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BIOMASS ENERGY CONVERSION AND UTILIZATION IN THE DEVELOPING COUNTRIES

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Preface

The Training in Alternative Energy Technologies (TAET) program at the University of Florida, ran for nearly five years--from late 1979 until June 1984. The training program was sponsored by the Office of Energy of the US Agency for International Development (USAID). The purpose of the TAET program was to train technical personnel from the developing countries in the theory and application of the renewable energy technologies: solar energy, hydropower, biomass energy, wind power, and geothermal energy. A total of 286 participants from 54 developing countries attended the nine training session that were organized by the University.

The TAET curriculum was designed to meet the following specific objectives:

1. To acquaint the participants with the alternative energy technologies.

2. To provide the participants with sufficient knowledge to assess the natural renewable energy resources of the participant's country and to determine the best possible technological options to utilize these resources so that the participant can provide input in establishing realistic national alternative energy programs for the participant's country.

3. To provide technically trained people with the knowledge to select among technological options and to identify their most appropriate applications.

The training program consisted of lectures, seminars, demonstrations, laboratory work, and field trips--activities designed to explain the theory, illustrate the practice, demonstrate the operation and maintenance of the alternative energy systems, and to provide detailed training for the program participants.

As part of that effort, a number of technical notebooks and laboratory manuals were written by the program faculty at the University of Florida. All of the written material and other documentation was collected and reorganized at the end of the training program in June 1984. This manual on biomass energy conversion and utilization in the developing countries makes available most of the material on biomass energy systems that was presented to the TAET participants during the course of the training program.

TABLE OF CONTENTS

Introduction

Approximately 7 percent of the world's energy is supplied by biomass energy--mostly from wood. While this fraction of primary energy supply may seem small, for about half the world's population--over 2 billion people--biomass energy is a vital fuel. For many developing countries, including most of the poorest ones, wood may comprise over 90 percent of the energy supply. And in the rural areas the dependency on wood as a fuel is even greater.

Wood is, of course, mankind's oldest fuel, and its principal use has remained unchanged over the millenia. Wood is used primarily for cooking food, and when wood becomes scarce, and therefore expensive, the poorest families in the developing countries--millions of people--are affected. When wood is scarce, nutrition is jeopardized as families economize by cooking less or by switching to inferior foods that require less cooking. When wood is scarce, the search for sticks and twigs can take women and children far afield, away from the village and domestic, agricultural, and school work.

Apart from wood, the other important biomass fuels are animal dung and crop residues. Together, these residues account for about 40 percent of biomass energy sources. Two countries, China and India, are the most dependent on dung as a source of energy, using 2 - 3 times more dung than fuelwood. Significant amounts of dung are also used in many other Asian countries; very little is burned in Africa and Latin America.

The utilization of biomass as a source of energy requires the use of a number of technologies. Often these technologies are rudimentary and inefficient--the open 3-stone fire is an example of a primitive stove with a low efficiency of energy conversion: only about 10 - 15 percent of the energy released as heat by the combustion of the fuelwood finds its way to the cookpot. The conversion of wood to charcoal is another technology that is often very inefficient when carried out in the traditional manner.

It is being increasingly recognized that there are better and more efficient ways of utilizing biomass as a source of energy. Wood can be gasified to produce a fuel gas capable of powering engines, pumpsets, and generators. Cookstoves can be made more efficient; charcoal can be produced from wood with little loss of material or energy. Animal dung can be digested in biogas plants to produce a fuel gas which can be used in engines and generators, or used for cooking food; the digester slurry retains the fertilizer value of the dung which would otherwise be lost if the dung were dried and burned. Liquid fuels can be produced from biomass and substituted directly for gasoline and diesel oil.

The first section of this manual presents the basic principles of anaerobic digestion, and shows how biogas plants are designed and constructed. This is followed by chapters on biomass gasification and the production of fuel alcohol.

Anaerobic Digestion

When plant and animal residues are held in a tank or pit in the absence of air, part of the biomass material will be biologically degraded and fermented by bacteria present in the mixture. One of the products of this process--called anaerobic digestion--is a gas, consisting mainly of methane, which can be used as a fuel. The gas, commonly known as biogas, can be used in the home for cooking, lighting, and heating. Produced in larger quantities, it can fuel spark-ignition engines or replace up to about 80 percent of the diesel fuel in a compression ignition engine.

The first recorded use of biogas gas was in 1895, when the town of Exeter, England, used the gas from a septic tank for street lighting. Not much later in Bombay, biogas from a waste disposal tank was used to power a number of small engines [1]. The purpose was not to generate a fuel gas, however; the stabilization of the wastes was often the objective. In 1911 one of the first large digesters was built in Birmingham, England. Only later was the gas utilized to generate electricity for use in sewage plants. In China, in the 1920's, the Chinese type of digester was developed. In 1937, two 46 m^3 digesters were constructed in Hebei Province which are still in operation today [2]. At about the same time, biogas research and development commenced in India.

There is now world-wide interest in this simple technology. China boasts about 7 million digesters; India has about 90,000 units in operation. There are thousands more in Korea, Taiwan and Nepal. Almost 50 developing countries have supported research and demonstration programs, and constructed small digesters in order to assess the potential of this promising technology.

The Digestion Process

In anaerobic digestion, organic wastes and other biomass materials are mixed with large populations of microorganisms under anaerobic conditions--air is excluded from the mixture. Under these conditions, mixed populations of bacteria develop which are capable of converting biomass materials to carbon dioxide and methane. Both gases bubble to the surface of the liquor where the gas mixture can be collected and used as fuel. As much as 80 - 90 percent of the degradable portion of the biomass material can be digested and converted to biogas.

Anaerobic digestion is a complex process and the microbiology of the operation is still not fully understood. The process can be represented as a two-step process, as indicated below

In the first stage, no methane is produced. The complex organic structure of the feedstock material is broken down by acid-forming bacteria into simple fatty acids: proprionic acid, acetic acid, and other monobasic aliphatic carboxylic acids. In the second stage, these organic acids are converted to carbon dioxide and methane by bacteria called methanogens. The methanogenic bacteria are obligate anaerobes, and even small amounts of dissolved oxygen will hinder this stage of the digestion process. For complete digestion of the soluble organic materials, several types of microorganisms are required. But the most important types grow slowly and their low rate of acid utilization and methane generation, even at optimal temperatures, make anaerobic digestion a relatively slow conversion technology.

Only part of the biomass feedstock is generally available for digestion. Inert material, such as ash, and lignocellulosic material cannot be digested by the microorganisms. The figure below indicates schematically the digestion process.

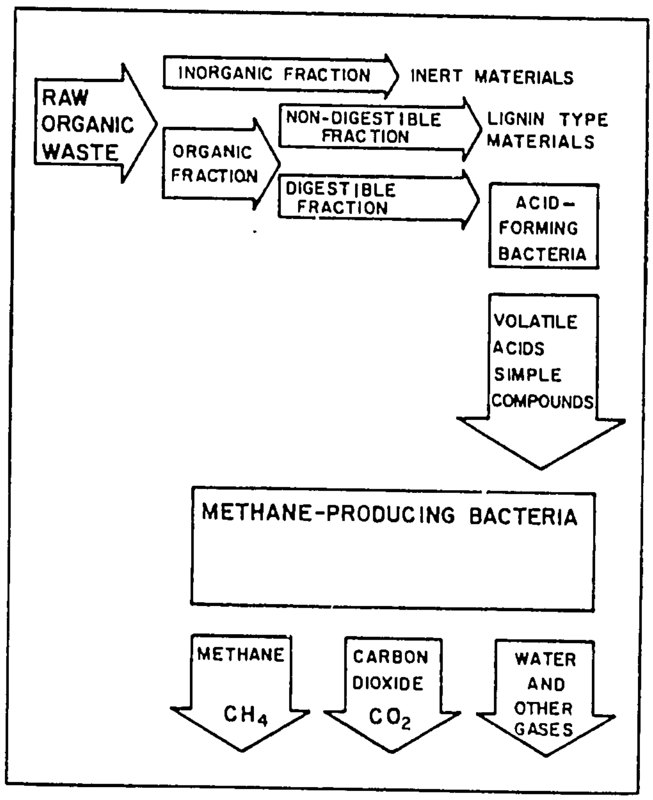


Figure 1. The Biological Breakdown of Organic Material in an Anaerobic Digester [3]

If the digester is operating well, the gas produced by the digestion process should be about two-thirds methane; the remainder being carbon dioxide. Both the composition of the gas, and the amount produced, are strongly influenced by a number of factors; these are discussed in the following sections.

