Bioenergy Systems Report

APRIL 1984: INNOVATIONS IN BIOGAS SYSTEMS AND TECHNOLOGY

INTRODUCTION

Two previous Reports in this series have reviewed the production and use of biogas fuels through the anaerobic digestion of various types of biomass. The first Bioenergy Systems Report, published in March 1982, focussed on "Biogas in Developing Countries." That initial Report concentrated primarily on family-sized plants in developing countries designed for the production of biogas for cooking and lighting. In March 1983 most of a Report on "Bioenergy for Agriculture" was devoted to the use of biogas to provide mechanical, electrical, and heat energy needed for the production and processing of agricultural products. That Report provided information on the design and operation of larger-scale digesters and the use of biogas in boilers and in internal combustion engines.

During the past year, information has become available on a considerable number of innovations in biogas systems and technology in both developed and developing countries. However, much of this information has not been widely shared among those in developing countries who are interested in the design of appropriate and effective bioenergy systems. Thus the primary purpose of the present Report is to provide a comprehensive review of recent innovations in the design and operation of biogas systems.

This Report contains information on about sixty distinct designs for biogas plants. These include plants designed for use by individual families (pp. 2 to 11), larger farm plants (pp. 12-18), plants used for the digestion of agroindustrial residues (pp. 19-23), and plants producing or recovering biogas from human wastes and residues (pp. 24-26). These plants vary widely in size, feedstocks, design, construction technique, materials, cost, operating principles, gas production, gas storage technique and capacity, and gas utilization. Some have been designed for use in developing countries; others have been used primarily in developed countries but may involve design elements which could be utilized in developing countries.

An effective biogas system must integrate an available feedstock, an efficient conversion technology, and a priority use of the gas. Many economic, social, cultural, management, and environmental factors may also affect the feasibility or operation of a given design. Development of an effective total system requires a full analysis of both technical and non-technical factors.

These Reports are sponsored by the Bioenergy Systems and Technology Project of the U.S. Agency for International Development. They are designed to contribute to wider international sharing of experience with systems and technologies which may be suitable, with appropriate modifications to fit local conditions, for the conversion of biomass to energy in developing countries.

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PART ONE: FAMILY BIOGAS PLANTS

All but a few of the biogas plants built in developing countries have been rather small units designed for use by individual families. The primary domestic use of the gas is for cooking, although many families also use biogas for lighting.

Only two basic types of biogas plants - the deep digesters with floating steel gasholders developed in India and the fixed dome plants which have been used in China - have been built in very large numbers in any developing country. Neither design has proved entirely satisfactory from both a technical and an economic standpoint, and important changes in these designs are now being made in the countries in which they originated as well as in other countries. Some new designs have emerged, notably the plastic bag digesters developed in Taiwan which are being used in both family and larger sizes and are reviewed on pp. 17-18. Few of the other new or modified designs have as yet been widely tested or used.

The Indian and Chinese biogas plants and most others built in developing countries are unmixed continuous or "plug-flow" digesters. A "plug" of fresh feedstock is added daily; it travels through the unit during the planned retention time which is determined by the daily loading rate and the volume of the digester. Since the rate of gas production is primarily influenced by temperatures in the digester, the necessary retention time in unheated digesters is determined mainly by climate and seasonal temperatures. If digesters temperatures are low, a longer retention time is necessary; it is provided by either a lower loading rate or a larger and thus more expensive digester.

1. Indian-type Family Digesters

Up to 1982 most of the biogas plants built in India used a standard design promoted by the agency which coordinated the Indian biogas program, the Khadi and Village Industries Commission (KVIC). The digester consists of a deep circular pit or well built of brick, mortar, and plaster. A dilute cow dung slurry is mixed in a small masonry tank on the surface and fed to the bottom of the digester through a narrow pipe. Larger models are divided into two chambers by a central brick wall, so that the slurry must flow up over the wall and down to the outlet pipe near the bottom of the second chamber. The biogas is captured in a gasholder consisting of an inverted steel bell or drum; it rides on a guide pipe attached to the masonry structure and rises to provide expanded biogas storage as gas accumulates.

The KVIC designs of the later 1970's provided for a deep pit with a rather small diameter. The depth provided a retention time of 50 to 55 days; the narrow diameter minimized the cost of the gasholder. However, research in the early 1980's showed that the retention time could be sharply reduced in warmer areas of central and southern India. Other studies show that, if the cost of both digester and gasholder is considered, the least expensive plant is one in which the diameter of the digester equals its depth. Field tests of these revised models indicated that their productivity in warm weather exceeded that of the KVIC plants, although they were less suitable for colder areas due to larger surface heat losses.

Changes in digester design in India have been slow but continuing. A government publication now recommends a 30 day retention time for south India, 40 days for central India, and 55 days for cool mountain regions in northern India. In 1981 an official report showed a KVIC digester designed to produce 3 m^3 of gas per day which had a 6 m^3 slurry chamber. Early in 1982 the Tata Energy Research Institute in Bombay published a biogas manual showing a KVIC plant, also rated a 3 m^3 of gas per day, which had a slurry chamber with a volume of only 3.5 m^3. The 40% reduction in digester volume had been achieved by reducing both the depth and diameter without changing the basic shape of the plant. However, several of the new digester models developed by other institutions in India are shallower and wider than the typical Indian plants.

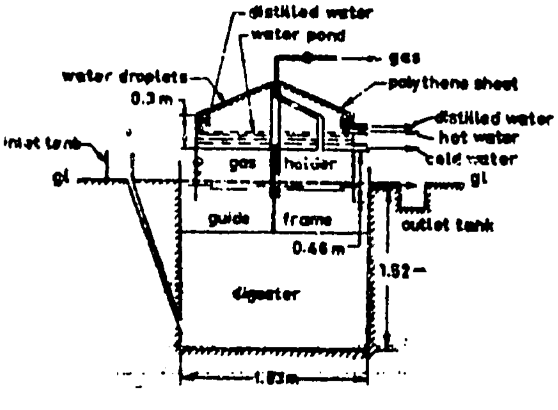
The most persistent problems with the Indian-type biogas plant are those related to the floating steel gasholder: (a) The gasholders are expensive; a recent Indian government publication indicates that the smallest KVIC-type plant providing a 30-day retention time costs 60% more than a Chinese-type plant of comparable size. (b) There have been serious corrosion problems with the gasholders. (c) A steel gasholder is a good heat conductor and, since it must be free to rise, it is very hard to insulate satisfactorily. Due to the heavy heat loss, this type of digester is not very effective in areas with ambient winter temperatures of 10 to 15°C.

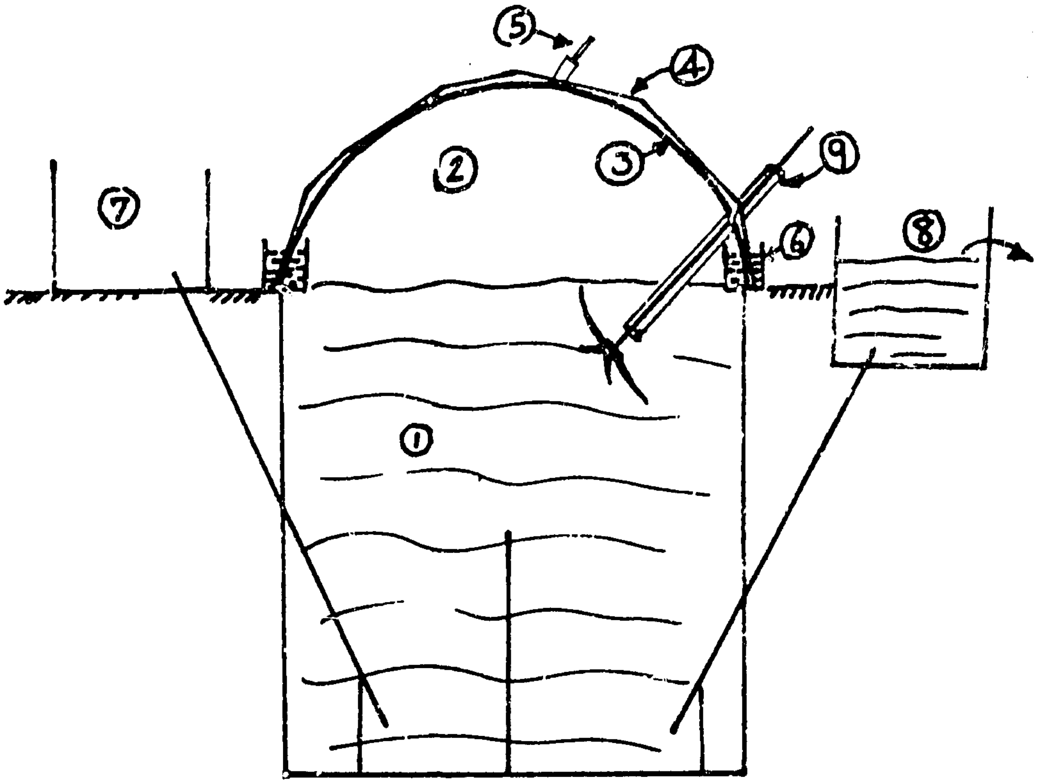
There have been a number of attempts to resolve some of these problems by using materials other than steel for the gasholder. The Structural Engineering Research Center at Roorkee, India, has developed gasholders made of ferrocement. They are relatively inexpensive, corrosion-resistant, and have a low thermal conductivity. However, they are heavy, difficult to transport, and subject to leakage problems. Moreover, their increased use is limited by the inadequate supply of cement which was one of the main constraints restricting the development of the Indian biogas program in 1982-83.

A firm in Bombay has produced a high density plastic gasholder, but the initial cost was about the same as that of a steel gasholder; the use of these gasholders in India has been limited. Plastic gasholders are now used in household biogas plants in Korea as one means of reducing heat loss from the digesters during Korea's severe winters. Due to lower winter productivity, many of the 29,000 household plants built in Korea between 1969 and 1975 are no longer used. The current Korean design involves a square concrete digester tank which has 1.8 m sides and is 1.8 m deep. A square floating gasholder is made of treated waste PVC plastic; 5 to 8 kg of stones are placed on top to increase gas pressure. In the winter the plants are insulated by surrounding the digester walls with a wide band of rice straw or hulls to a depth of at least 1 m and by building a vinyl-covered framework over the digester. Even with these measures, the digester cools very quickly when air temperatures drop. Korean experts state that the basic defect of the design is that the slurry around the gasholder is exposed to the cool outside air.

This type of heat loss can be limited by the use of a "water-jacket" design in which the gasholder floats in water in a ring around the top of the digester. In India KVIC has recommended the wider use of water jackets as a means of reducing corrosion in steel gasholders, since a gasholder floating in water is less prone to corrosion than one floating directly in the slurry. The water jacket plants also avoid excessive dilution of the slurry by rainwater seepage and are more sanitary and odor free than the conventional Indian plants. The main disadvantages are the additional construction cost and the need for stirring rods on the bottom of the gasholder for scum breaking, since the gasholder itself does not rise and fall in the slurry.

A design developed by the Indian Institute of Science (IIS) in Bangalore deals with the heat loss problem in the KVIC plant by turning the steel gasholder into a solar collector. As shown below, the sides of the gasholder are extended 0.3 m above the top to form a water tank. The inside of the tank is painted black and it is covered with a polythene sheet. The tank functions as both a solar still and a solar water heater. Evaporation from the tank condenses on the plastic sheet; the distilled water runs down the sheet and is captured in a channel around the rim. Solar-heated water from the tank is tapped off into the inlet tank for slurry mixing; this use of hot water helps maintain optimum temperatures in the digester and permits a shorter retention





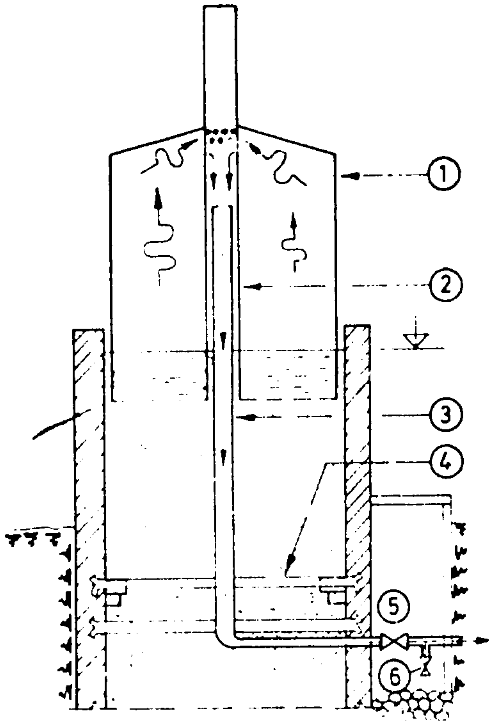
time and a significant reduction in the size of the digester. This "ASTRA" model reflects IIS studies on the optimization of digester dimensions which indicated that the diameter of the digester should be at least equal to the depth of the slurry chamber. The diameter of the pilot unit was 1.83 m, while the depth of the chamber was only 1.62 m. The ASTRA model has not yet been widely used in India.

