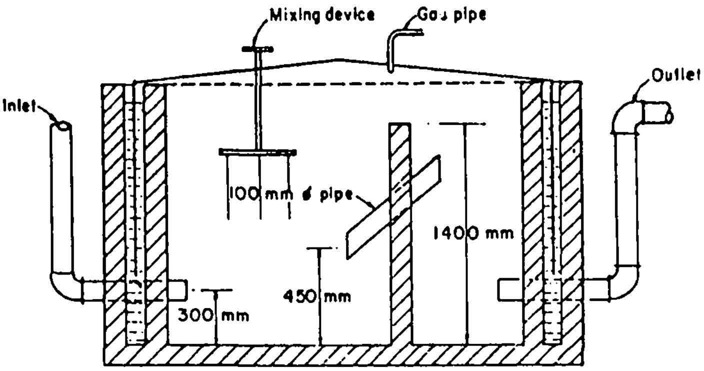


Oil Drum Digester (Indonesia) (2)

Made from oil drums which tend to rust out within a few years.



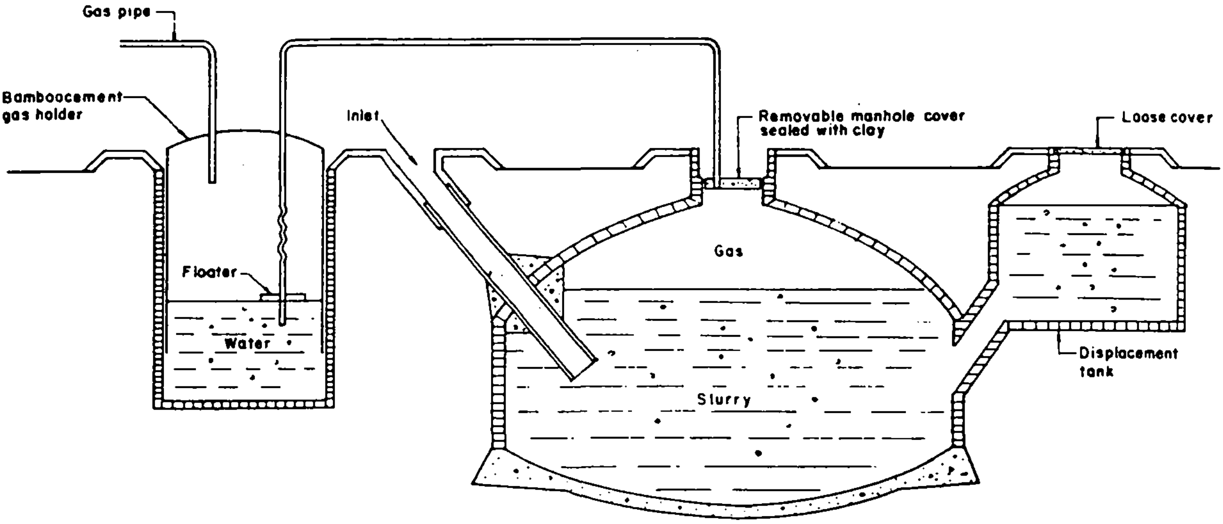
A - without a waterseal



B - with a waterseal

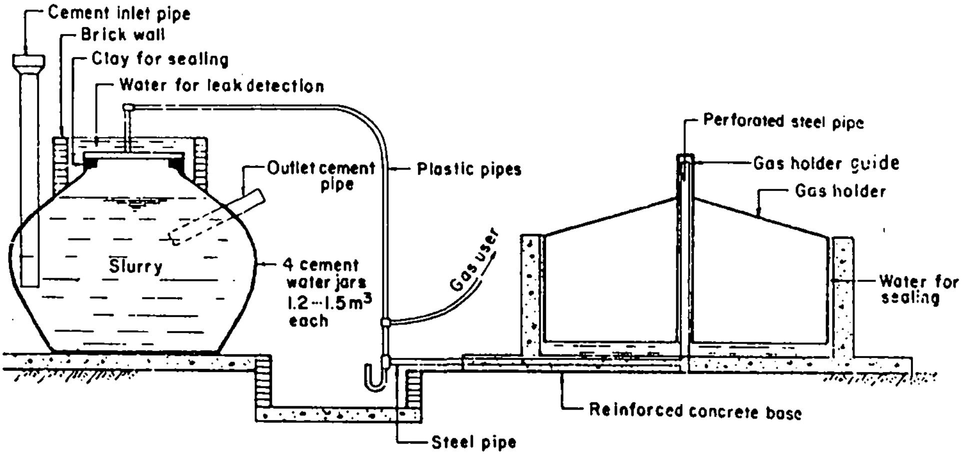
Two-Chamber Rectangular Digester with Floating Gas Holder (Philippines) (2)

A rectangular digester with a cube-shaped gas holder bogged down by serious clogging problems.