Carbon-Nitrogen Ratio

The ratio of carbon to nitrogen (C/N) in the feedstock to the digester has been found to critically affect the operation of the digester and the composition of the gas. If the C/N ratio is too high, the digestion process is limited by the availability of nitrogen, and the gas produced consists mainly of carbon dioxide with some hydrogen, methane, and nitrogen. If the C/N ratio is too low, the digestion process is limited by the availability of carbon and the gas produced will consist mainly of carbon dioxide and nitrogen, with some methane and hydrogen; and ammonia may be produced in solution raising the pH to the point where the microorganisms are killed.

For optimal performance the C/N ratio should be somewhere between 20 or 30 to 1, a ratio that occurs naturally in cow dung. For materials that possess C/N ratios outside the optimal range, it is necessary to mix together feedstock materials so as to produce a final C/N ratio that falls within acceptable limits. For instance, in China, straw, grass, and weeds are mixed with manure from pigs and nightsoil to provide a balanced feedstock for small family digesters. Table 1 gives physical and chemical characteristics, including carbon-nitrogen ratios, for some common waste materials often used in digesters.

Table 1. Physiochemical Characteristics of Waste Material

Waste	Total Solids TS, %	Volatile Solids, VS T of TS	Carbon %	Nitrogen %	C/N
Cattle manure	16	77	35.8	1.8	19.9
Pig manure	25	80.7	38.3	2.8	13.7
Poultry manure	48	77.4	35.7	3.7	9.7
Carabao manure	15	80.5	37.0	1.6	23.1
Duck manure	53	23.6	21.9	0.8	27.4
Pugo manure	30	81.8	33.7	5.0	6.7
Slaughterhouse waste			14-20	7-10	2
Fish scraps				6.5-10	5.1
Nightsoil	15	90	47.7	7.1	6.7
Urine				15-18	0.8
Blood				10-14	3
Kitchen wastes	31	92	54.3	1.9	28.6
Corn stalks	86	92	43.9	1.2	56.6
Rice straw	89	79	35.7	0.7	51.0
Corn cobs	82	96	49.9	1.0	49.9
Peanut hulls	90	95.5	52.7	1.7	31.0
Fallen leaves			41.0	1.0	41.0
Weeds			14.0	0.54	27.0
Kwangkong	4	84	33.5	4.3	7.8
Water lily	5	77	33.0	2.9	11.4
Grass trimmings	15	87	39.2	2.5	15.7
Rotted sawdust			52.(	0.25	208
Raw sawdust			51.0	0.1	511
Paper				nil	

Adapted from Woods [15]

Temperature Dependency

The temperature maintained in the anaerobic digester strongly affects its performance. The optimum temperature for the methanogenic bacteria that produce the biogas is about 37° C--mammal body temperature. Digestion will continue down to about 10° C but the process slows drastically and gas production falls almost to zero. An example of the relationship between residence time, temperature, and gas generation that was measured in one study is shown below in Figure 2. The inverse relationship between temperature and residence time is illustrated here: the warmer the temperature of the digester (up to 37° C) the less time is required to accomplish digestion.

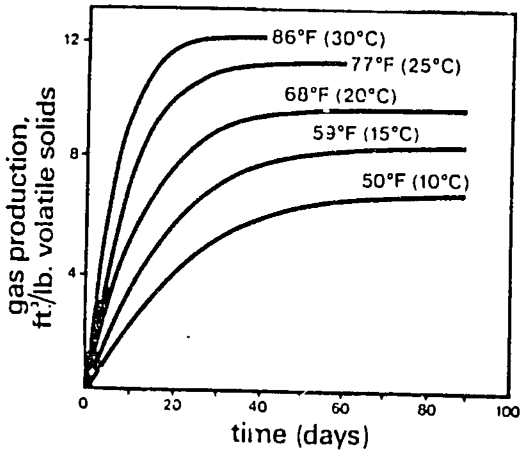


Figure 2. Biogas Production as a function of Slurry Temperature and Residence Time [5]

It is absolutely essential to fully understand the influence of temperature on gas production. For instance, it is common to express the amount of biogas produced as a fraction of the volume of the pit holding the digesting slurry. This is to say, one might speak of a rate of gas production of 0.5 m^3/m^3 per day. This convention of normalizing gas production with respect to the volume of the pit is very useful, and it can be used to demonstrate the effects of temperature on the rate of digestion and hence of gas generation.

If the digester is kept warm with the slurry temperatures in the vicinity of 37° C, daily gas production will be about 1 m^3/m^3 often higher. If the temperature falls to 10° C, gas production will drop by an order of magnitude--down to 0.1 m^3/m^3 per day. If the digester is unheated, slurry temperatures will usually be close to the mean 24-hour temperature at the site--most digesters, except for the very smallest ones, having sufficient thermal mass that diurnal variations in temperature are effectively dampened out.

Indian-Type Digesters

Researchers and technologists in India have been working with biogas technology since the 1930's. About 90,000 biogas plants are in operation. The typical Indian design consists of a pit lined with brick, an inlet pipe, and a metal gas cover to trap the biogas as it bubbles up out of the slurry. A typical early design is shown below.

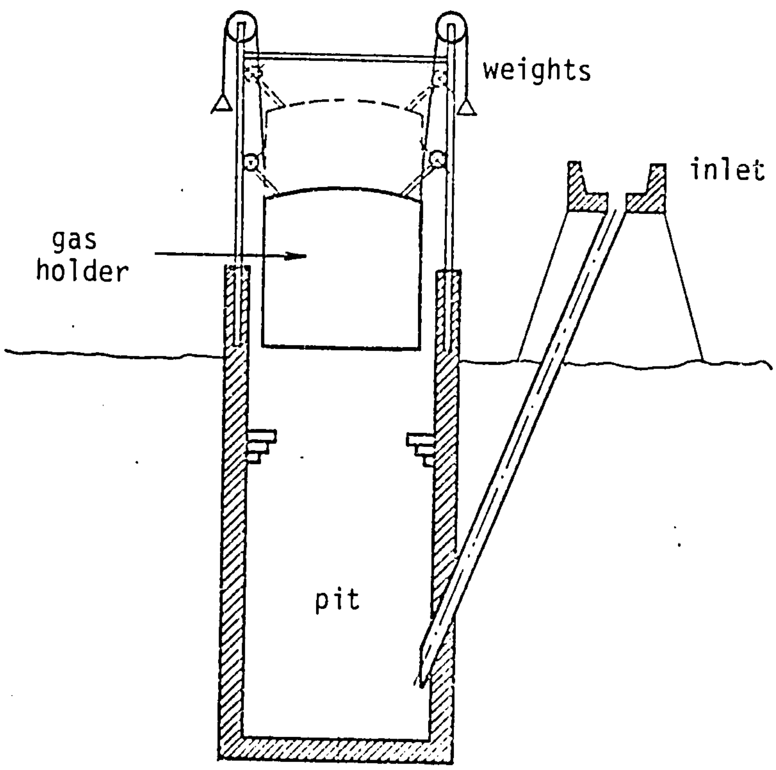


Figure 3. Typical Indian Digester of Early Design

The operation of the digester is extremely simple. Dung, or other suitable biomass material, is mixed with water, and the slurry is allowed to pass down the inlet pipe into the digester pit. The slurry remains in the digester anywhere from 30 to 50 days, during which time gas is produced from the mixture and bubbles to the surface. The digester is usually fed each day, and each day a volume of slurry equal to the incoming material will pass out of the digester either through an exit pipe, or by simply overflowing the rim of the pit through a notch as shown in Figure 4.