In another promising innovation, the steel gasholder is replaced by a plastic balloon inside a protective framework in the shape of a geodesic dome. The design, developed by the Shri AMM Murugappa Chettiar Research Center in Madras, is shown above. The depth of the digester (1) is not greater than its diameter. The masonry structure is similar to that for a KVIC plant but includes a water jacket (6). A large sheet of black low-denisty polyethylene plastic (3) covers the top of the digester and is attached to stays in the water jacket in a manner which permits it to assume a spherical shape when inflated with biogas. The plastic balloon is covered by a geodesic dome structure (4) which can be made out of various materials including plastic pipe and wooden poles. Due to the lack of the steel gasholder, which breaks the scum in the KVIC plants as it moves up and down, a scum breaker or stirring rod (9) proved essential. Initially the rod was inserted through the plastic as shown above, but in later models a stirring device was built into the masonry structure. The cost of such a "JWALA" biogas plant was estimated in 1981 to be less than half that of a KVIC plant of comparable size; the cost of the JWALA plants has been lowered since then as a result of a reduction in the size of the geodesic dome. The JWALA plants are also somewhat more productive than the KVIC plants.

Further biogas innovations may be feasible under a reorganized and somewhat decentralized National Project on Biogas Development in India. In September 1982 responsibility for the coordination of the National Project was transferred to a new Department of Non-Conventional Energy Sources in the Ministry of Energy. It provides support for biogas staffs in the governments of 19 states and territories and for the operation of biogas units in 110 districts selected for intensive biogas development. KVIC continues to provide technical assistance and handles about 30% of the construction of biogas plants in each state.

Institutions in several other countries have adapted the basic Indian designs to fit local conditions. The Ministry of Energy in Kenya found that circular galvanized tanks, which are commercially available in Kenya for cattle-watering, could be turned over and used as gasholders for biogas plants. The National Research Center in Egypt found that very unstable sandy soil along the Nile prevented excavation for a very deep KVIC-type Indian digester; in the redesigned 5 m^3 unit the diameter and the depth of the slurry chamber are equal (1.75 m).

In most Indian-type biogas plants the gas flows into the house through a hose attached to the top of the gasholder, but these hoses are subject to deterioration and leakage. These problems are avoided in most of Nepal's 800 Indian-type plants by the use of an underground gas pipe as shown in the sketch below. From the gasholder (1) the gas flows through holes into the slide pipe (2) and into the open end of the center pipe (3) which is connected with the main gas valve (5). It passes through a moisture trap (6) before proceeding through an underground pipe to the house; the moisture trap must be at the lowest point in the pipe.



2. Chinese-type Family Digesters

Although there have been many variations in construction materials, shape, and size, virtually all of the biogas plants built in China until recently have followed a common basic design. Slurry occupies most but not all of the main chamber. As biogas is produced, it collects under the usually domed roof of the digester; pressure builds up, and the slurry is pushed out of the digester into the adjacent vertical outlet chamber. When the gas is used, slurry flows back into the main chamber.

Compared to the Indian-type biogas plant, the Chinese design has several advantages: (a) Since there is no steel gasholder, the Chinese units are considerably less expensive and can be built entirely from locally available materials. (b) The underground digester is less affected by colder ambient winter temperatures. (c) Due to the wide inlet, removable cover, and lesser depth, the Chinese design permits the use of plant material as a feedstock and facilitates the more frequent cleaning which is necessary when such material is used.

However, the Chinese plants also have important disadvantages: (a) There have been persistent leakage and seepage problems. The design requires that gas and liquids be retained within a masonry structure despite an internal pressure buildup which can exceed 100 cm (water column). Although vigorous efforts have been made to prevent gas leakage and liquid seepage through careful construction and the application of several coats of plaster and other sealers to the inside of the digester, leakeage problems are the most frequent reason for the inadequate functioning of two million digesters or about one third of the six million biogas plants in China. (b) Gas pressure can be very high but constantly varies depending on the amounts of gas produced and used. If gas pressure becomes excessive, some gas is lost by venting though a pressure-relief device. (c) Gas produced from slurry which has been pushed up into the outlet chamber is lost to the atmosphere. (d) Finally, the gas production of the Chinese-type biogas plants is very low.

Since digester temperatures in these underground digesters are mainly influenced by earth temperatures, the most important factor affecting gas production seems to be climate. A Chinese biogas expert gave 0.15 m^3/m^3/day as the annual average for all Chinese digesters in 1980, but the gas rates vary substantially from north to south and from summer to winter. The Chengdu Biogas Research Institute in central China reported gas rates from 0.17 to 0.28 during a November to April period in 1981-82, but winter rates have dropped as low as 0.07 under field conditions in some northern areas. The Chengdu Institute found that digester temperatures were never more than 3°C above or below the earth temperatures at 210 cm below the surface; during a November-June period digester temperatures ranged from 11 to 20°C and were always far below the optimum level for anaerobic digestion of about 35°C.

China's temperate climate is less favorable for the operation of unheated underground digesters than that of more tropical areas. In one test in Egypt in which digester temperatures ranged from 22 to 24°C, gas production rates ran from 0.19 to 0.23 m^3/m^3/day. Closer to the Equator in south India, a Chinese-type digester produced .32 m^3/m^3/day; similar rates are reported from modified Chinese-type digesters in Guatemala, where year-round earth temperatures are around 25°C. On the other hand, the thirty Chinese-type digesters built in Peru's Andean region at altitudes between 2,000 and 4,000 meters produce only about 0.1 to 0.2 m^3/m^3/day or about the same amount of gas as the average digesters in China.

Although the Chinese-type digesters do not work very well in cool climates, they are nonetheless more effective in such climates than the Indian type due to the substantial heat loss through the gasholders in the typical Indian plants. A modified version of the Chinese biogas plant known as the "Janata" plant was developed in 1977 by the Gobar Gas Research Station in Ajitmal, Uttar Pradesh. Up to 1981 the principal variation from the Chinese designs was the elimination of a manhole in the domed roof in order to limit gas leakage; the only access to the slurry chamber was through .6 m diameter holes between the chamber and the inlet and outlet tanks. However, this limited access apparently proved inadequate, and the Janata design shown in a 1982 biogas manual has a manhole which is sealed with a concrete disc during digester operation.

Nearly 800 of the Janata plants were built in northern India in the 1970's and many more have been installed in the 1980's, although no figures are available. The Indian government recommends these plants for cooler areas with ambient temperatures of 10 to 15°C. Due to the elimination of the steel gasholder, the Janata plant is considerably cheaper than the KVIC plant; an Indian government publication indicates that the average cost of the smallest Janata plant is about 2450 rupees, compared to 3750 to 4800 rupees for a KVIC plant of comparable size.

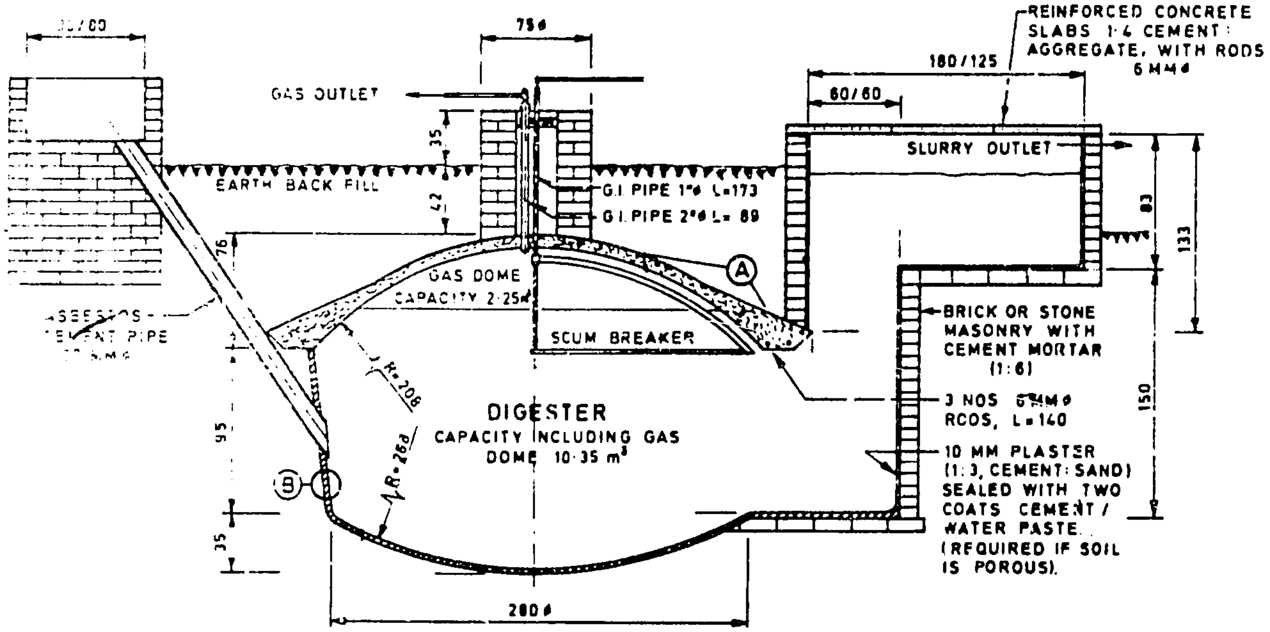
Another variation on the Chinese model was orignated by Development and Consulting Services (DCS) of Butwal, Nepal. Like the early Janata plants, the manhole in the domed roof has been eliminated to limit gas leakage. However, there is a sealed "conning tower" containing the gas outlet pipe and a handle for turning a scum breaker inside the digester. In the initial digester built by DCS in 1979 the floor, walls, and dome were all made of carefully cemented and plastered bricks and were painted with an epoxy paint. However, in the roadless hill country in Nepal it was difficult to obtain heavy timbers to support the brick roof during construction. Since the only access to the digester was through an enlarged slurry outlet, plaster drying was very slow and fumes from the paint made it very difficult to work in the confined space.

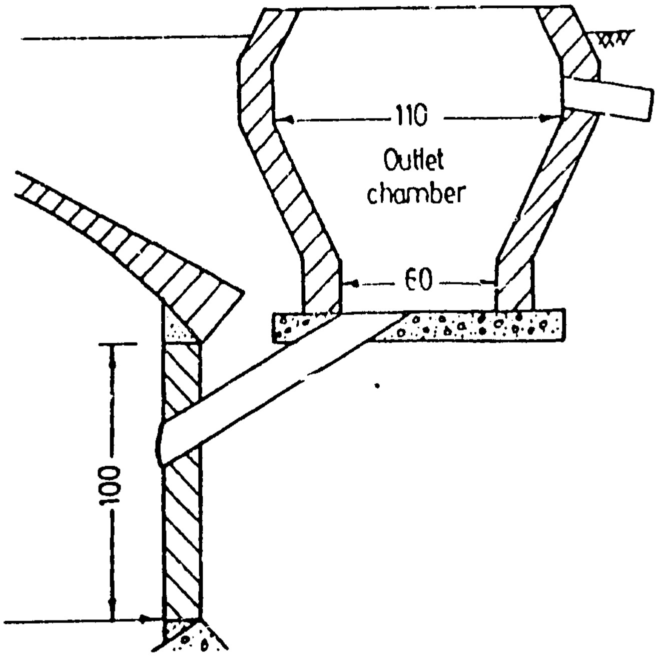
As a result of these problems, DCS designed a new model shown in the sketch below. The first step in the construction of the unit is digging a 2 m diameter hole about 2 m deep. A domed form is built in the hole, and the concrete digester roof is poured. Subsequently the area under the roof is excavated and the dirt walls and floor are covered with two coats of plaster and a coat of a mixture of acrylic plastic emulsion and cement. DCS and the Gobar Gas Company in Nepal had built eleven of these plants by late 1980, and there are presumably now a much larger number of these units among the roughly 400 Chinese-type biogas plants in Nepal.

The Chinese have developed many variations in the size, shape, and construction materials of the digesters to fit local conditions. Biogas plants have been built of brick, stone, slate, concrete, and mixtures of lime and clay and of lime and concrete. Most plants are circular with domed roofs, but rectangular plants with flat roofs are popular in some areas. Construction techniques also vary, and include some noteworthy methods. Half of a "ball" digester is built in a shallow half-sphere hole, with the other half built above ground; a deeper pit is then dug alongside, filled with water, and the ball is floated into final underground position. A "cast-in place" digester begins with a circular trench filled with concrete to form the digester walls; just enough earth is removed from the center to provide a form for a cast concrete roof. The remainder of the digester is then excavated through the center manhole.

None of these variations in materials and construction techniques has solved the gas leakage problems with the typical Chinese digesters. Moreover, these problems have become more serious in recent years as changes in the organization of Chinese agriculture have given the individual farmer more control over his own animals, residues, and individual allocation of land. The relatively more prosperous Chinese farmers want more reliable and convenient biogas plants, and it has not been possible to meet this demand with the present digesters. According to unofficial reports, the previous design is now being deemphasized and will not be the typical Chinese design in the future.