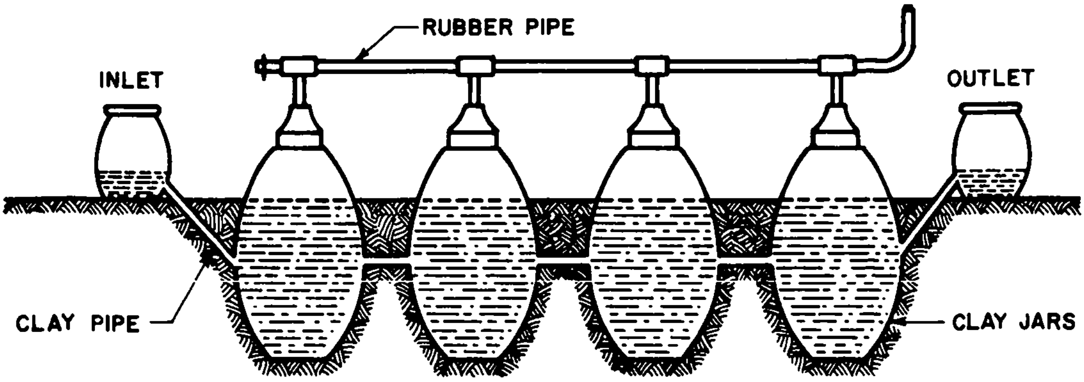
Fixed Dome Digester with Separate Gas Holder (Sechuan, China) (2)

The digester dome subjected to little pressure is easy and cheap to construct. The gas presure is constant and hence appliances and engines may be designed and used at their optimum working conditions.



Jar Digester with Separate Gas Holder (Thailand) (2)

A batch system continuously supplying gas, this digester is less expensive than the floating gas holder digester.

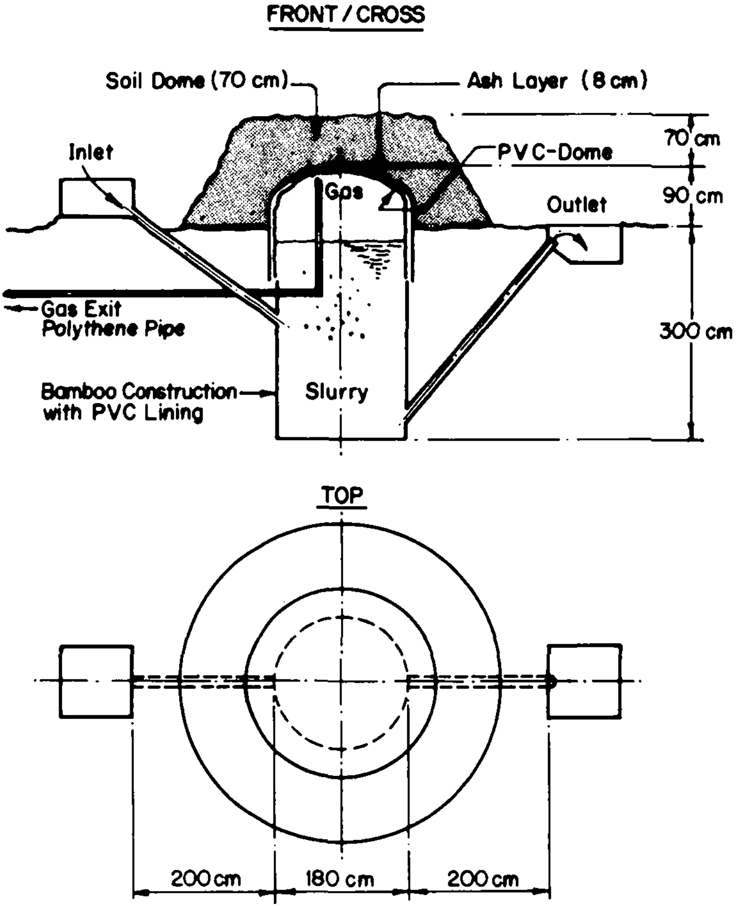


The "Surahi" Biogas Plant (6)

Mainly consists of large mud jars connected in series with three-inch thick clay pipes.