The gas generated by the digestion process is trapped under a cover which, in the Indian design, is free to move up or down according to the volume of gas contained beneath it. The pressure of the gas therefore remains relatively constant while it is being drawn off for use.

The early Indian digesters often had gas holders that were so weighty that they over-pressurized the gas. Often the weight of the holder would be counter-balanced by weights attached to cables which were slung over pulleys and tied to the heavy cover. The pressure of the gas could therefore be controlled by adjusting the weights.

Later design used lighter covers which did not require counter-balancing. Figure 4 shows a more recent design popular in both India and Nepal [6]. In this design, the gas is taken off through a center pipe which also functions as a guide post for the gas holder.

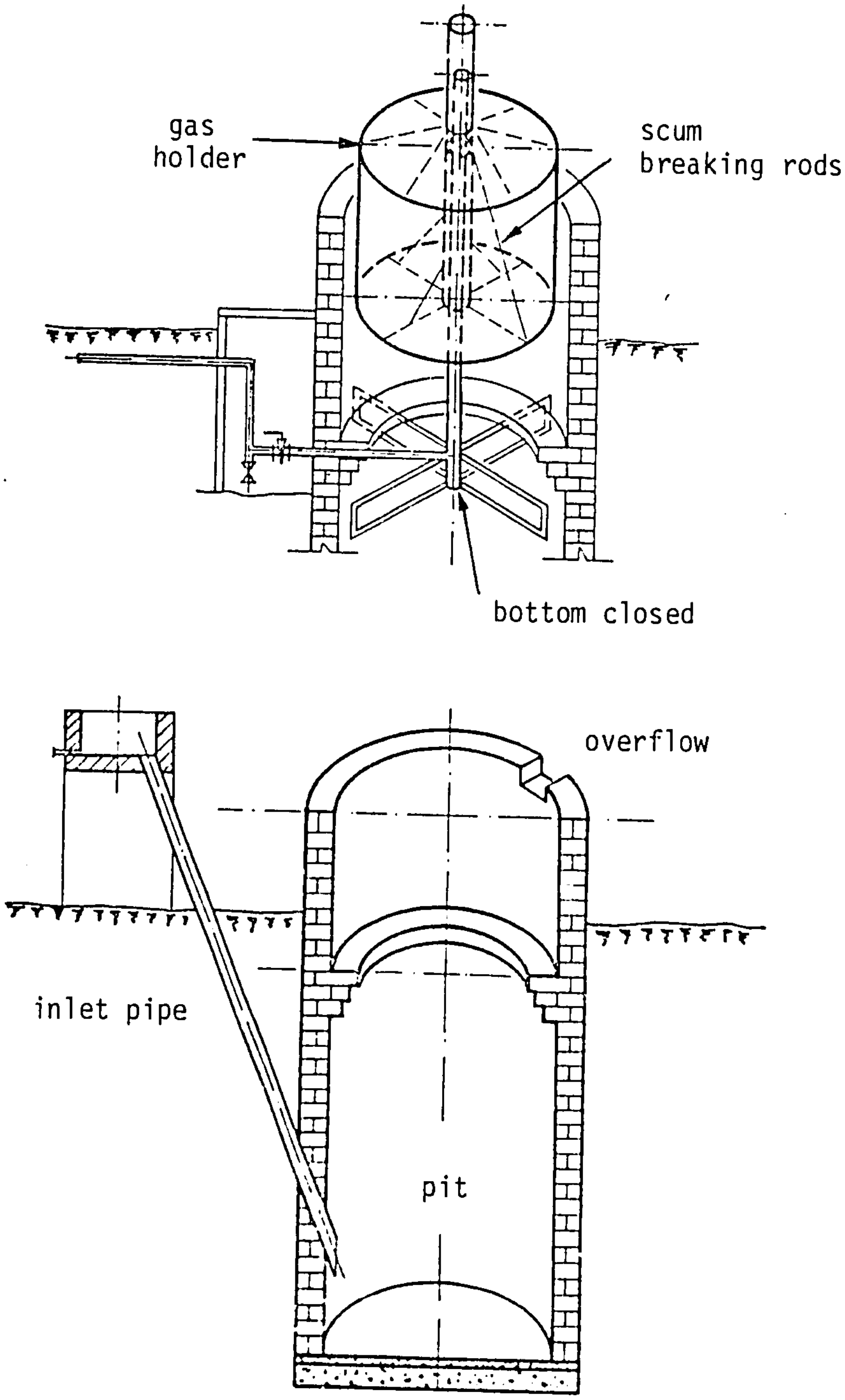


Figure 4. Alternative Digester Design [6]

A more detailed sketch of the construction of this alternative design of gas holder is shown below.

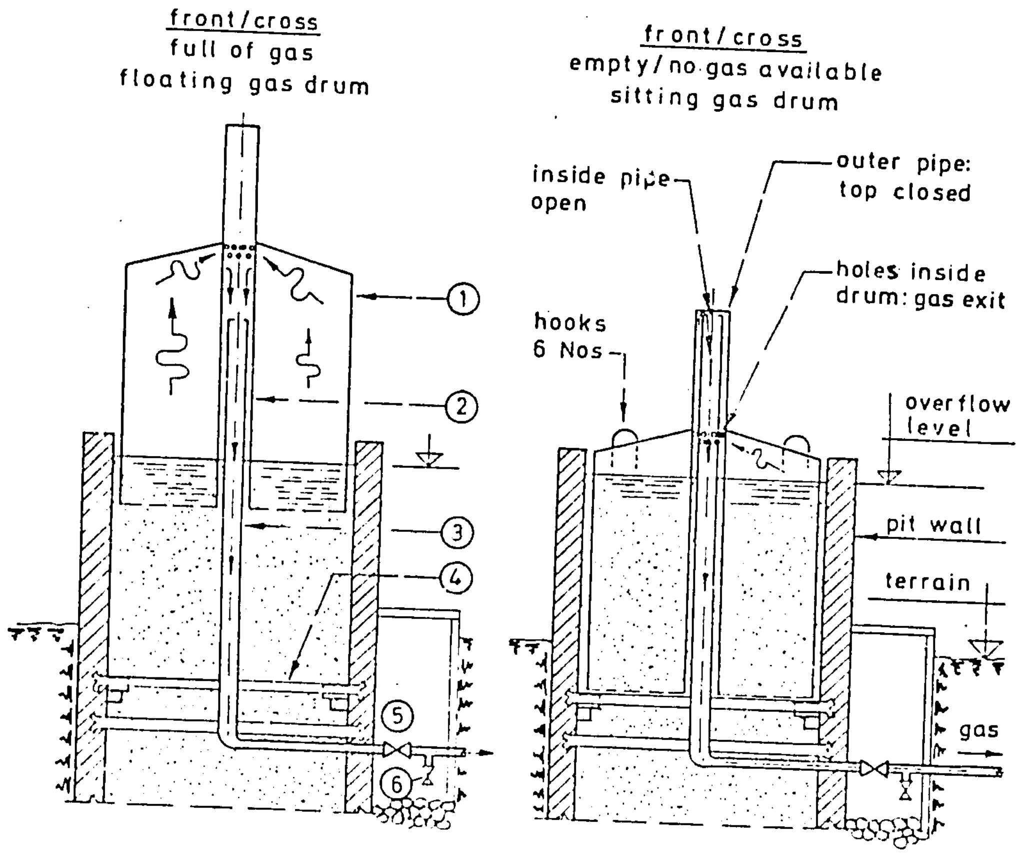


Figure 4(b). Alternative Gas Holder Design Showing Gas Exit Arrangement [6]

1. gas drum
2. slide pipe (G.I. 2-1/2" Ø)
3. center and gas exit pipe 2" Ø
4. cross supports
5. main gas valve
6. moisture trap

Some Indian digesters used a two-chamber configuration with an exit pipe leading up from the floor of the second compartment, as shown below. It is not clear, however, that this arrangement has any advantages.