Separate plastic gas storage bags are now being used in China with many masonry digesters including both new units and older digesters. The addition of the storage bag reduces the pressure in the digester and eliminates the need for elaborate plastering and other measures to avoid gas leakage. Elimination of the pressure-holding requirement has also made it possible to build digesters with easier access for the periodic digester cleaning which is necessary due to the use of agricultural residues along with human and animal wastes. In north China both digester and gas storage bags are in the barn with the animals; in south China the digester is outside and the bag is inside, usually





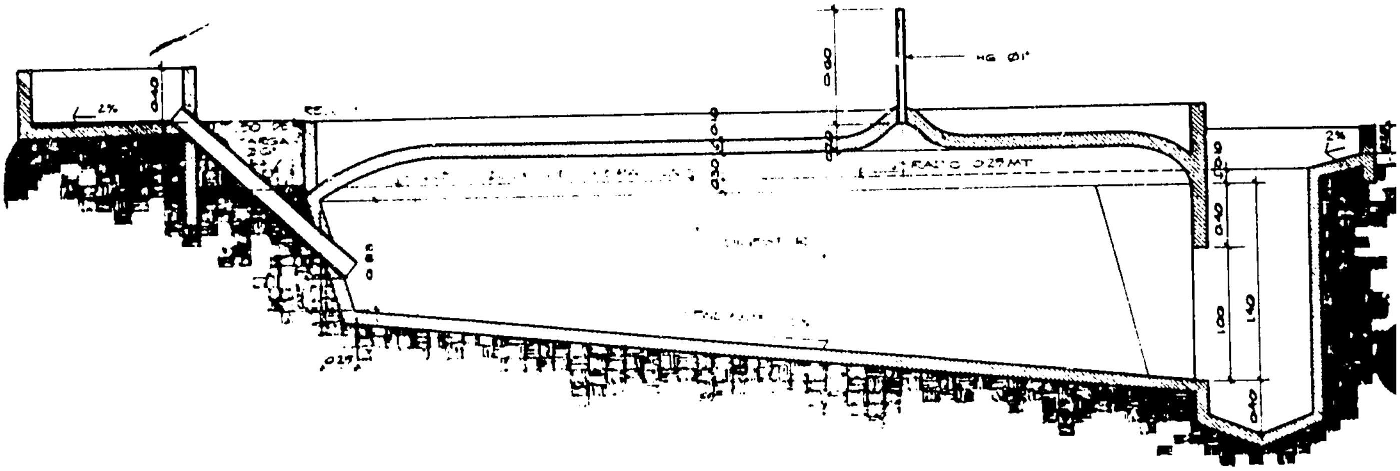
suspended from the ceiling of the kitchen. The Chinese biogas agency is also promoting the increased use of plastic bag digesters (see p. 17).

Efforts to increase the effectiveness of the Chinese type digesters continue at research institutions in several countries. For example, studies at the National Research Centre in Egypt indicated that changes in the design of the outlet chamber could reduce the loss of gas generated from slurry which was pushed up into the outlet chamber. NRC redesigned the outlet chamber to minimize the movement of slurry. As shown in the sketch above, the new component has a wide top but a narrow bottom which is connected to the main chamber by a small-diameter pipe rather than by a wide opening as in most Chinese-type digesters. It assists the stabilization of gas pressure while keeping the required gas storage capacity; a sharp decrease in gas losses was noted.

3. Horizontal Digesters

Two types of horizontal digesters have been designed and tested at the Central American Research Institute for Industry (ICAITI) in Guatemala. The institution's initial horizontal digester was developed under a project funded by the Inter-American Development Bank; it was a rectangular tank with sloping concrete floor, walls of concrete block, and a top of reinforced concrete which was mostly covered with earth. Initial gas collection was through a small square metal gasholder floating in a water jacket; however, this model and later ICAITI models were designed for use with a separate external gasholder, usually a plastic bag or inverted bell floating in a container of water.

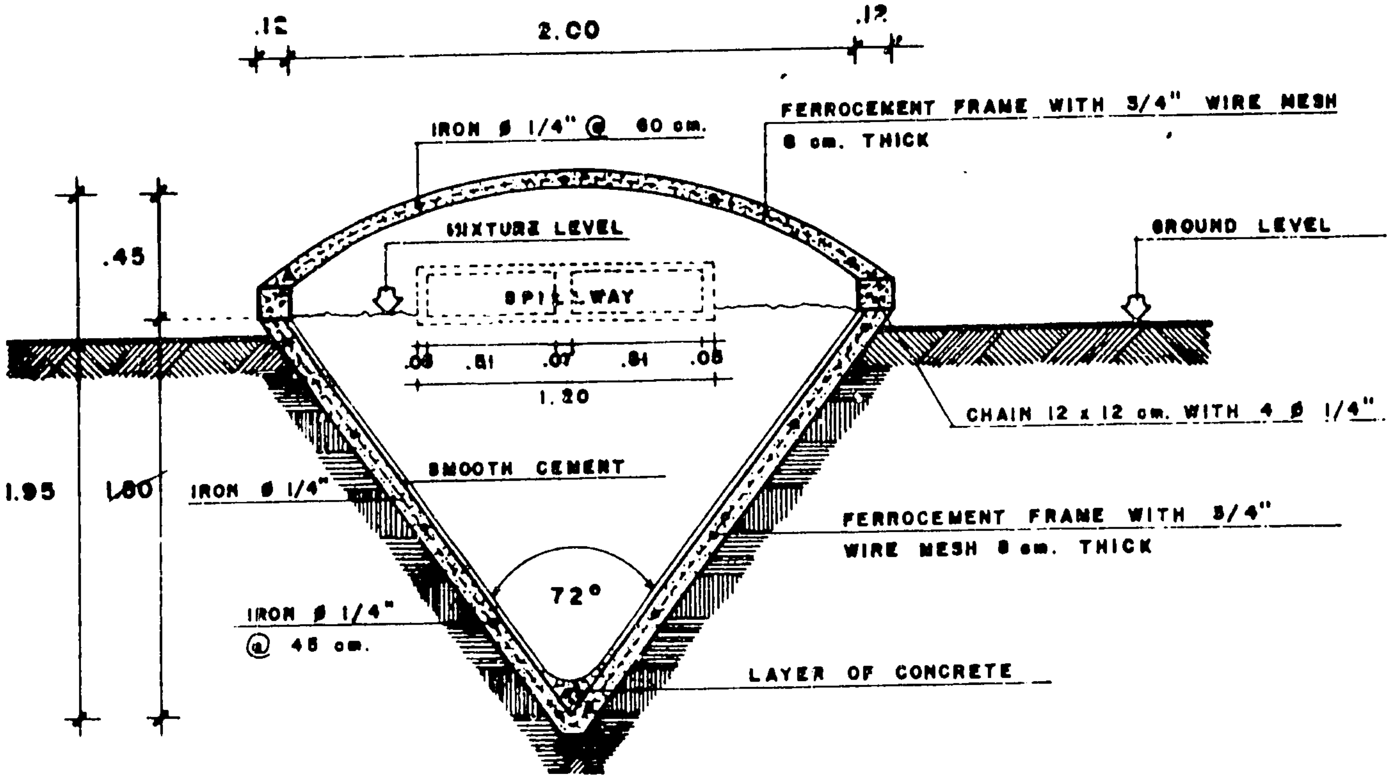
A new horizontal digester has been designed by ICAITI under a renewable energy project funded by the U.S. Agency for International Development through its regional office for Central America (ROCAP). A sketch of the 15 m^3 unit is shown at the bottom of this page. The sloping floor and walls are made of poured concrete beams filled in with concrete blocks; the slightly domed roof is of reinforced concrete. The outlet chamber functions like its counterpart in the typical Chinese biogas plant; when gas builds up



under the roof, slurry is pushed into the outlet chamber. In this manner internal gas storage space, which is initially only about 10% of the liquid volume, is doubled. However, a separate external gasholder is also necessary.

About 25% of the total volume of the feedstock used in the ICAITI digester can be plant material, if it is properly chopped; the rest is manure and water. The slurry enters the main chamber through two parallel inlet pipes. The loading rate provides a retention time of about 30 days. The unheated unit operates at 25°C, which is about the earth temperature in Central America. Gas production is around 5 m^3 per day or .33 m^3/m^3/day. Scum in the digester is broken by a floating device which is moved back and forth in the digester with plastic ropes running through the inlet and outlet openings. The 10% slope of the floor of the digester allows sludge to settle into a sump at the bottom of the outlet chamber, from which it can be removed with a bucket on a long handle. The 1.0 m opening between the main chamber and the outlet chamber is large enough to permit a man to enter the main chamber for digester cleaning. Seventeen of the 15 m^3 digesters have been built by the Ministry of Agriculture of Guatemala in cooperation with ICAITI, and the ICAITI biogas team has also installed some of the units in Costa Rica, Honduras, and El Salvador. A manual on the digester has been published in Spanish by ICAITI under the USAID project.

Another horizontal digester has been developed by the Institute for Electrical Research (IIE) in Cuernavaca, Mexico. The 10 m^3 family version of the IIE unit consists of a 7 m long V-shaped trough covered by a domed roof, as indicated in the cross-section sketch below. Both the walls and roof are made of 8 cm thick ferrocement (i.e., mortar reinforced with wire mesh). The unit is designed for use with dilute manure slurry with about 8% total solids. Since there is no provision for sludge removal or digester cleaning, the use of plant materials is not feasible in this digester. Slurry is mixed in an elevated loading sink, reached by steps; the 3 m drop of the slurry to the bottom of the digester provides some turbulence for digester mixing. Gas is captured under the roof of the digester; since there is very little



internal gas storage capacity, the design is recommended for applications involving steady use of the gas which will prevent the buildup of excessive pressure within the digester. No gas production data was available for the preparation of this Report. According to IIE, the cost of the units range from \$52 to \$89 per m^3 of digester volume, which is the lowest of four digester types tested in Mexico. A 40 m^3 version of the IIE plant has been in operation for several years at an agricultural school, and several 20 to 40 m^3 units have been built in off-grid communities in Mexico. A 52 m^3 version of the IIE digester provides fuel for an engine in Peru.

4. Packed-Bed Digesters

The Thailand Institute of Scientific and Technological Research in Bangkok uses screened and diluted pig wastes in an anaerobic filter (see pages 20-22) with a packed bed consisting of rings of bamboo 3.8 cm in diameter and 2.5 cm long. The 200 liter digester was made from an oil drum. The rings proved to be an ideal packing medium for packed-bed digesters designed for operation in rural areas. Considering both gas production and the reduction of pollution, the optimum feed flow rate was 30 liters/day; the high gas production rates ranged from 1.0 to 1.26 liters per liter of digester per day. TISTR concluded that the volume of gas normally produced by a 3 m^3 conventional family digester in Thailand (about 1.2 m^3 per day) could be produced by a packed bed digester which was only half as large (1.5 m^3) as the conventional unit with a one-third savings in construction costs. A mini-digester of this type, producing 100 liters/day for rural family lighting, would cost only about \$30.

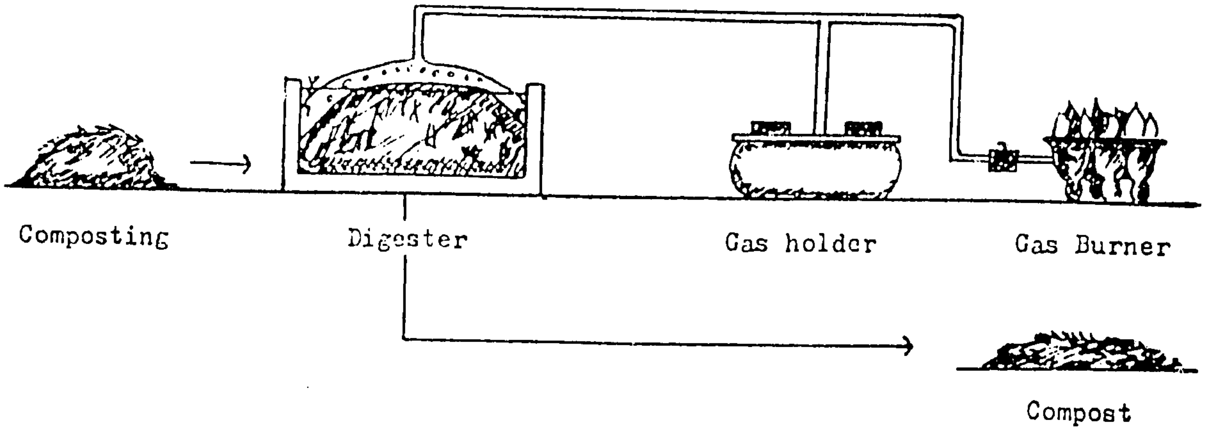
5. Digesters for Crop Residues

Indian biogas pioneer Ram Bux Singh designed a batch digester for vegetable wastes in the early 1970's. The circular brick digester had a domed top containing a manhole and a small steel gasholder riding in a water jacket. One third of the volume of the digester was filled with chopped vegetable wastes, one third was filled with cow dung, and the remainder was filled with water or effluent from a conventional biogas plant. The digester contents were stirred by pulling on a flexible wire rope running through a pipe in the top of the gasholder; it was connected to crossed boards suspended in the slurry. If temperatures were between 16 and 23°C, gas production began within 20 days and continued for at least four months.

The Punjab Agricultural University in India has experimented for several years with a "Kachara" continuous digester using chopped rice straw or wheat straw. Field tests were conducted in 1983 with a model with improvements in the stirring device and other features. Data have been assembled on the digestion of a variety of wastes including crop residues, tree leaves, and fruit peels. Residues are chopped into pieces no larger than 8 cm. Leafy materials fermented more easily and produced more gas than relative woody materials. Semi-solid lumps of undigested material remain floating in the digester and are removed to the fertilizer pit.

Uncut millet stems were used as the primary feedstock in three digesters built by the International Association for Rural Development at a small hospital in Upper Volta. Two 4 m^3 digesters and a 12 m^3 unit were modified "Indian" models with a floating steel gasholder riding in a water seal; inlet and gas outlet pipes extended through the steel gasholder. The units were batch fed with 50 kg of millet stalks and 20 kg of animal manure for each m^3 of digester capacity. The feedstock was composted for 7 to 10 days to permit aerobic digestion prior to use in the anaerobic digester. Retention time was 50 days. The three digesters produced about 2,000 m^3 of biogas per year; the gas was used for refrigeration, sterilization, water pumping, and the operation of a 2.5 kVA generating set.