For details, contact:

Centre of Science for Villages
Wardah - 442001, Maharashtra
India

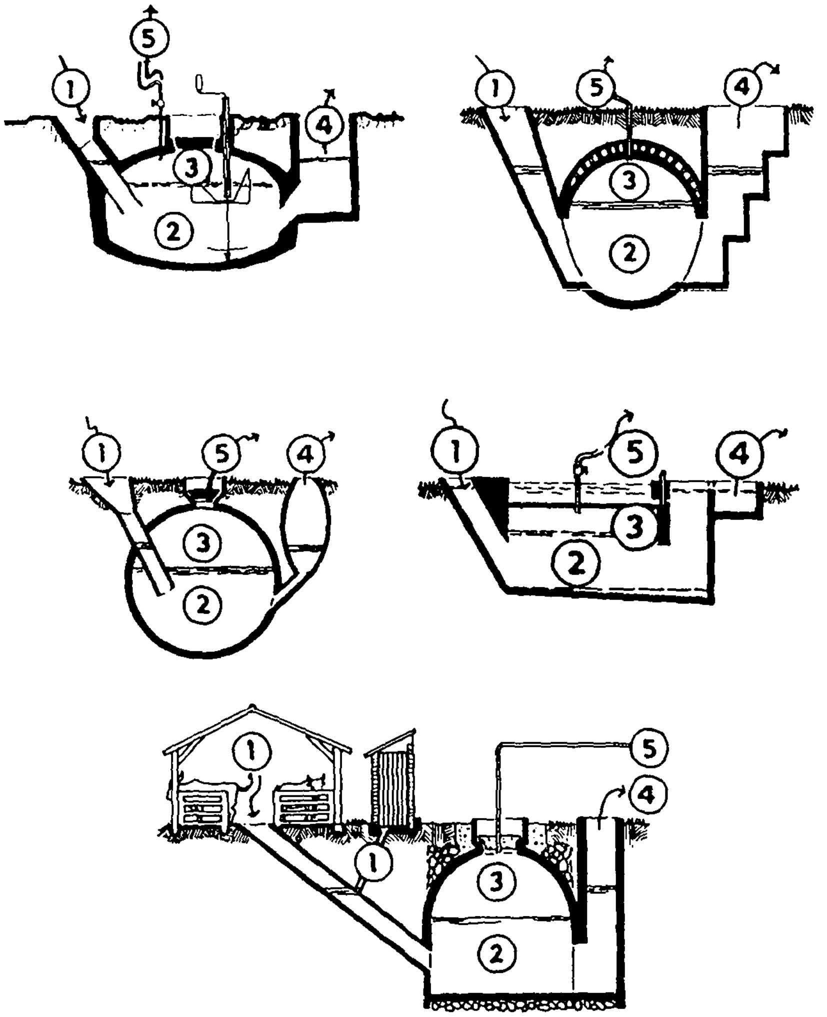


The Bamboo-Mud Biogas Plant (4)

Designed by J.R. Pokhrel in Nepal, this biogas plant is made of bamboo and mud with bamboo poles cut into strips to line a hole in the ground and plastered with mud.

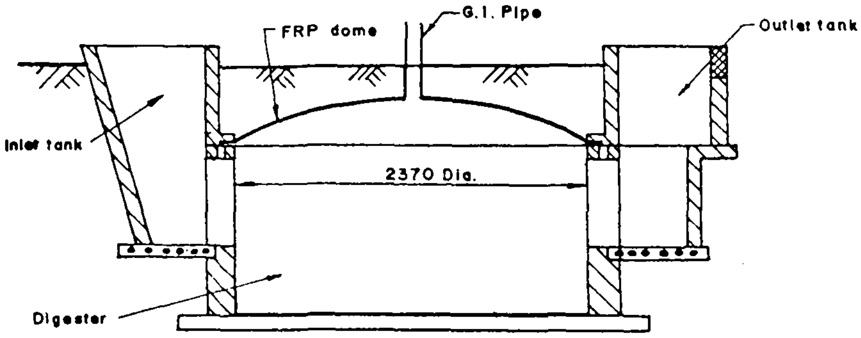
For details, contact:

Biogas Newsletter
Gobar Gas Development Committee
P.O. Box 1309
Kathmandu, Nepal



Various Dome Biogas Plants (3)

(1) Inlet; (2) Digester; (3) Gas Holder; (4) Outlet; (5) Gas Pipe

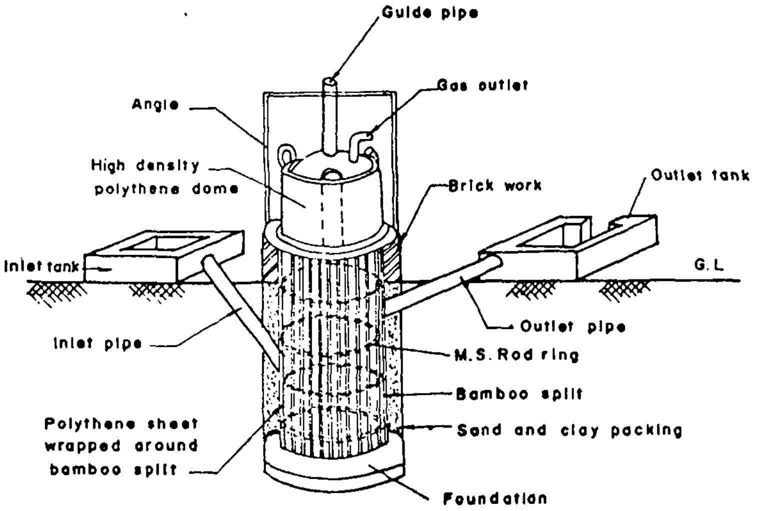


The Gayatri Model (1)

An improvement over the Janata Model which uses a pre-fabricated fiberglass reinforced plastic instead of the brick-dome this minimizing use of cement.

For details, contact:

Satyanagar
Bhubaneswar, India

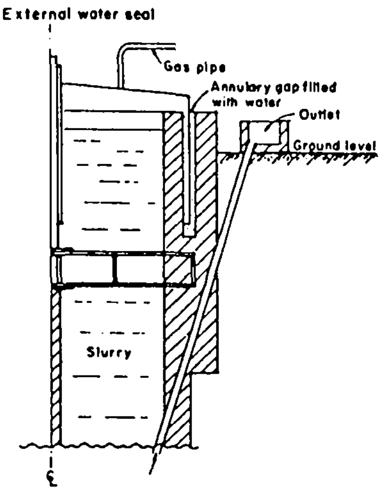


The Bajwa-KVIC Model (1)

An improvement over the KVIC model in which the digester is made of bamboo strips mild steel roads and low density polyethylene sheets.

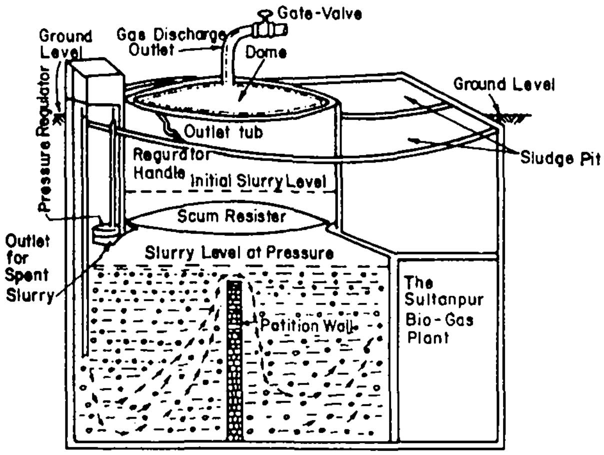
For details, contact:

C.V. Krishna
Government Implement Factory
Satyanagar, Bhubaneshwar
India



Digester with Floating Gas Holder and Water Seal (Pakistan) (2)

Although more expensive, ensures all gas is collected in a gas holder.



The Sultanpur Biogas Plant (5)

A continuous-fed fixed dome plant with a scum resister firmly held at the upper end of the digester right under the dome.

For details, contact:

Mr. M.S. Quidwai
Vikas Engineering Corperation
Uttar Pradesh, India

REFERENCES

(1) Biogas Technology, An Information Package, compiled by V. Vijayalekshmy, TATA Energy Documentation and Information Center, 1985, 189 pp. (P.O. Box 698, Bombay House 24, Aomi Mody Street Bombay 400 023, India).