The biggest disadvantage of the Indian type of digester is its cost. The steel gas holder is an expensive item, and one not easily fabricated in the rural areas of many developing countries. The gas holder alone may account for 40 percent of the cost of the digester [7].

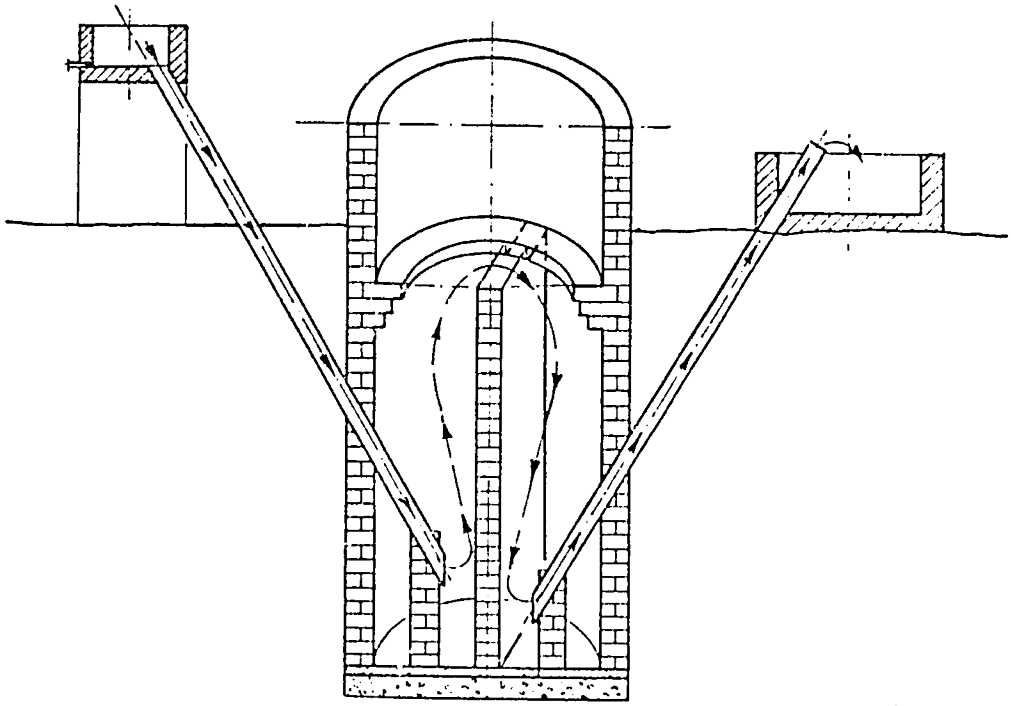
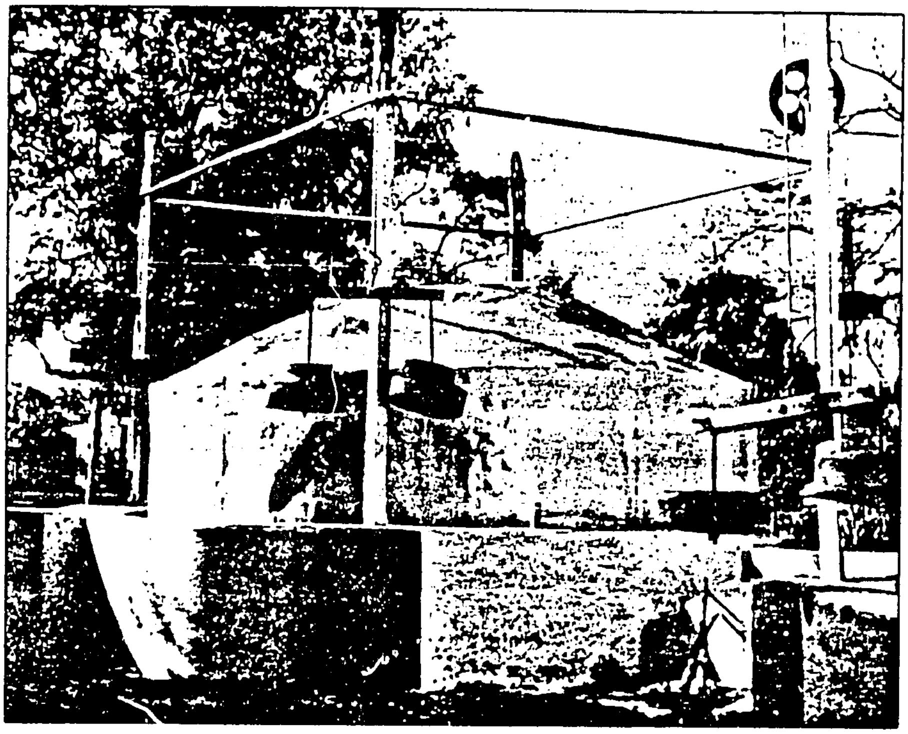
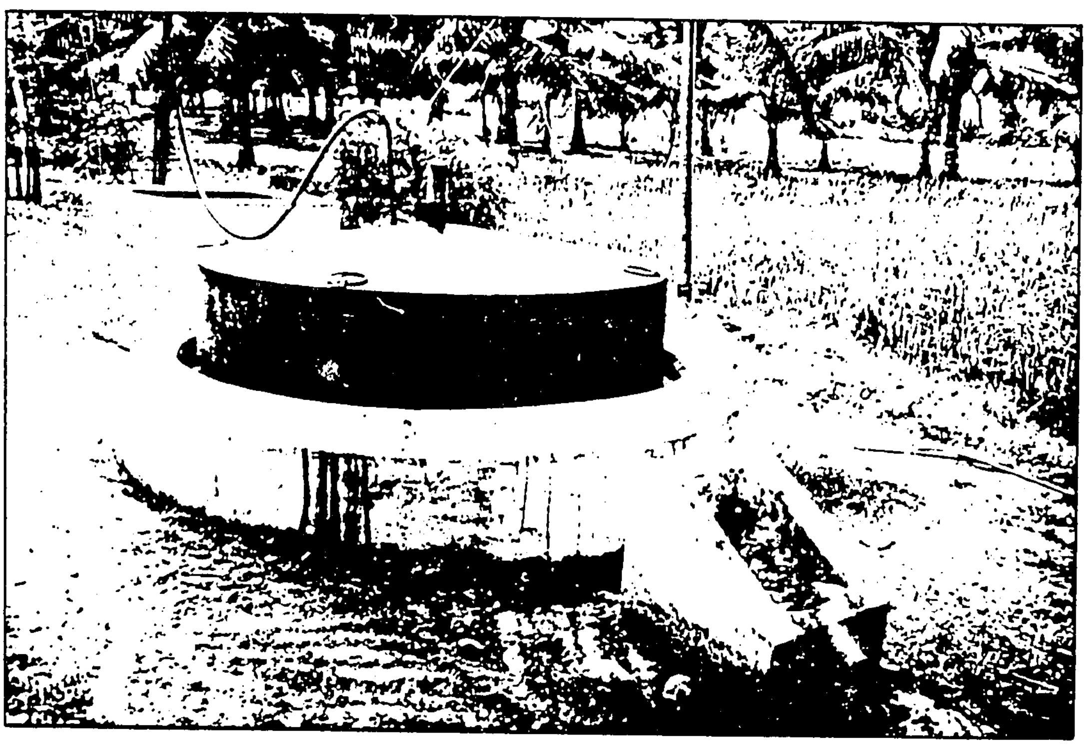