Rice straw, other crop residues, and a variety of other plant materials are widely used along with animal manures and human wastes in family biogas plants in China. The Chinese digesters have been designed with rather wide openings between the inlet or



mixing tank and the main digester chamber which permit the feeding of rather bulky materials.

The Korean Government's Office of Rural Development has developed a low-cost batch digester for the "dry" fermentation of straw and manures; about 900 of the units have been built on farms in Korea. The design, shown in the sketch above, consists of a brick and cement tank covered with a removable PVC plastic dome and a separate gasholder consisting of an inflatable plastic bag. The unit is fed a mixture consisting of 100 kg of straw and 150 kg of manures per m^3 of digester volume. Prior to use the straw and manures are composted outside the digester for one week in summer and three weeks in winter, in order to reduce the C/N ratio of the straw from about 84 to around 45. The digester is seeded with some effluent from conventional liquid digesters; the unit operates with a total solids (TS) concentration of about 28%, compared to TS levels below 10% for most conventional digesters. About 1 m^3 of biogas per day is needed for cooking for the average five-person family in Korea; this gas requirement is provided for 90 days in summer and 60 days in winter by loading 300 kg of straw and 450 kg of manure in a 3 m^3 digester with a 1 m^3 gasholder. Winter gas production rates can be increased to 1.5 times the summer level by insulating the digester with composting straw and manure; the heat produced by the composting process raises digester temperature to about 30°C even in the coldest winter season in Korea.

Crop residues and other plant materials are used in a number of larger heated digesters in New Zealand. The Invermay Agricultural Research Centre in Mosgiel, New Zealand, has developed a unique system for the digestion of potential "energy crops" as well as several types of crop residues. Crops of corn (maize), kale, and oats are grown on the Invermay "energy farm," harvested with a fine-chop silage harvester, and stored as silage. This feedstock is digested in a 45 m^3 supported bag digester described on p. 18. It receives about one ton of chopped silage per day, mixed with enough water to allow handling by a slurry pump. Each day's load remains in the digester for about 15 days and is converted into about 100 m^3 of biogas; the gas production rate is thus about 2.0 m^3/m^3/day. Some of the gas is used for digester heating; the rest is scrubbed to remove carbon dioxide and hydrogen sulphide, compressed into cylinders, and used in Centre vehicles (See "Biogas for Vehicles," p. 27).

6. Community Biogas Plants

A community plant provides cooking gas to most or all families in a village. Over fifty community plants have been built in India and a hundred more are planned. Two-thirds of the completed units were larger versions of the typical Indian family biogas plants with floating steel gasholders; they provide cooking gas for 30 to 100 families using mainly cow dung. At most sites human wastes drop directly into the digester from a community toilet above. Six plants in northern India are larger versions of the Chinese-type "Janata" plants. So far the community plants have involved soical rather than technical innovations.

PART TWO:
LARGER FARM BIOGAS PLANTS

While most of the biogas plants built in developing countries have been family sized units producing gas for cooking and lighting, most of the biogas installations in developed countries have been larger units producing fuel for use in internal combustion engines to generate mechanical and electrical power. This striking difference arises primarily from basic differences in the scale and type of agricultural activity between the developed and developing countries.

On many farms in North America and Europe, large numbers of animals or poultry are confined in relatively small areas. Most of the biogas plants in these countries have been built on dairy farms, cattle feedlots, large pig farms, or large poultry farms. In an era of tightening environmental regulations, there are serious problems related to the disposal of the large quantities of manure accumulated on these large farms. A biogas plant can convert the manure to energy and odorless fertilizer, reduce expenditures for these inputs, and increase farm income through the sale of energy or fertilizer. Dewatered digester effluent can be used for livestock bedding; single-cell protein can also be extracted from the digester solids.

The typical farmer in most developing countries does not have enough animals to permit the operation of a larger-scale biogas plant. The collection of dung from numerous farmers for use in a larger plant presents practical and organizational problems as well as economic and social issues related to payment for the dung and distribution of the products of the biogas plant. However, there are some important opportunities for larger-scale biogas plants in developing countries. Larger plants have been built at large dairy farms, large pig farms, slaughterhouses, livestock watering stations at boreholes in arid areas, and other places where a substantial number of animals are concentrated in a limited area. In such locations biogas plants can provide a means of meeting high-priority energy needs including water pumping and the generation of relatively small but vitally important quantities of electric power.

One major barrier to the development of larger-scale biogas plants in developing countries is the lack of experience in most of these countries with digester heating. With only a few exceptions, the heating of digesters has been viewed in developing countries as too complicated and expensive. Despite high air temperatures in many cases, the contents of the mostly underground digesters remain at temperatures which are close to the earth's temperature and thus well below the optimum temperature for anaerobic digestion (about 35°C). Even in the tropics, earth temperatures are around 25°C.

Without heating, digestion is very slow and retention times must remain rather long; a large digester is required to produce a sufficient quantity of gas to operate even a small engine for restricted periods. In China, where gas production rates remain very low, a digester volume of 250 m^3 is needed to produce enough gas to operate a 10.8 HP engine/generator for 6 hours a day. Although gas production rates are somewhat better in some larger unheated units in developing countries, they involve a rather large cost for a rather modest benefit.

The great majority of the digesters in developed countries are heated to around 35°C; gas production rates are several times higher than those from unheated digesters in developing countries. Even if up to a third of the biogas is used for digester heating, the net biogas production still greatly exceeds that from most unheated digesters. If the biogas is used in an engine, waste engine heat can be used to heat the digester.

A striking example of the effects of digester heating is provided by a comparison of the productivity of two flexible-top digesters of virtually identical size. A pioneering 350 m^3 unheated system built for the German Agency for Technical Cooperation at a slaughterhouse in the Ivory Coast produces 120 m^3 of gas per day or about .34 m^3/m^3/day. The gas is used in a 12 kW engine/generator to produce 138 kWhr per day. In contrast, a 360 m^3 digester at the Marindale Dairy in

California, heated by waste heat from a biogas-fueled engine, produces 645 m^3 of gas per day or 1.74 m^3/m^3/day; the gas is used to drive a 34 kW generating set producing 820 kWhr per day for sale to the local power company. Although the California system is somewhat more complex and expensive, it produces six times as much power as the unit in Africa.

If digester size remains constant, heating to 35°C permits higher loading rates, shorter retention times, and higher gas production; if the manure supply is limited, digester heating permits the use of a smaller and cheaper digester to produce the same amount of gas as a larger unheated digester. Digester heating also reduces the pathogens in the effluent; research at the Institute of Gas Technology in Chicago showed that enteric bacteria and viruses generally survived better in the effluent at 25°C than at 35°C.

The technical complexity and cost of digester heating with waste heat from a water-cooled engine are relatively modest. The main requirement is for a heat exchanger in or around the digester (usually consisting of a simple coil of pipes) which is connected to the engine's radiator. The National Research Centre of Egypt is heating a digester using a simple heat exchanger which captures heat from the exhaust of a small air-cooled engine.

Because of the large quantities of manure available at some farms and feedlots and the economies of scale associated with larger systems, most of the biogas systems in developed countries have been rather large. Experience with modest-sized heated systems producing biogas for use in engines is rather limited. However, through the greater international sharing of some of the experience gained with larger farm biogas plants, it should be possible to develop systems whose size, complexity, and costs are modest enough to permit relatively wide use in developing countries.

Although a few larger versions of the "Chinese" and "Indian" family digesters have been built, most of the larger biogas plants have used one of the following three types of designs: (a) a fixed-top digester consisting of a steel or concrete tank with an attached or separate gasholder; (b) a flexible-top digester consisting of an open concrete or masonry tank covered by an inflatable plastic or rubber gasholder; or (c) a partly-buried plastic bag in which the below-ground segment serves as the digester and the above-ground portion functions as the gasholder. Examples of each type of system will be provided in the following sections.

1. Fixed-top Digester Systems

Fixed-top digesters are widely used in Europe. A recent survey by the Catholic University of Louvain in Belgium identified 550 biogas plants in the ten European Community countries plus Switzerland. There is about 95,000 m^3 of digester volume on European farms. The typical European farm biogas plant has an insulated steel or concrete fixed-top digester, equipment for stirring and heating the contents of the digester, and a separate floating steel gas holder. While the survey noted a three-fold increase in the average reported gas production rates between 1980 and 1982, the typical unit now produces about 1 m^3 of gas per m^3 of digester per day, which is considered the lowest limit for economic viability of these plants. The principal reasons cited for poor system performance were gas leakage, failure of feedstock pumping and loading devices, blockage of pipes, inefficiency of mixing systems, settling and water entry during feedstock storage, digester heating problems, and settling of feedstocks in the digester and/or scum formation.

Most of these European plants cost from \$300 to \$500 per m^3 of digester capacity; the most expensive units are those which include an engine and are built by a contractor on a "turn-key" basis. The Louvain survey obtained economic data on 32 on-farm plants; only a few had short payback periods. Five had 3 to 6 year payback periods, while eight plants will pay for themselves in 7 to 10 years. The main reasons for the poor economic ratings of the plants were excessively high construction costs, poor system reliability and performance, and poor use of the biogas.

A recent European Communities report describes a plant built by the International Association for Rural Development with funding from the biogas demonstration program of the European Communities. The 90 m^3 plant was installed in 1981 on a farm near Courtrai in Belgium which has 80 sows and 350 piglets. The fixed-top digester is a vertical, cylindrical steel tank covered with insulation. It is heated to 35°C and the contents are mixed by drawing off effluent at the bottom and reintroducing it at the top. Gross gas production averages 80 m^3/day or slightly below 1.0 m^3/m^3/day. The gas is used in a 15 kW electric generating set; 5 kWhr per day is used for the system pumps, and net power production is 58 kWhr per day. Waste heat from the water-cooled engine is used to heat the digester, the piggery, and part of the farmhouse.

Large biogas plants have been built on a number of large pig farms in Italy, due partly to governmental subsidies available from a program to control water pollution. A survey of 64 biogas plants in Italy indicated that 38 are on pig farms; 26 of these are single-stage digesters with an average volume of about 750 m^3. Nine other plants on pig farms are two-stage systems which include an unmixed and unheated second stage; the average total volume of these large systems is over 1700 m^3. All but a few of the Italian biogas plants are built of steel or concrete and are insulated, mixed, and heated. Most of the units have heat exchangers outside the digester or inside the digester walls, while only a few have heating coils inside the digester. The average retention time for single-stage plants using pig manure is 17 days. The average gas production is near the European average (1.077 m^3/m^3/day). Half of the Italian plants use some or all of the gas to produce electricity and hot water in "cogeneration" units, typically the 15 kW "Totem" units made by Fiat. Sixty percent of the Italian plants use some or all of the biogas as a boiler fuel.

A 205 m^3 fixed-top digester system began operation early in 1983 at a 300 sow farrow-to-finish pig farm at Stratford, Ontario, Canada. The system was designed by Canviro Consultants, Ltd. of Kitchener, Ontario. About 14 m^3/day of swine wastes are pumped from pits beneath slatted-floor barns. The digester is completely below ground, in order to reduce heat losses through the tank walls and roof. The contents of the digester are heated by waste heat from the biogas-fueled 90 kW engine-generator set. The system is producing an average of 525 m^3 of gas per day or 2.5 m^3/m^3/day.

Only a few larger fixed-top digesters have been built in developing countries. In 1981 the International Association for Rural Development built a 60 m^3 European-type fixed top digester at a village near Kigali in Rwanda. The gas is used in an automobile engine which drives a 12.5 KVA generator; waste heat from the engine's radiator is used to heat the digester. The volume of this digester is only about one-sixth of that of the unheated digesters described on pages 11 and 12 which provide fuel for generating sets of comparable size in China and Ivory Coast.

An important demonstration of a quite different type of heated fixed-top digester is being conducted by the National Research Council of Egypt. Technical assistance is provided by the U.S. National Academy of Sciences; financial support is provided by Volunteers in Technical Assistance with funds supplied by the U.S. Agency for International Development. The unit was designed to provide space heating for a two-story chicken house at Shubra Kass, center of an area with 600 poultry farms.

The 50 m^3 digester, shown on the opposite page, is a "tunnel" model with a concrete base and an arched roof of bricks and mortar. Initial loading is through two manholes which are then sealed with precast concrete plugs; subsequent feeding is through a wide (30 cm diameter) cement inlet pipe. The interior of the digester is plastered with several coats of mortar, using techniques developed for the digesters usually built in China. However, the digester does not have to retain high pressure as in the Chinese models. The system includes a separate floating steel gasholder built to Indian specifications; gas pressure is increased by adding concrete blocks on top of the gasholder. Mechanical mixing with the four stirring rods shown in the sketch did not prove effective, and a gas recirculation system is being added to provide a more efficient means of mixing and scum breaking.