(2) Updated Guidebook on Biogas Development, Energy Resources Development Series No. 27, United Nations, 1984, 173 pp.

(3) Biogas Manual for the Realisation of Biogas Programs, Gerhard Eggeling Bremen Overseas Research and Development Association, Germany, 1982, 116 pp.

(4) Biogas Plant Built of Bamboo and Mud, Biogas Newsletter, Nepal, No. 14, 1981.

(5) Novel Scum Breaker, Invention Intelligence, Vol 19, No. 1, 1983.

(6) News from the Centre of Science for Villages, Biogas News, February, 1982.

Division Chairman urges active support from ENVI alumni and friends

Dr. Chongrak Polprasert, newly appointed chairman of the Environmental Engineering Division (ENVI) of the Asian Institute of Technology encourages alumni and friends to lend their support to the Division as part of the current determined effort to keep the Division strong.

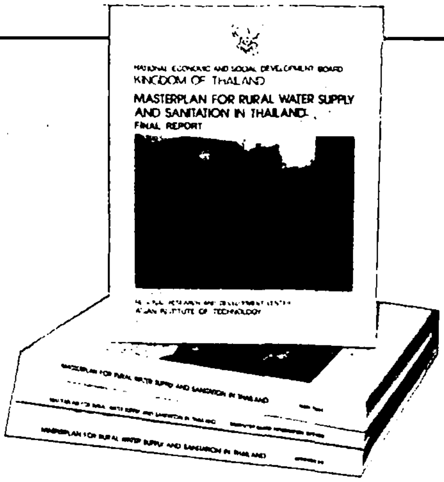
The past records of alumni achievements, sponsored research projects conducted in the Division, and publications of faculty and students in international journals clearly show ENVI's distinguished contribution to, and leadership in the region. The Division's resources, however, are expected to be quite limited, and the restraints imposed will present a more challenging task in the near future.

Graduate teaching and academic research are two tasks that the Division plans to pursue vigorously in order to attract and retain outstanding teachers in the field. It is thought that this policy will in turn attract outstanding students who might otherwise apply for graduate study in developed countries and probably add to the "brain drain" from the region. In order to implement its policy, the Division has been in the process of planning with a view to expanding its research dimensions and collaborative activities, and to recruiting qualified faculty and students. The Division is also planning to put up an Environmental Engineering Fund to support the activities necessary for educational and research purposes.

As alumni, you can help expressing your concern for, and support of, the Division. Your suggestions for improving the Division programs, and any other recommendations you can give, will be warmly appreciated.

Incidentally, we will be celebrating the 25th anniversary of the Division in 1989, and on this occasion, it has been suggested that we should hold a technical symposium and a home-coming day. Your suggestions and ideas regarding this anniversary would also be very welcome.

MASTERPLAN FOR RURAL WATER SUPPLY AND SANITATION IN THAILAND, 4 VOLUMES, 1985



NATIONAL ECONOMIC AND SOCIAL DEVELOPMENT BOARD
KINGDOM OF THAILAND
MASTERPLAN FOR RURAL WATER SUPPLY AND SANITATION IN THAILAND
FINAL REPORT
REGIONAL RESEARCH AND DEVELOPMENT CENTER
ASIAN INSTITUTE OF TECHNOLOGY

Prepared by the Environmental Engineering Division through the Regional Research and Development Center, Asian Institute of Technology, Bangkok, under the auspices of the National Economic and Social Development Board, Kingdom of Thailand.

Final Report, xxii+112 pp.

Final Report, Main Text, xv+316 pp.

Final Report, Computer-Based Information System, 21 pp. + 6 appendices.

Final Report, Appendices – 20 appendices. (US$80.-)

The four-volume report presents a comprehensive survey of the present water supply and sanitation situation of the rural areas in Thailand, analysis of the causes of the current problems and recommendations to achieve the physical targets, objectives and goals. Studies were made on the physical, demographic, socio-economic, health and sectoral institution background of the program area, and the existing conditions of the rural water supply and sanitation sectors. Based on the findings and analysis of the current situation, the rural water supply and sanitation masterplan is proposed which includes recommendations on the institutional aspects, investment requirements and information dissemination. The study also includes the project management information system which incoporates the establishment of a database for the sector and the monitoring and evaluation of the program.

Obtainable:
ENSIC, AIT
P.O. Box 2754, Bangkok 10501
Thailand