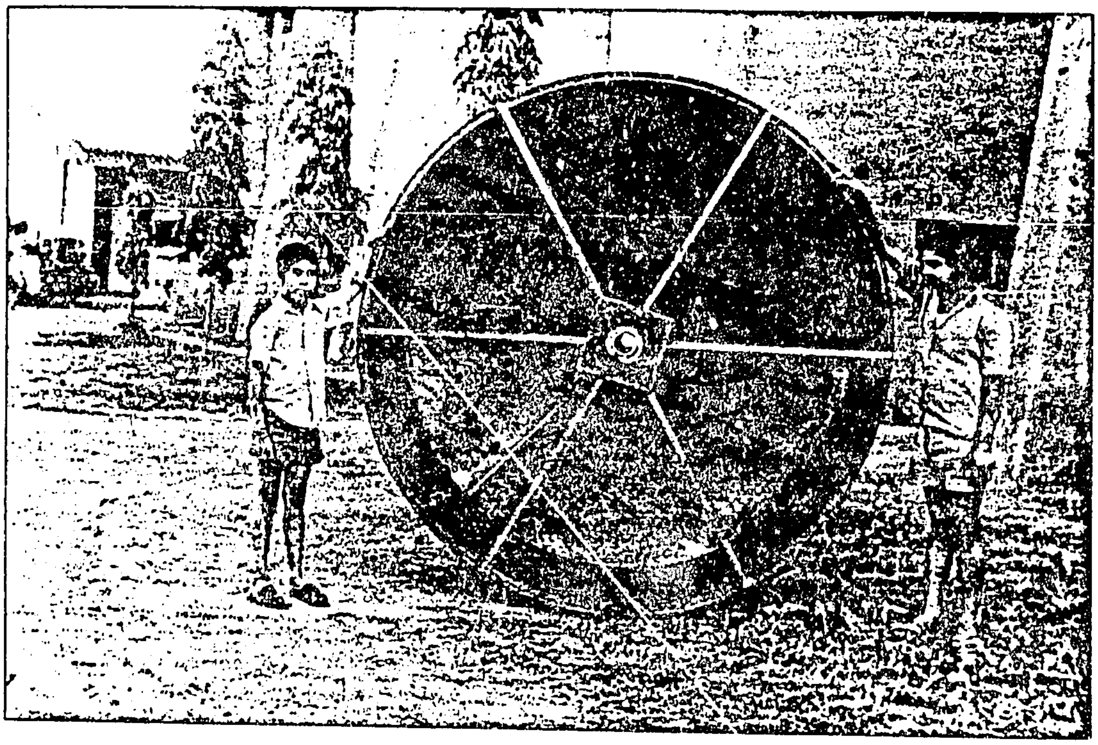
Figure 5. Two Chamber Construction [6]



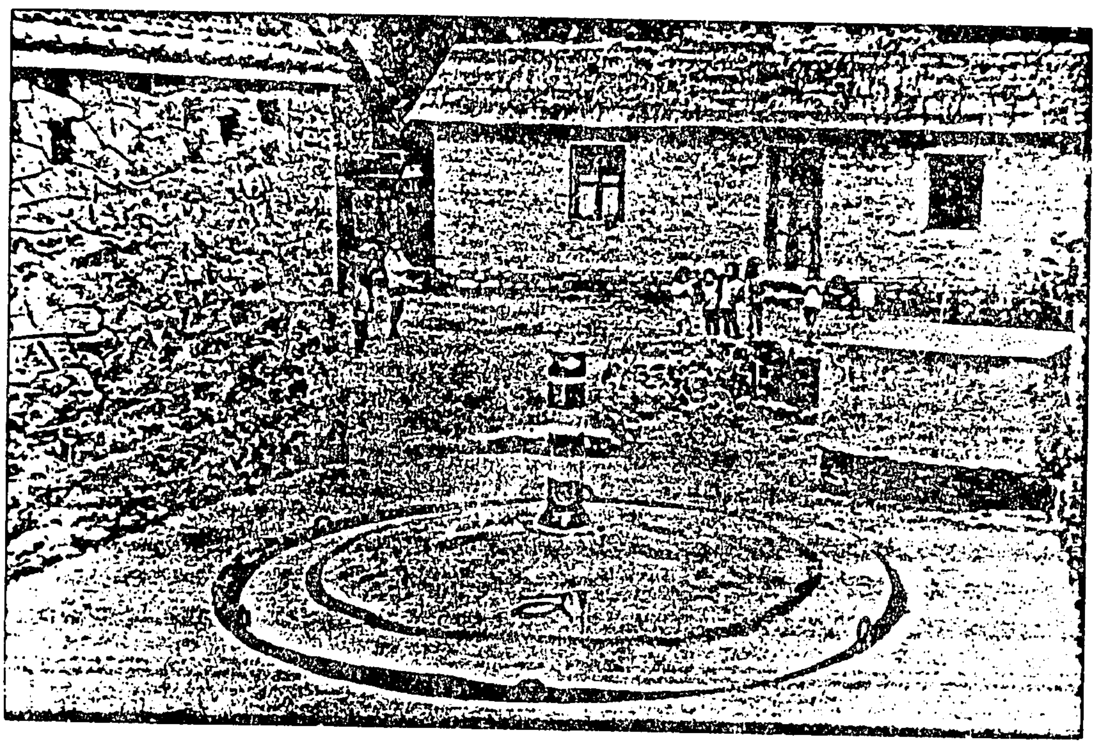
Large floating roof digester; note the counter-weights attached to the heavy gas holder.



Small floating roof digester in Nepal. The inlet chamber can be seen behind the unit. In the foreground is the outlet.



Typical gas holder for a floating roof biogas unit. Note the central pipe used as a guide post.



Large floating roof digester in Nepal. The gas holder is empty; the top of the cover is painted as a prayer wheel.

Chinese-Type Digesters

Most of the digesters built in China are circular units with domed roofs similar in appearance to the one shown below.