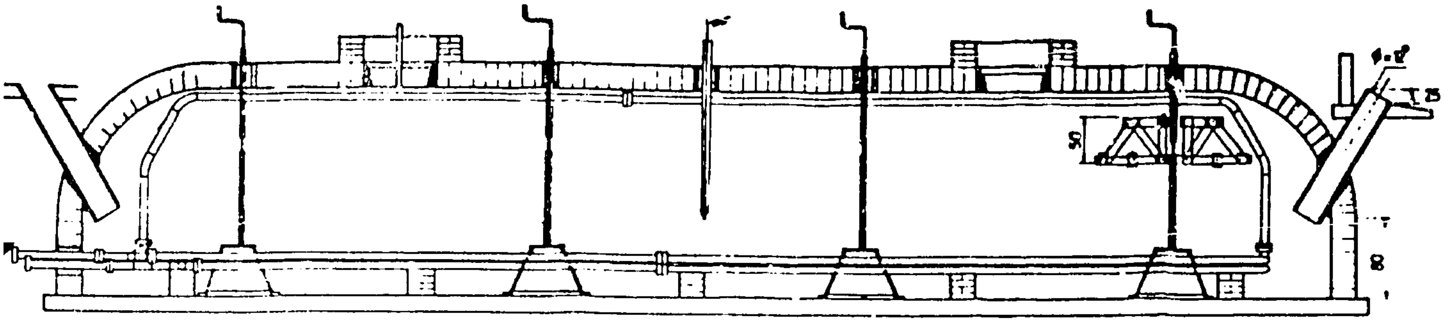
In the Egyptian system digester heating is provided by circulating hot water through five tubes which are mounted slightly above the concrete floor of the digester. The circulating pump is controlled by a thermostat to maintain digester temperature at 35°C. In the initial plant the water was to have been heated by burning 10 to 15 m^3 of biogas per day in a gas water heater. Subsequently, a 4 KVA Honda gasoline engine-generator was modified to operate on biogas; the power will be used for illumination in the poultry house and for other electrical equipment at the site. Water is heated in a specially-designed heat exchanger around the engine's exhaust; the device proved to be very effective and the hot water is now used for slurry mixing and digester heating. A solar panel is being added to heat the slurry water so that the engine heat can be used primarily to heat the digester. Heat loss from the digester was reduced by enclosing the digester in a greenhouse consisting of a framework of iron, and wire mesh which is covered by a polyethylene sheet.

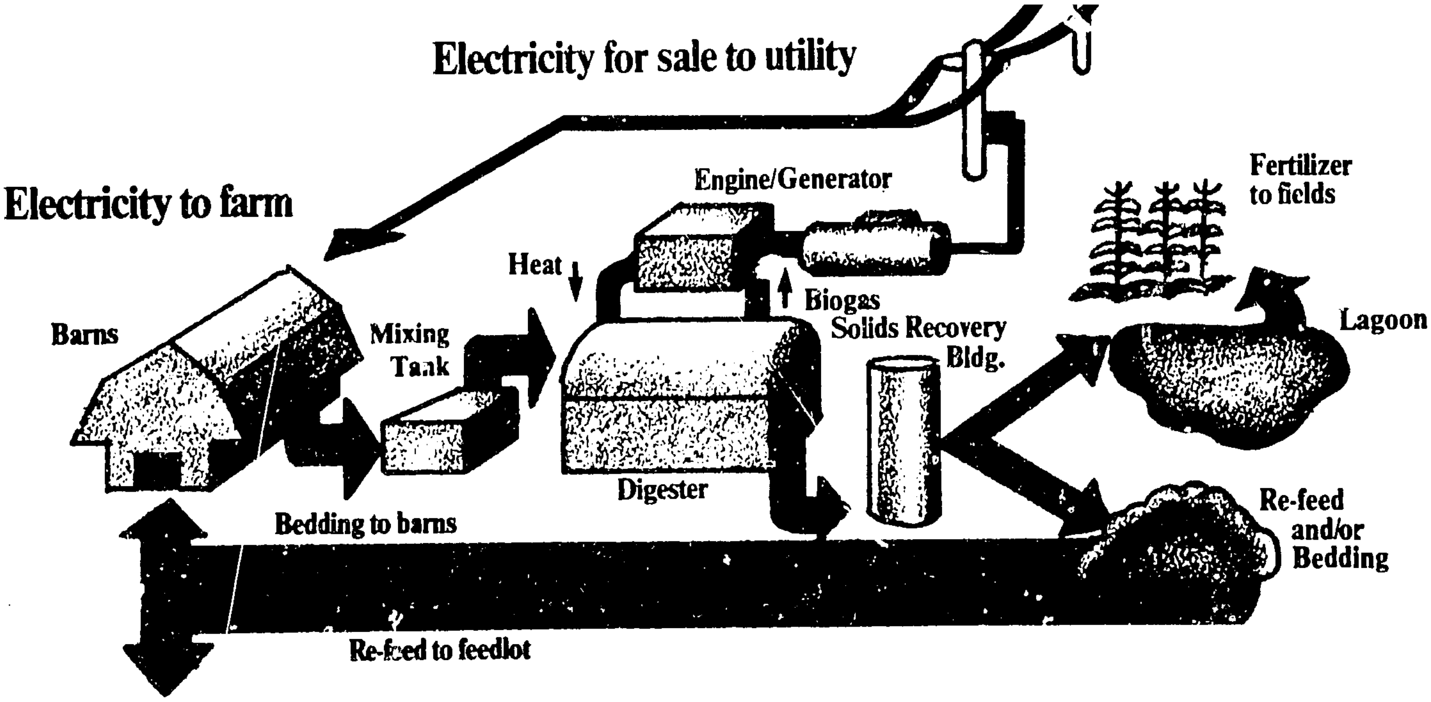
Prior to startup the NRC estimated that the system would produce at least 50 m^3 of gas per day or more than 1.0 m^3/m^3/day. Modifications described above have precluded a full assessment of system performance, but early results indicate that the anticipated gas production level of 1.0 to 1.2 m^3/m^3/day was a reasonable estimate.

2. Flexible-top Digestion Systems

In contrast to the fixed-top completely mixed digesters which are widely used in Europe, the most common farm biogas system in the U.S. is an unmixed plug-flow system using an inflatable plastic gasholder. This type of system begins with an open "swimming pool" or trough; the chamber is usually built of concrete, although some are only earth pits lined with plastic. The chamber is covered with an inflatable gasholder made of plastic or other flexible material. In the typical plant the biogas is used to generate electric power for use on the farm and/or for sale to electric utility companies. At least 25 of these biogas-to-power systems have been or are being installed on farms in the U.S. Information on some of these systems was provided in the Bioenergy Systems Report on "Bioenergy for Agriculture" published in March 1983.

Manure from about 600 cows is converted to biogas in a 680 m^3 flexible top digester at the Baum Dairy in Springport, Michigan. The, digester is heated with waste heat from the system's initial engine-generator set. About two m^3 of gas is produced from the manure of each cow; total gas production is about 1200 m^3 or about 1.76 m^3/m^3/day. To utilize the full supply of biogas, a 90 kW generating set was added along with the original 65 kW unit; all of the power is used on the large farm. The liquid and solid fractions of the digester effluent are





separated in a centrifuge. About 900 tons a year of dewatered digester solids with a moisture content of 70 to 75% are used as bedding material for the dairy cows. The liquid fraction of the effluent is pumped to a lagoon and ultimately used to fertilize the farm's corn (maize) fields. The initial system cost $225,000 in 1981 including digester, 65 kW generator, centrifuge, holding pits, and buildings. The cost per m^3 was about $330. Even before the second generator was added the system was producing power worth $30,000 a year and bedding worth $36,000 as well as substantial savings in waste disposal costs. The payback period for the system was about three years. The system, shown in the sketch above, was built by Energy Cycle division of the Butler Company of Kansas City, Missouri.

Many factors influence the economics of biogas-to-power systems. The digester is often only about 40% of the total system cost, while 30 to 50% is for the engine-generator. One firm indicates that the total installed costs of such systems range from $1800 to $2400 per kW, with the lower costs for larger systems. In the U.S. the economics have been most favorable on large farms with substantial manure disposal problems and large expenditures for electric power, livestock bedding, and fertilizer.

There is very little experience with smaller biogas power systems. However, there are indications that flexible-top digesters could be utilized in the design of biogas power systems suitable for developing countries. A recent biogas study for the World Bank noted that there may be a considerable potential for the use of such digesters in developing countries due to lower capital costs and relatively high gas production rates. A biogas-to-power system with a flexible-top digester built for the German Agency for Technical Cooperation in the Ivory Coast was described on pp. 19-20 of the Report on "Bioenergy for Agriculture" published in March 1983.

A unique low-cost variation of the flexible-top digester has been developed at Royal Farms in Tulare, California. Manure from 1,000 sows and 6,000 to 7,000 young pigs is flushed daily into a three-stage anaerobic lagoon. In 1982, the California Energy Commission funded a 1,070 m^2 hypalon plastic cover, supported by floats and polypropylene ropes, over a part of the large primary lagoon. Gas accumulates under the cover and is collected through perforated pipes; natural pressure is boosted by a 1/2 HP suction blower. Daily gas production has ranged from 710 m^3 in winter to 1,025 m^3 in summer.

The gas is used in a 13.4 liter, 1200 RPM Waukesha gas engine. A pressure-activated device throttles the engine to match the availability of biogas, eliminating requirements for biogas storage and for close supervision of the unit. The engine drives a 70 kW induction generator which produces power at exactly the same frequency and voltage as the power grid. This type of generator cannot operate when the power from the grid is interrupted; however, since expensive switch gear is not required, an induction generator is the least expensive way of generating power which is to be sold to the grid. The power produced at Royal Farms is sold to the regional electric utility at the "avoided cost" rate specified by federal legislation. Initial operation indicated that the system would produce power worth $36,000 a year. The system cost $89,000 and the payback period was estimated at 2.9 years. The power unit was provided by Perennial Energy Inc. of Dora, Missouri.

3. Plastic Bag Digestion Systems

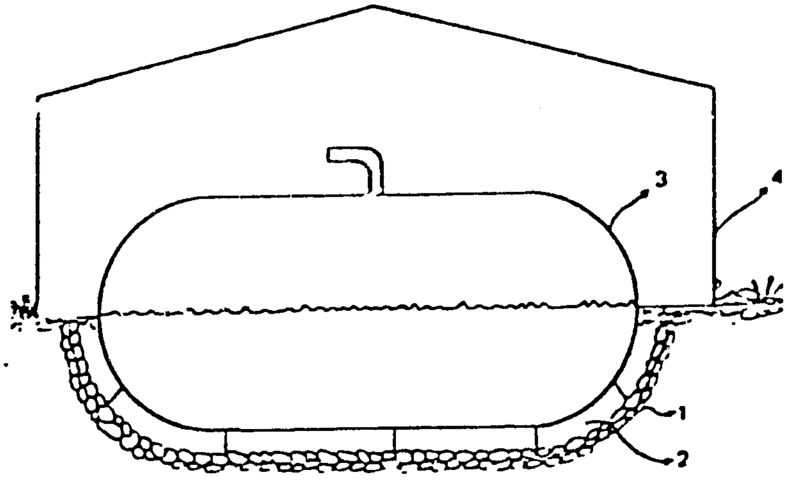
A plastic bag has been used as both digester and gasholder in family biogas plants and in larger farm systems. The most widely used bags are made in Taiwan of a Red Mud Plastic (RMP) material which contains wastes from aluminum production; these metal oxides provide resistance to ultra violet light which causes deterioration in many other plastic materials. The RMP digesters are shaped like a sausage; the lower half rests in an earthen pit shaped to its contours, while the upper half serves as the gasholder. Since the opaque plastic allows solar heat to enter the digester, temperatures are considerably higher than in unheated masonry digesters. Gas production rates have reached .6 to .7 m^3 per m^3 of liquid volume of the plastic digesters per day in China and Korea, and reports from the developers of the RMP digesters suggest even higher rates.

RMP plastic digesters are used on many pig farms in Taiwan. Three to four parts of water are added for each part of manure to reduce the concentration of ammonia nitrogen to a level which is not toxic to methane-forming bacteria. The digesters are sized to provide 0.5 m^3 of total capacity (including 3 m^3 for the digestion chamber and .2 m^3 for gas storage) for each hog. The retention time is between 12 and 15 days, which is a much shorter period than is needed for other unheated digesters. An average of .3 m^3 of biogas is produced daily for each 90 kg hog.

The Taiwan Livestock Research Institute tested a RMP digester on a farm with 200 sows and 1,000 other pigs. The gas was used in a 50 kW engine driving a generator rated at 25 kW. Maximum power output with biogas was 24 kW. Biogas consumption was 22.5 m^3/hr or .93 m^3/kWhr. In summer the biogas system replaced three-fifths of the energy used on the farm for heating, pumping, irrigation, and other purposes; in winter, the unit provided one-fifth of the farm's energy requirements.

Use of the bag digesters in the People's Republic of China was delayed by the poor durability of the plastics initially used and by the low thermal efficiency of the low pressure burners which must be used with these units. However, both problems have reportedly been solved, and a national plan for the expanded use of bag digesters was drawn up in 1982.

The Costa Rican Institute of Technology (ITCR) has experimented extensively with plastic bag digesters, and the bags are now manufactured in Costa Rica. A cross section sketch, from an ITCR manual in Spanish on the construction and operation of these units, is shown on the next page. The excavation is lined with a rock bed (1) which provides the necessary firm base for the bag and facilitates drainage of rain water. The rock bed is usually covered with styrofoam sheets (2) to insulate the digester from the cooler rocks and soil. The bag (3) is about twice as wide as it is high; the length is three to four times its width. A bag with a total capacity of 15 m^3 (about half of which is liquid capacity) is 7.6 m long, 2.06 m wide, and 1.10 m high. The bag is surrounded by a plastic greenhouse which protects the bag from ultra-violet radiation, provides



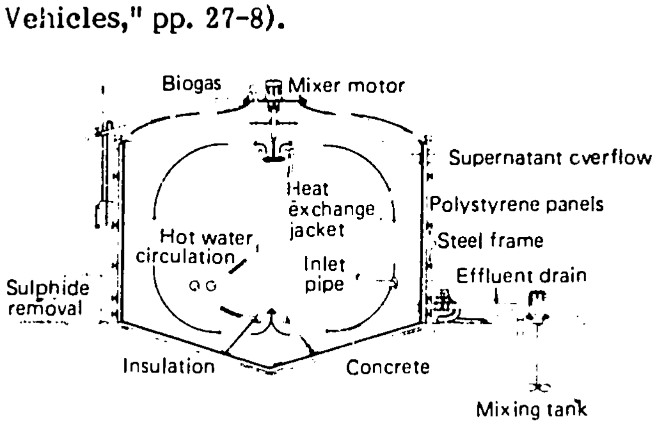
additional insulation, and serves as a passive solar collector. Gas production averages about .66 m^3 per m^3 of liquid capacity per day which is at least double that of most unheated masonry digesters.

Agricultural engineers at the University of Hawaii produced 1.5 m^3 of gas per m^3 of digester per day in a 20 m^3 RMP plastic digester using sludge recycling. The digester effluent flows to a settling basin, and the heavier sludge is recycled back to the digester.

The International Association for Rural Development provided a heating system for the plastic digester installed at a poultry farm near Marche in Belgium late in 1980. The lower portion of the plastic bag, which is below ground level, has a liquid capacity of 20 m^3. The upper portion of the bag holds 20 m^3 of biogas; it is covered with an insulated roof. The unmixed plug-flow unit uses dried poultry manure, diluted to 6% total solids, with a retention time of 40 days. The digester is heated to 35°C by burning about 6 m^3 of biogas per day to heat water which circulates through a coil at the bottom of the digester. Total gas production averages 20 m^3 per day or about 1.0 m^3/m^3/day. The net gas prodution (14 m^3/day) is used to heat the hen houses and for space heating and cooking in the farm house.

The Department of Poultry Science of North Carolina State Univeristy at Raleigh used manure from 4,000 caged laying hens in a Red Mud Plastic digester from Taiwan with an 8 m^3 liquid volume The heavily insulated and roofed unit was heated to around 50°C by burning some of the biogas and was operated as a thermophilic digester utilizing a separate group of bacteria which thrive at such temperatures (see page 19). After two years the high temperatures caused the plastic in the primary digester to blister, although there was no significant deterioration in the RMP plastic of another bag used mainly as an effluent holding tank at considerably lower temperatures. The system operated with a retention time of only four days; the gross biogas production was up to 4.0 m^3 per m^3 of liquid volume per day, which is much higher than any other farm digester described in this Report. Due to the high energy input for digester heating and slurry mixing, the net energy ouptput was only about half the gross energy in the biogas but nonetheless exceeded that of digesters operating at optimum temperatures (around 35°C) for mesophilic digestion.

A quite different type of bag digester is manufactured by Mangorei Industries Ltd. of New Plymouth, New Zealand. The digester tank consists of a butyl rubber bag surrounded by insulating panels held in place by a steel frame. Mixing and heating are provided by a propellor driven by an electric motor which sucks the slurry through a tube surrounded by a water jacket; hot water, usually heated in a biogas fired boiler, is pumped through the jacket. A cross-section of the digester unit is below. At an 18,000 bird poultry farm at Waikaouaiti, New Zealand, a 55 m^3 Mangorei Industries digester produces 68 m^3 of biogas per day or about 1.2 m^3/m^3/day. Electricity, which is relatively cheap in New Zealand, heats the water for digester heating; all the biogas is used in vehicles, replacing very expensive motor fuels (see "Biogas for Vehicles," pp. 27-8).



PART THREE: BIOGAS FROM AGROINDUSTRIAL RESIDUES

The use of anaerobic digestion for the treatment of agroindustrial residues and wastewaters has been spurred by anti-pollution regulations as well as by the search for low-cost sources of industrial energy. In many plants the reduction of the pollution potential of the wastes, measured in terms of Biological Oxygen Demand (BOD) or Chemical Oxygen Demand (COD), is an even higher priority than the production of energy.

A survey in 1983 indicated that 23 types of agroindustrial wastes are treated in digesters in processing plants in Europe; the combined volume of these agroindustrial digesters is 174,000 m^3. There are digesters in 18 sugar beet refineries, 13 distilleries, 6 potato processing and starch plants, 3 pectin plants, and several slaughterhouses. Only those at the sugar refineries and slaughterhouses use solid wastes; all of the others process agroindustrial wastewaters.

There is some experience with the treatment of agroindustrial residues in conventional completely-mixed digesters. The Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia tested various fruit processing wastes in a 23 m^3 pilot digester which is completely mixed through biogas recirculation. However, most agroindustrial firms have been primarily interested in digesters which can process high volumes of diluted feedstocks using relatively short retention times. This has required either digestion at higher thermopilic temperatures or the use of one of the newer types of high-rate digesters.

1. Thermophilic Digestion

In most digesters biogas is produced by the action of a group of bacteria known as mesophilic bacteria; the optimum temperature for mesophilic digestion is 35°C. However, biogas can also be produced by another group of bacteria which thrive at temperatures around 50°C. Advantages of this thermophilic digestion include much shorter retention times, increased digestion efficiency, and increased destruction of pathogens. Disadvantages include greater sensitivity to temperature variations, the need for better mixing and more continuous feeding, and the additional energy needed for digester heating. However, some agroindustrial wastes leave the processing plant at temperatures higher than 50°C.

Biogas from thermophilic digestion of stillage is replacing some of the wood fuel in the boilers of the Phuket Distillery Company's plant in Thailand. Molasses alcohol slops or stillage contains BOD of up to 30,000 mg/l and is further concentrated in a sump to a BOD level of 50,000 mg/l. The stillage is cooled to around 55°C and sodium hydroxide is added to reduce acidity. The digester apparently has a volume of about 500 m^3; the flow rate is up to 60 m^3/day. The biogas is recirculated through diffuser manifolds near the bottom of the tank to maintain adequate mixing in the digester. Effluent leaves the digester with a BOD level of 12,000 mg/l. It flows to a settling tank, and some of the sludge from that tank is recycled to the digester. The effluent is then aerated for five hours in an activated sludge unit; some of the sludge from this unit is also recycled to the digester. The system produces nearly 1,000 m^3 of biogas per day or about 2.0 m^3/m^3/day. The gas is used as a boiler fuel replacing about 20% of the wood used by the distillery.

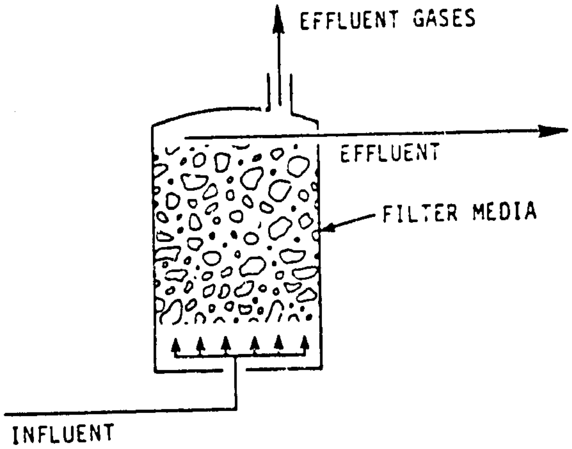
Thermophilic digestion is also being used to treat some of the 3.75 million m^3 of effluent from Malaysia's 185 palm oil mills. This wastewater has a BOD level which is 100 times that of domestic sewage and is a major contributor to environmental pollution in Malaysia. When treatment of the effluent became mandatory under Malaysian law in 1978, most mills began to use deep anaerobic ponds. Several mills developed tank digestion systems for conventional mesophilic digestion of the effluent. Liquor from the anaerobic ponds is mixed in equal or somewhat larger fractions with raw mill effluent in an acidification pond, where it is retained for one day. The mixture is then pumped to the tank digester; the retention time for these mesophilic digesters is usually about 20 days. To speed up digestion a pilot plant for the thermophilic digestion of palm oil mill effluent has been operated in Mayalsia for two years; digestion at 50°C permits a retention time of only 10 days. About 1.0 m^3 of biogas is produced for each kilogram of volatile solids removed from the effluent. Biogas is used in large generating sets to produce abut 500 KVA of electric power; about 1.8 kWhr is generated with each m^3 of biogas

2. Anaerobic Contact Reactors

This downflow process, developed in the 1950's, uses a completely mixed reactor. The feed enters near the top and is drawn off at the bottom. The liquid flows to a settling tank where the sludge containing methane-forming microorganisms settles out and is then returned to the digester. Anaerobic contact digesters are used in at least nine agroindustrial plants in Europe. There have been some problems with these digesters related to the unpredictable and slow settling of the microorganisms from the digester liquid and the need for high sludge recycling rates.

3. Anaerobic Filter Reactors

This type of digester, shown above, was developed in the 1950's to use relatively dilute and soluble wastewaters with low levels of suspended solids. It consists primarily of a column or chamber filled with a packing medium; the methane-forming bacteria form a film on the large surface of the packing medium and are not carried out of the digester with the effluent. For this reason these digesters are also known as "fixed film" or "retained film" digesters. The liquid enters at the bottom and flows up through the packing medium; as the organisms in the liquid pass over the bacterial film, they are converted to biogas. Due to the high concentration of bacteria, the gas production rates in these digesters are much higher than in conventional digesters. Gas rates of up to 5 m^3/m^3 of digester/day have been reported.



A great variety of non-biodegradable materials have been used as packing media for anaerobic filter reactors including various types of stone, several clay and ceramic materials, plastic shapes, coral, mussel shells, reeds, and bamboo rings. The most desirable characteristics of the media are a large surface area and a porous surface to which the microbes are easily attached.

Advantages of the anaerobic filter systems compared to conventional digesters include their ability to handle diluted wastewaters, higher loading rates, shorter retention times, smaller , tankage requirements, lower energy requirements, and the potential for rapid restart after a prolonged shutdown period. The principal limitation on these digesters is their inability to handle hard-to-digest suspended solids, which accumulate in the packing medium and interfere with digestion.

In 1982 a sugar refinery in northern Italy installed two anaerobic filters using a stone packing medium with a combined volume of 2,700 m^3. The system operates with a loading of 15 to 20 kg BOD/m^3/day and a one day retention time; BOD and COD removal efficiencies ranged from 70 to 80%. The anaerobic filter design was chosen because of its proven ability to restart rapidly at the opening of the season for sugar beet harvesting, after the plant had been shut down for seven months of the year. Several anaerobic filter systems are used for the treatment of industrial, chemical, and brewery wastes in the U.S.

The systems usually have COD loading rates which range from 8 to 16 kg/m^3/day and retention times ranging from 5 hours to 12 days.

A very large anaerobic filter system has been installed by the Bacardi Corporation at the world's largest rum distillery near San Juan, Puerto Rico. The company faced a serious problem of meeting tightened governmental controls on the disposal of stillage from the molasses-based plant. After successful tests with two laboratory-scale anaerobic filters and three pilot-scale units, Bacardi built a full scale system which includes a 3.5 million gallon (13,247 m^3) digester. The tank is 120' (36 m) in diameter and 42' (13 m) high. It is filled with 350,000 ft^3 (9912 m^3) of plastic packing media consisting of alternating flat and corrugated sheets of vinyl plastic. The media are made in 2' x 2' x 4' bales rising to a height of 30' (9 m) within the tank. The total surface area provided for the immobilized microbes is approximately 300 acres (121 ha). The plastic media are submerged in stillage which flows in at the top; eight 1.5 HP pumps draw the stillage from eight ports at the bottom of the tank and recirculate it back to the top of the tank.

By December 1982 the digester was receiving more than 400,000 gallons (1514 m^3) of stillage per day and producing over two million ft^3 (56,640 m^3) of biogas per day. The unit was producing about 4.2 m^3 of gas per m^3 of digester per day. Retention times range from eight to ten days. Full operation was resumed quickly after three-week plant shutdowns in mid-summer and again in mid-fall. The system removed up to 92% of the BOD and 75% of the COD in the stillage. The total system includes a large stillage holding tank, cooling tower, heat exchangers, and pumping system; it cost over $8 million. The biogas is used as a boiler fuel in the distillery.

A methane generation system based on the Bacardi system is included in an expansion program at the Asian Alcohol Corporation's large distillery at Bacolod City in the Philippines. The system will produce 20 to 30% of the energy used in the plant in the initial phase and up to 40% of the plant's energy in the second phase of the expansion.

Very high gas production rates were achieved in experiments with the digestion of stillage from the distillation of rice at the Chinese Academy of Science's Institute of Energy Conversion at Guangzhou. The partially packed reacter was a combination between an anaerobic filter and an upflow anaerobic sludge blanket (UASB) reactor (see pp. 22-23). The reactor chamber contained three trays with 10 to 40 cm layers of quartz pebbles, crushed stone, or cinders with 3 to 5 cm diameters. The two spaces between the filter trays served as a sludge blanket, with less flushing out of bacteria than in other UASB reactors. The partial packing approach also helped to reduce clogging, which was not a problem during the experiments. To avoid the use of expensive alkalines to improve the pH, the raw stillage was mixed with recycled digester effluent in the ratio of 1 part raw stillage to 2 or 3 parts effluent. Gas production rates of up to 10 liters per liter of digester volume per day were achieved with stillage from the distillation of rice. The rates were 4.79 liters/liter/day for wastewaters from the processing of sisal hemp and 2.5 liters/liter/day for rubber processing wastewaters. This partly-filled anaerobic filter (PFAF) system has been used at a slaughterhouse and a distillery in China.