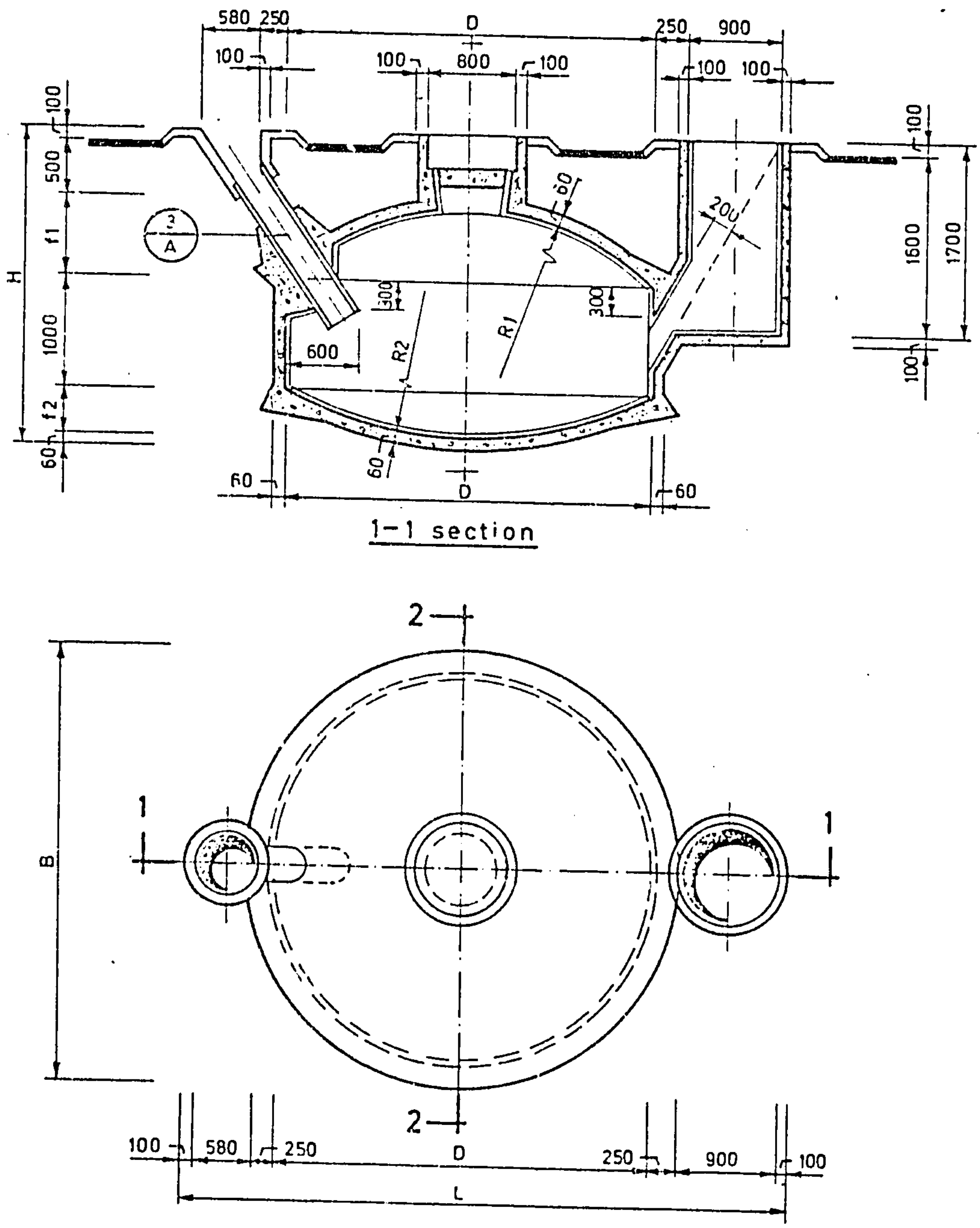


Figure 6. Typical Chinese Digester [6]

There are many kinds of digester designs in operation in China. Their predominant feature, and one that stands in contrast to the Indian designs, is that the gas holder is a fixed structure. As gas accumulates beneath it the pressure increases, forcing slurry up the inlet and outlet pipes until the hydrostatic pressure generated by these fluid heads is equal to the gas pressure beneath the center dome. This kind of digester, therefore, operates at a much higher pressure than a floating roof digester.

There has been a concerted effort in China to encourage the construction of biogas units in the rural areas, particularly in the province of Sichuan. The anaerobic digester is viewed as an integral part of the household unit which may also include several animals, generally pigs. The digester operates on animal manure, nightsoil, and crop residues and the gas produced is used for cooking and lighting as shown in the sketch below.

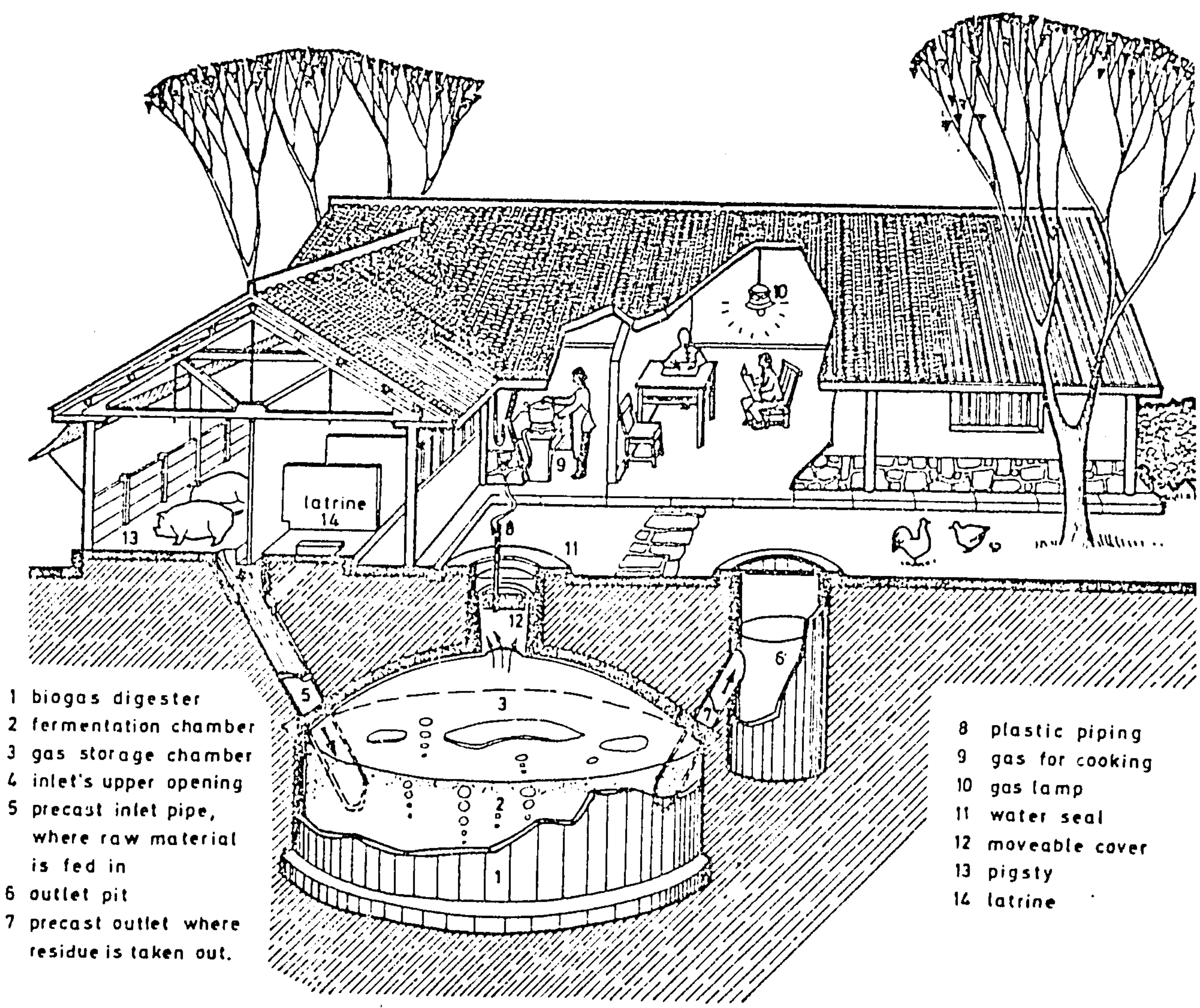
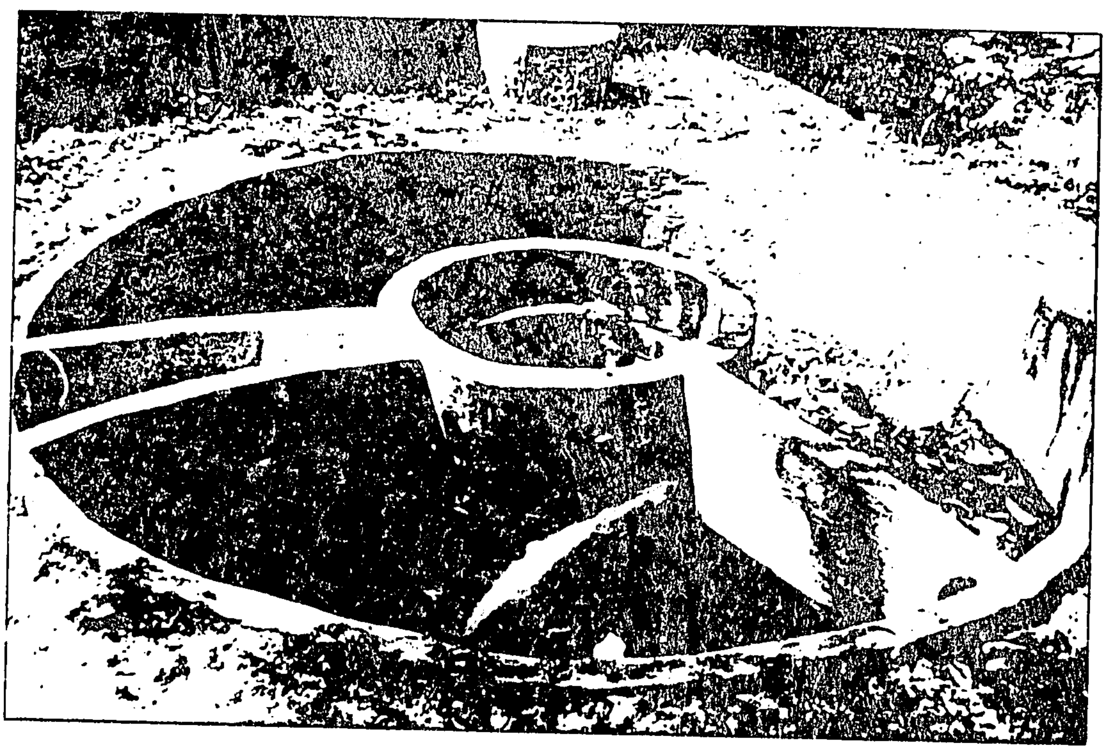