The Institute of Gas Technology in Chicago operated a two-phase system to digest low-pH (2.3) and high COD (12,000 to 45,000 mg/l) wastewaters from the soft drink bottling industry. A continuously stirred tank reactor was used as the initial acid-phase reactor; a packed bed anaerobic filter was used as the second phase. The system could be operated at 2.5 times the loading rate and one-half the retention time of a single-stage digester, yet with about the same biogas yield and a higher COD reduction efficiency.

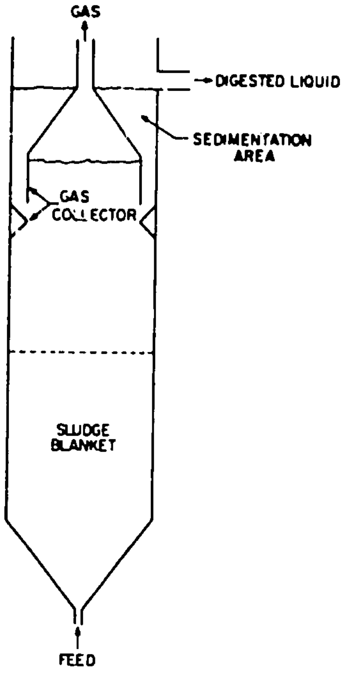
Experiments at the University College in Galway, Ireland, have demonstrated that, by using a two-phase system, it is possible to digest crop residues which were previously considered unsuitable for anaerobic filters. The digestion of crop residues in conventional digesters has been limited by the slowness of the initial hydrolysis of the cellulose and other biopolymers and the resulting very long retention times, as well as by various pumping and handling problems. However, the Galway researchers have developed a simple two-phase system which consists of a batch hydrolysis reactor and a second-stage anaerobic filter. The batch reactor is initially fed with straw or green crop residues, digested pig slurry, and a 10% innoculum from a previous batch. Excessive concentrations of volatile acids in the first-stage reactor were prevented by the periodic replacement of about 40% of the volume of the reactor with effluent from the second-stage reactor. The displaced liquor is rapidly converted into biogas in the limestone-packed anaerobic filter of the second-stage reactor; it is operated with a retention time of only three days, but gas production compares favorably to that in conventional single-stage digesters with much lower loading rates and longer retention times.

The Central American Research Institute for Industry (ICAITI) in Guatemala has developed a two-phase digestion system including an anaerobic filter which produces large quantities of biogas from coffee pulp juice. Coffee pulp, the mesocarp and peel of the coffee berry, represents 40% by weight of the fresh berry; disposal of the pulp is a serious problem at coffee processing plants. ICAITI experiments in 1981 indicated that the anaerobic digestion of the raw pulp would be an uneconomic means of providing fuel for coffee drying due to the long retention times. Moreover, if some of the juice is removed, the residual pulp can be burned directly in coffee dryers.

In 1982 and 1983 ICAITI developed a coffee drying system using biogas from coffee pulp juice, the liquid which is squeezed out of the wet pulp. The system was developed under a grant from the U.S. Agency for International Development. The system begins with the production of a "bagasse-like" solid fuel from the wet coffee pulp, using a low-cost screw press developed by ICAITI. The coffee pulp juice goes to a two-phase system which includes digestion in a column packed with polyurethane sponge. In laboratory tests the sponge-packed methanogenic phase produced from 1.87 to 3.18 m^3 of gas per m^3 of digester per day. In the commercial unit the biogas would be burned in a coffee dryer along with dried coffee pulp; previously the dewatered pulp from the screw press would be dried in a silo dryer using stack gas from the coffee dryer. ICAITI has built a mobile 1 m^3 pilot digester using the sponge-packing; it is being tested at a coffee processing plant near Guatemala City.

3. Upflow Anaerobic Sludge Blanket Reactor

The upflow anaerobic sludge blanket (UASB) process, shown below, was developed in The Netherlands; it is similar to the anaerobic filter in that it involves a high concentration of immobilized bacteria within the reactor. However, the UASB reactors contain no packing medium. The methane-forming bacteria are concentrated in the dense granules of the sludge blanket which covers the lower part of the reactor. The feed liquid enters at the bottom; the biogas is formed as the liquid flows up through the sludge blanket. The upward movement of the gas bubbles keeps the sludge fully mixed. The bacteria are



retained in the reactor for very long periods through the operation of gas collection devices resembling inverted funnels; they allow the gas to escape but encourage the settling of the suspended solids which contain the bacteria. Very high gas production rates (up to 10 m^3/m^3/day) have been reported with UASB processes. Ten full-scale UASB plants are in operation in Europe using wastewaters from sugar beet processing and other dilute wastes containing mainly soluble carbohydrates. Seven other plants in Europe use a process developed by the French sugar industry research institute (IRIS) which involves both a sludge bed and an anaerobic contact digester.

The National Research Council of Italy tested olive mill wastewaters in a 5 m^3 pilot-scale USAB digester. Start-up problems were minimized by diluting the waste to avoid excessive concentrations of volatile acids and by improving the C/N ratio through the addition of urea. The NRC concluded that the USAB process was a promising solution to the problem of olive mill wastewaters, which contribute very heavy pollution loads.

Chemical engineers at the University of Sydney in Australia demonstrated that sucrose-based stillages from cane juice, sugar beet, and sweet sorgum can be rapidly and efficiently digested in UASB reactors. Effluent was recycled to reduce acidity levels. Loading rates of 25 to 35 kg COD/m^3/day were reached; treatment efficiencies were greater than 95% for soluble COD.

A sludge blanket reactor is included in a two-phase process for the production of boiler fuel from sweet potato canning wastes which was developed at Louisiana State University at Baton Rouge. The process was tested in experiments in the laboratory and in a pilot plant using a 10,000 gallon rail tank car. A demonstration plant designed to use 80 tons per day of alkaline sweet potato peels has been built at a cannery in Louisiana. The peels will be conveyed from the cannery to a grinder and then discharged into a 500,000 gallon (1892 m^3) acid pond. Separation of the acid-formation and methane-generation steps is thought to allow optimization of the types of bacteria, concentration, pH levels, and other conditions for each step. Semi-processed wastes from a previous day's cannery operations will be stored in the acid pond until boiler fuel is needed. Earlier experiments demonstrated that high rates of gas production could be achieved with these wastes in a separate methane reactor using a heavy anaerobic sludge blanket, without the extended start-up period usually required in other systems. Biogas production will thus match the cannery's intermittent operating schedule, eliminating the need for expensive facilities for the storage of feedstocks and/or biogas. When boiler fuel is needed, acids will be pumped from the acid pond into a 950,000 gallon (3595 m^3) methane pond under a heavy sludge blanket consisting of methane-forming bacteria. High gas production rates will begin soon after feeding; the gas will be captured by a flexible cover over the methane pond and will be pumped through a demister to two cannery boilers, replacing some of the natural gas now used by the cannery.

4. Downflow Fixed Film Reactors

Both the anaerobic filter and UASB reactors described in previous sections are upflow units. However, in the Downflow Stationary Fixed Film (DSFF) reactors developed by the National Research Council of Canada the liquid feed enters at the top and the effluent passes out at the bottom. These reactors use a biofilm formed on support materials arranged in vertical channels. These channels must be relatively large to avoid filling up with film and the total surface area is thus relatively small compared to other fixed film reactors. However, operation of the reactor in the downflow mode avoids the accumulation of suspended solids which is often a problem with upflow anaerobic filters. Gas production from the DSFF units in Canada has extended to 5.0 m^3/m^3/day in some cases. These reactors are not suitable for the treatment of very dilute wastewaters containing less than 200 mg COD per liter. Several DSFF systems have been built or planned in Canada.

PART FOUR: BIOGAS FROM HUMAN RESIDUES

1. Biogas From Sewage

Anaerobic digestion systems were used to produce heat energy and/or electric power in sewage treatment plants in many U.S. municipalities in the 1940's and 1950's, as well as in several other countries. However, most of these systems were abandoned in the 1960's due to the low cost of electric power from the grid. As a result of increased energy costs during the past decade, a number of cities have now turned back to sewage digestion to provide energy needed by treatment plants and other facilities. Biogas is being used in plants in several states to fuel engines and electrical generating sets. Biogas provides low pressure steam for a Chicago plant and boiler fuel for a steam power plant in Los Angeles. Waste heat from biogas-fueled engines helps heat a New York plant. New systems in two cities provide gas fuel for the operation of city vehicles (see p. 27). A British firm, Hamworthy Engineering, has built digester systems at eight sewage plants in England and Wales.

By 1985 about 170,000 m^3 of biogas from sewage will be used daily in a gas turbine for electricity generation at a Los Angeles Sewage Plant. Hot turbine exhaust gas will be used to generate steam for a steam turbine, and the total power output from the two turbines will be 15 MW.

Four types of digesters have been used in sewage plants in the U.S.: (1) The standard sludge digester has a single stage and is unmixed; only some of the units are heated. Retention times range from 30 to 60 days. (2) In a single-stage high-rate digester there is a homogenous active zone produced by complete mixing with continuous feeding and withdrawal. The digester is heated to between 30° and 35°C. Loading rates are considerably higher than in the standard-rate digesters and retention times range from 15 to 20 days. (3) A two-stage process is a combination of the mixed and unmixed systems described above. The initial stage is a completely mixed digester; the mixed liquor then flows to the second stage, which operates like an unmixed standard-rate digester. (4) The fourth option is an anaerobic contact digester. It is similar to the two-stage digester described above except that a portion of the digested sludge from the second stage is recycled to the first-stage digester to increase the rate of waste utilization.

About 600,000 ft^3 (16,992 m^3) of biogas is produced daily at a sewage treatment plant in New Delhi, India. About 50 km of pipe has been laid to bring the biogas to 5,000 families for use in cooking; 50 to 60 additional km will be laid to bring the total number of families served to 10,000. Before the distribution system was begun the biogas was used to produce 800 kW of electric power; the generating sets now provide a standby source of power for the sewage treatment plant. Similar biogas distribution systems are being considered for two other New Delhi sewage plants. Sewage-based biogas plants are included in India's national project for biogas development. One plant was recently commissioned at Padrauna in Uttar Pradesh, two more plants are under construction, and 18 additional plants have been proposed.

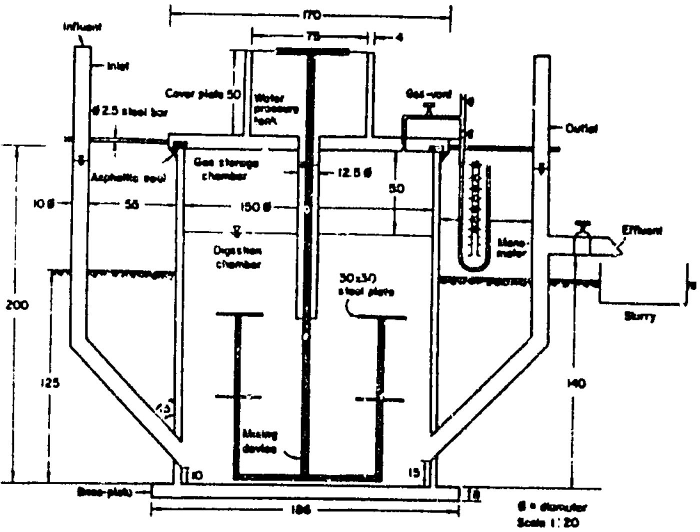
Several institutions in the U.S. are experimenting with the indirect production of biogas from sewage by first growing water hyacinths in sewage lagoons. Various fast-growing plants consume 85 to 95% of the pollution in the wastewater and are an excellent feedstock for biogas production. The Gas Research Institute is supporting an experimental unit to produce biogas from hyacinths grown in wastewater ponds at Walt Disney World in Florida. A pilot treatment plant using hyacinths has recently begun operation in San Diego, California. A study by Black & Veatch in Kansas City, Missouri, confirmed that the most difficult and expensive aspect of methane production in a hyacinth wastewater treatment system is the harvesting of the hyacinths.

A 270 m^3 rubber bag digester has been installed at Lae in Papua New Guinea to produce biogas from municipal sewage and slaughterhouse effluents.

2. Biogas From Night Soil

Human excreta, generally known as night soil, is used in biogas plants in several countries. Biogas could be generated in family-sized septic tanks, but studies have indicated that night soil from 40 to 60 people would be required to produce enough cooking gas for one family. A few large plants using only night soil have been built in China, India, and Nepal. The largest of these is the biogas power plant at Foshan in China's Guangdong Province. It uses about 170 tons a day of night soil in 28 connected 47 m^3 digesters; the plant has a total digester volume of 1316 m^3 and produces up to 720 m^3 of biogas daily. The gas is stored in two flexible plastic gasholders and used in two diesel generating sets to produce about 90 kW of electricity.

Night soil is more frequently used as a supplementary feedstock along with animal manures and/or plant materials. In China, where untreated human wastes have traditionally been spread on the fields as fertilizer, these wastes are now widely used in family biogas plants along with pig manure and plant materials. The privy, pig sty, and digester are grouped together on the family's individual plot; the pig and human wastes pass directly into the digester. An Indian biogas agency estimated in 1980 that night soil was being used along with cow dung in about 20,000 digesters in India or about one-fourth of the total. However, a more recent survey of biogas plants in the state of Gujurat indicated that 72% of the family digesters were connected to latrines. Night soil from community toilets is added to the cow dung in most of the community type biogas plants which are being built in India. The Carbon/Nitrogen ratio of night soil is too low for optimum digestion, but the C/N ratio can be improved by adding any type of high-carbon material.