Figure 7. Chinese Biogas System [6]


Chinese type, fixed roof, digesters under construction. The unit below is in India. Note the gas plug in the background.



Horizontal Digesters

The Indian and Chinese digester designs are difficult to construct with pit volumes larger than about 50 cubic meters. There is therefore increasing interest in horizontal digesters, particularly for larger scale units. There are also a number of advantages with horizontal digesters. First, they sit either on the ground or in a shallow trench, so earth-moving is minimal; this feature also avoids problems that a high water table sometimes causes for buried digesters. Second, there is some evidence that digestion rates are higher, although the reasons for this are not year clear [10]. Third, their simplicity generally results in a lower capital cost in comparison with the Indian and Chinese types.

Many horizontal digesters have been built and operated in the U.S. These are often large digesters with pit volumes sometimes as high as 1000 cubic meters. One such system (but not that large) is shown below.

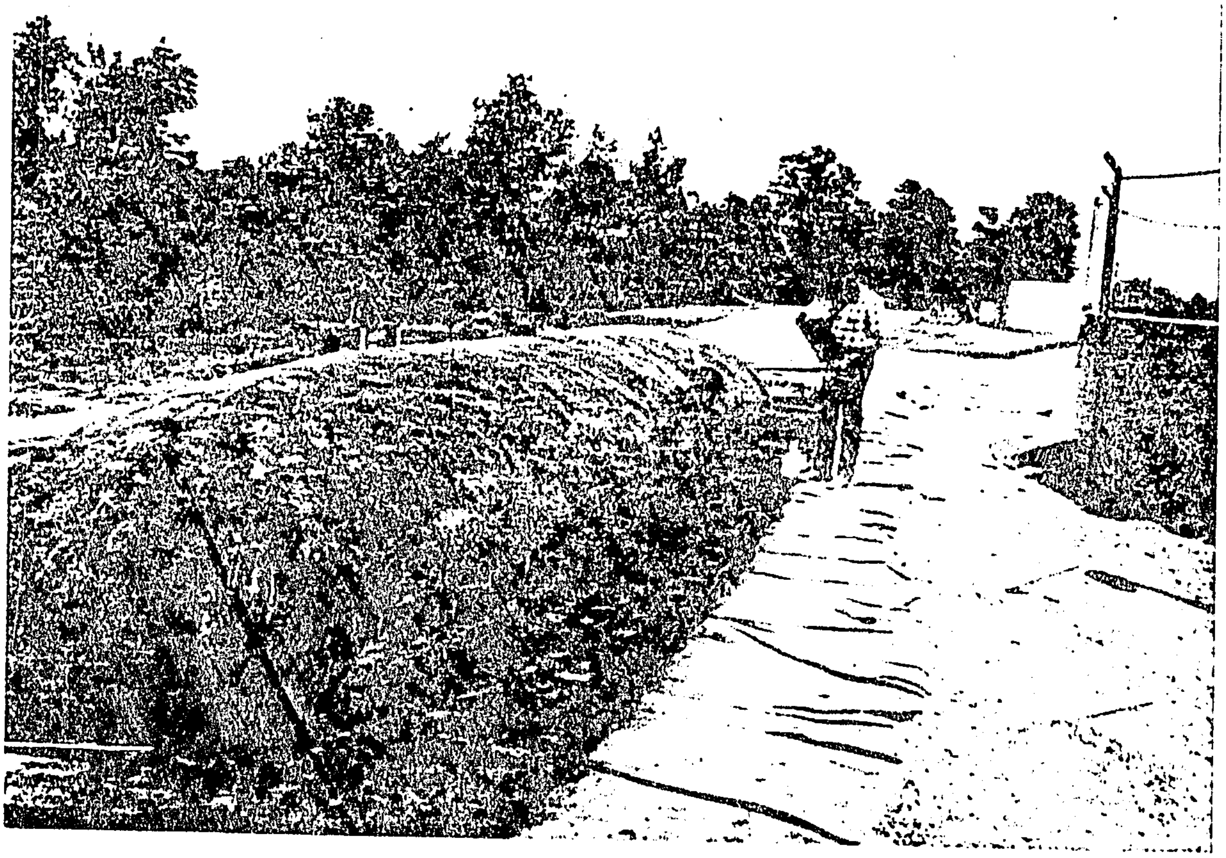
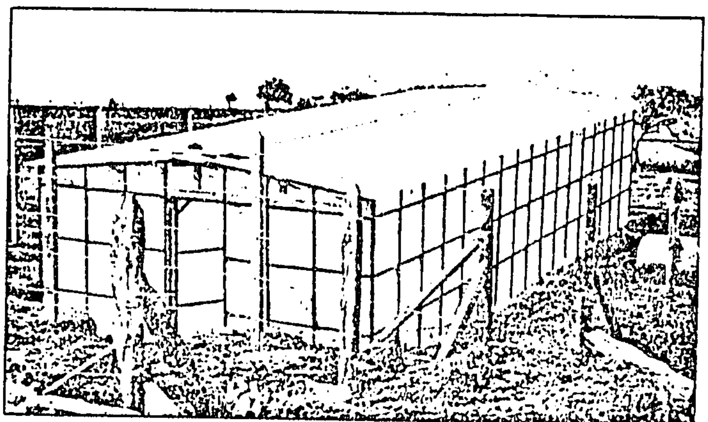


Figure 8. Photograph of a full-scale 65 Cow Dairy Horizontal Digester in Operation at Cornell University [10]