A low-cost ferrocement digester has been developed by the Asian Institute of Technology in Bangkok for use with night soil mixed with rice straw and water hyacinths. The 3.5 m^3 digester, shown in the sketch above, resembles the Chinese digesters in operation if not in shape. Gas accumulates under the sealed lid of the digestion chamber; gas pressure forces slurry up through a central pipe into a concrete water pressure tank on the top of the digester. When gas is drawn out, pressure is reduced and the slurry flows back into the digester. A steel mixing device (shown in heavy lines on the sketch) extends from the top of the water pressure tank through a connecting pipe into the digester. The total cost of the 3.5 m^3 ferrocement unit was about US$215.

Four of these digesters were built alongside four 200 m^3 fish ponds. The digesters were fed with a mixture of night soil, rice straw, and water hyacinths in proportions which produced a C/N ratio of 25:1 in a slurry with about 10% solids. Retention time was 50 to 70 days. Biogas production ranged from 0.18 to 0.35 m^3 per kg of volatile solids added each day. About 90% of the COD (Chemical Oxygen Demand) in the influent was eliminated during digestion.

The effluent from these digesters was used to produce algae in the adjacent ponds as feed for fish (Tilapia nilotica). Organic loadings in the four ponds were 0, 25, 50, and 100 kg COD/ha/day; fish yields varied with the organic loading, from 0.7 tons per hectare per year for the control pond receiving no effluent to 3 tons/ha/year for the pond with the 100 kg loading. These experiments were supported by the International Development Research Center in Canada.

3. Biogas from Solid Wastes

In recent years substantial quantities of biogas have been obtained from landfills containing biodegradable urban solid wastes. Biogas is produced at 14 landfills in the U.S. and a number of sites are being developed; there are 36 disposal sites in Europe, as well as at several landfills in Canada and Brazil.

The composition and energy content of urban wastes varies considerably from country to country. One analysis of solid wastes in the U.S. indicated over 40% paper and cardboard, 30% other biodegradable materials, and 30% non-biodegradable materials. In many other countries most of the paper, glass, metal, and other resuseable materials are sorted out before the waste is landfilled; the remaining waste thus contains a low percentage of non-biodegradable material. Analysis of a Brazilian landfill indicated that only 23% of the waste was paper and cardboard but 62% was garbage and other organic material; only 15% was non-biodegradable. This comparison suggests that the energy content of existing landfills in developing countries may be even higher than those in developed countries.

Some landfills have produced biogas for more than 20 years. The rate of decomposition depends on the composition of the refuse, climatic conditions, soil types, moisture content, and the depth of fill. In dry climates the moisture content of the landifll may be inadequate for maximum gas production, but the moisture can be too high for optimum digestion in some moist climates.

Gas is recovered by drilling a series of wells to the full depth of the fill. The holes range from 12 to 36" (30 to 91 cm) in diameter. Perforated plastic or fiberglass pipes are installed in the center of each hole and the pipes are surrounded by gravel or other loose material through which the gas can pass. The area round the pipe is sealed with concrete at the surface. At the deeply-filled 120-acre Palos Verdes landfill near Los Angeles, the wells are 100 to 125' (30 to 38 m) deep. Each well draws about 320 ft^3 (9 m^3) or gas per minute.

At five of the larger landfill gas recovery plants in the U.S., the gas is treated to remove carbon dioxide and hydrogen sulphide; the resulting high-BTU gas is mostly methane. It is sold to gas utility companies for distribution to industrial and residential customers through their natural gas pipeline systems. From 14,000 to 18,000 m^3/day of landfill gas is scrubbed of carbon dioxide and added to the distribution system of Rio de Janeiro's gas company. The landfill system saves $1 million per year by reducing the use of naphtha (which is refined from imported crude oil) for the manufacture of town gas in the Brazilian city.

Seven of the U.S. landfill gas projects provide untreated biogas for use as boiler fuels in industrial plants including two oil refineries, a steel mill, a chemical plant, and a gypsum mill. One project fuels the heating system for a convention and recreation center. Gas from two landfills in Los Angeles is piped to a steam generating plant where it is used to generate 28 million kWhr per year.

A third option is to use the biogas in engine-generator sets for electric power generation. The city of Glendale, California, has installed a new system to use landfill gas to generate 1,600 kW of power. Biogas from landfill in Palo Alto, California, will soon provide 13 million kWhr of power annually for the city's sewage treatment plant.

Biogas can also be produced from urban wastes without landfilling. A plant to produce methane from these wastes has been under development since 1975 at Pompano Beach, Florida, under the sponsorship of the U.S. Department of Energy. Operation at full design capacity of 36 tons per day has been delayed by persistent problems with the feed preparation, digester mixing, and scum accumulation. Most of these problems have now been solved and tests at full design lading are planned. The Institute of Gas Technology in Chicago has developed a pilot process for the production of biogas from urban solid wastes mixed with sewage sludge.

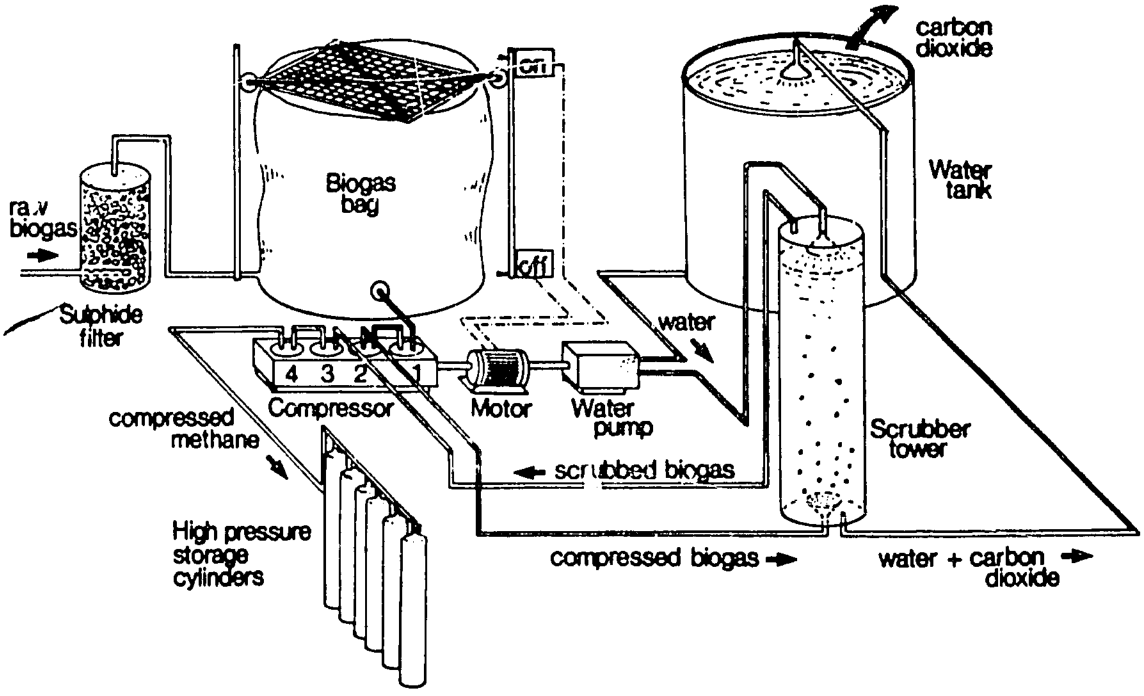
BIOGAS FOR VEHICLES

Biogas from sewage fueled a 5-ton garbage truck at the Dadar sewage treatment plant in Bombay, India, in the late 1930's. The truck ran 55 miles on four pressurized cylinders containing 1400 ft^3 (39 m^3) of unscrubbed biogas. About 144 ft^3 (4.38 m^3) of the gas equalled 1 gallon (3.78 liters) of gasoline (petrol). Biogas consumption was about 26 ft^3 (.74 m^3) per mile for this heavy truck.

In 1981 the Anglican Water Authority in England tested biogas as a fuel for petrol powered vans and diesel tank trucks at its sewage treatment plant at Colchester. Gas was treated to remove carbon dioxide (CO_2) and hydrogen sulphide (H_2S); the scrubbed biogas contained more than 95% methane. Vehicles were converted to the use of biogas with commercially available kits designed for use with liquified petroleum gas or compressed natural gas. The drivers of these and other biogas-fueled vehicles have reported that the major noticeable difference in vehicle operation with methane was a 5 to 15% loss in acceleration.

The city of Modesto, California, will soon operate more than 200 city vehicles on methane from sewage. The system was designed by Central Plants, Inc. of Commerce, California, and includes the firm's "Binax" process for gas scrubbing. Compressed biogas flows through a counter flow of water in a pressurized tower; the CO_2 and H_2S are dissolved, but the methane is not affected. The water is purified in a non-pressurized tower, which releases the unwanted gases to the atmosphere. Each day the new plant will produce up to 114,000 ft^3 (3,228 m^3) of methane or the equivalent of 1,140 gallons (4,314 liters) of gasoline. Each converted vehicle will carry two or more cylinders of compressed methane; each holds the equivalent of 3.5 gallons (13.2 liters) of gasoline. Another "Binax" scrubber will be used to remove CO_2 from sewage gas for use in 50 city vehicles at Hagerstown, Maryland.

Several large farms in New Zealand are producing methane for use in vehicles with a biogas scrubbing system, shown below, which was developed in New Zealand at the Invermay Agricultural Research Centre. The raw biogas flows from the digester through a filter which removes H_2S and then to a plastic biogas bag. When the bag is fully inflated, the frame at the top starts the pump and compressor. The gas is compressed in the first stage of a four-stage compressor and is pumped to the bottom of the scrubber tower. Water at an equal pressure is pumped to the top of the tower;



the CO_2 in the biogas dissolves easily in water under pressure, as in carbonated soft drinks, while the methane rises to the top of the tower. The water with dissolved CO_2 flows to an open tank where it loses pressure and the CO_2 is released to the atmosphere. The scrubbed biogas is now 95% pure methane. (See March 1983 Bioenergy Systems Report, pp. 16-17, on removal of hydrogen sulphide from biogas prior to use in engines.)

One of these biogas scrubbing systems is used at a 18,000-bird poultry farm at Waikouaiti, New Zealand. A 55 m^3 digester of the type shown on page 18 produces 68 m^3 of biogas per day, and two more digesters are being added. The expanded system will provide fuel for at least 30 vehicles. A similar 90 m^3 digester operated by a religious community at Cust, New Zealand, produces fuel equivalent to 43 gallons (164 liters) of gasoline per day using mixed animal wastes and fouled silage. The gas is used in 15 vehicles and saves the community about $30,000 a year in petrol costs.

Some of the biogas produced by a 2,000 m^3 digester at a liquor distillery in China is used to fuel three heavy trucks; this use of biogas saves 50 tons of fuel annually.

BIOENERGY USER NETWORK

The formation of the Bioenergy User Network (BUN) was formally announced in Bangkok on February 4 at the second meeting of the BUN organizing committee. The meeting was attended by committee members from Jamaica, Indonesia, Sudan, and Costa Rica as well as by representatives of the U.S. Agency for International Development and other donor agencies. A strategy was developed for expanding Network membership. During the formative period BUN activities will emphasize (a) creation of mechanisms to transfer bioenergy expertise among developing countries through a skills bank of member country specialists and (b) evaluation of bioenergy services and equipment including assessments of experience of member countries and identifying consultants, manufacturers, suppliers, donors, and potential investors. BUN will also sponsor regional courses and workshops and will suggest priorities for research on fuelwood species, direct combustion, charcoal manufacture, thermal gasification, anaerobic digestion, and engine systems and on social and cultural factors affecting these bioenergy systems. Inquiries concerning BUN membership and activities should be directed to: BUN, c/o Betsy Amin-Arsala, Suite 1440, 1616 North Fort Meyer Drive, Arlington, Virginia 22209 USA.

1984 BIOENERGY DIRECTORY

The 1984 International Bioenergy Directory and Handbook is now available from the Bioenergy Council of the U.S., 1625 Eye Street, N.W., Suite 825 A, Washington, DC 20006, USA. The 600 page publication was edited by Dr. Paul F. Bente, Jr., the Council's Executive Director. The directory provides descriptions of 627 bioenergy research and operational projects, about half of which are in the U.S.; the rest are carried out in 59 other countries including 31 developing countries. The volume covers biomass resources, microbial conversions (including both ethanol and biogas projects), thermal conversions, fuel tests, and related studies. New features of the 1984 volume include essays by leading experts on selected aspects of bioenergy technology, recommendations for a 100-volume reference library on bioenergy systems, and an easier-to-read printed format. The Directory and Handbook sells for $95 plus $15 for first class mailing overseas.

BIOENERGY CONFERENCES

Bioenergy '84 World Conference and Exhibition, Gothenburg, Sweden, June 18-21, 1984. Contact: Bioenergy '84, Swedish Trade Fair Foundation, P.O. Box 5222, S-402-24 Gothenburg, Sweden, or Bioenergy Council of the U.S, Suite 825 A, 1625 Eye Street, N.W., Washington, DC 20006, USA.

International Biogas Conference, Cairo, Egypt, November 17-24, 1984. Contact: Dr. M. M. El Halwagi, National Research Centre, 12 Al Tharir Street, Dokki, Cairo.

(See December 1983 B.S.R. for additional information on these conferences.)