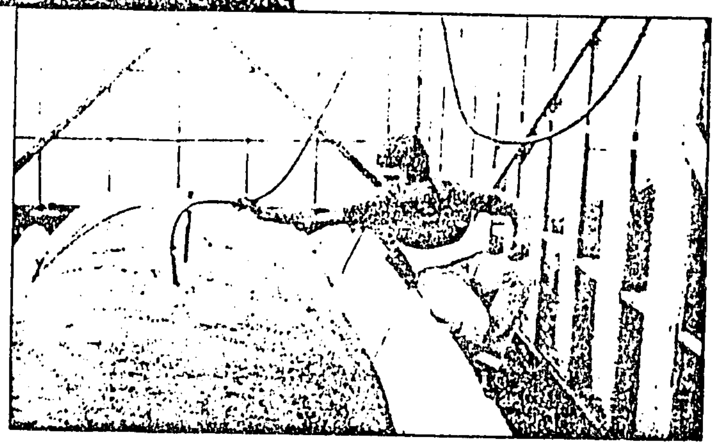
As shown in Figure 8, the gas is collected under a flexible rubber sheet firmly bonded to the walls of the pit. The pit itself is just a shallow horizontal trench often lined with the same rubber or plastic sheeting used for the cover.

It is possible to construct a horizontal digester using a long cylindrical rubber bag. These bags are available in sizes up to about 500 m^3 from a number of suppliers [25].

A small installation in Costa Rica is shown in the photographs below. This unit has a volume of 15 m^3 and takes the wastes from 30 dairy cows.



Cobertor del biodogestor plástico



Vista del biodogestor en operación dentro del cobertor

Figure 9. Photographs of a Small (15 m^3) Bag Digester in Costa Rica [12]

Horizontal digesters can be built with a fixed roof in a manner similar to the small Chinese type of digesters, except that the digestion chamber is now much longer, and the slurry moves through the chamber from one end to the other. A unit built recently in Egypt is shown below.

This digester incorporates both heating pipes and stirrers to improve gas production and to break up any surface scum that might form on the slurry. The unit is designed to digest chicken manure, and has a volume of about 50 m^3.

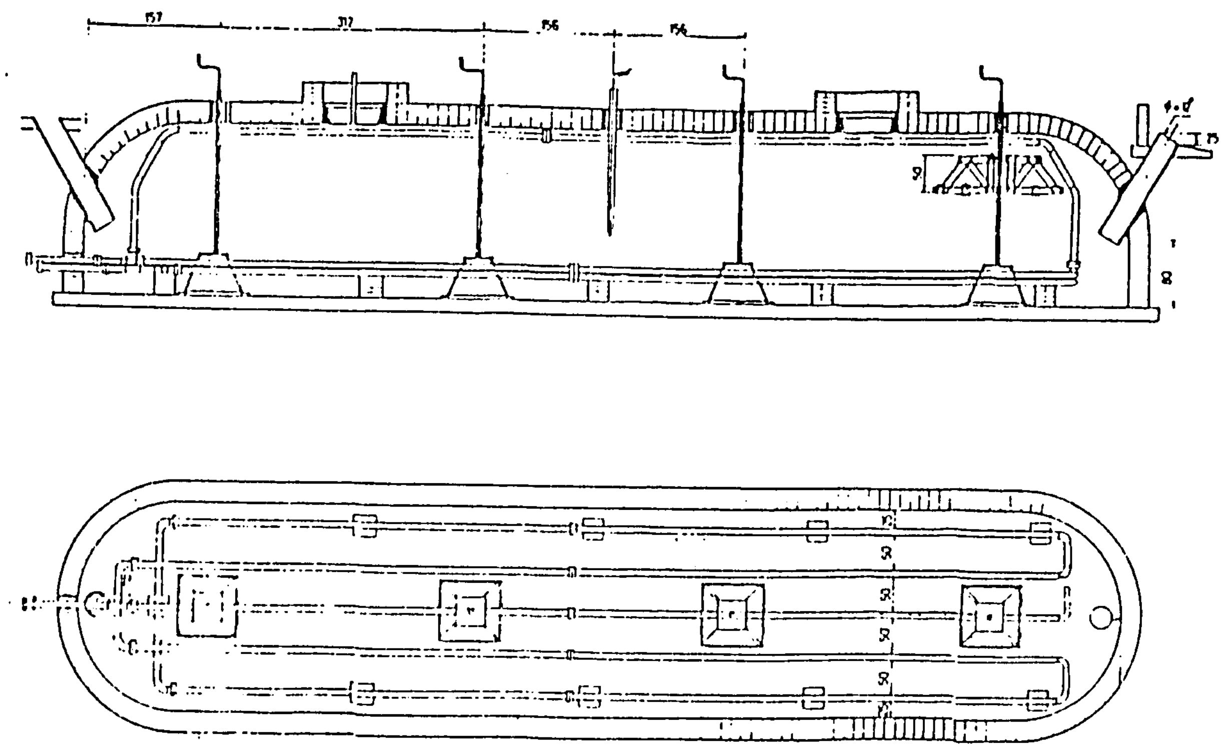
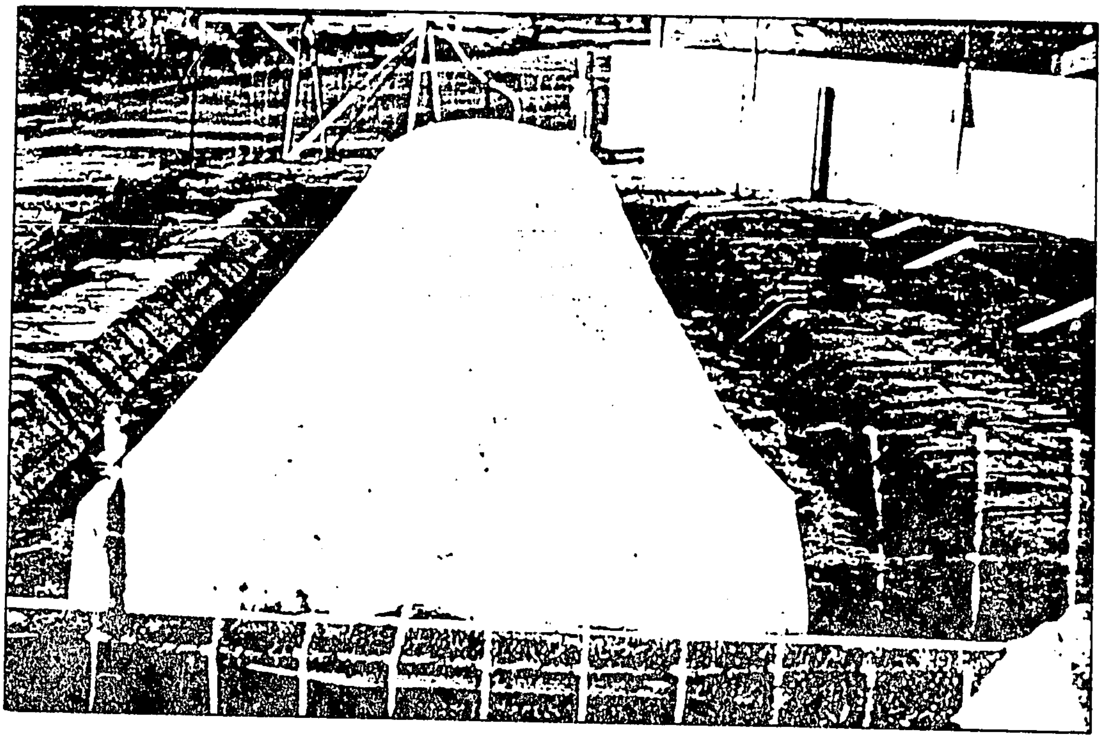
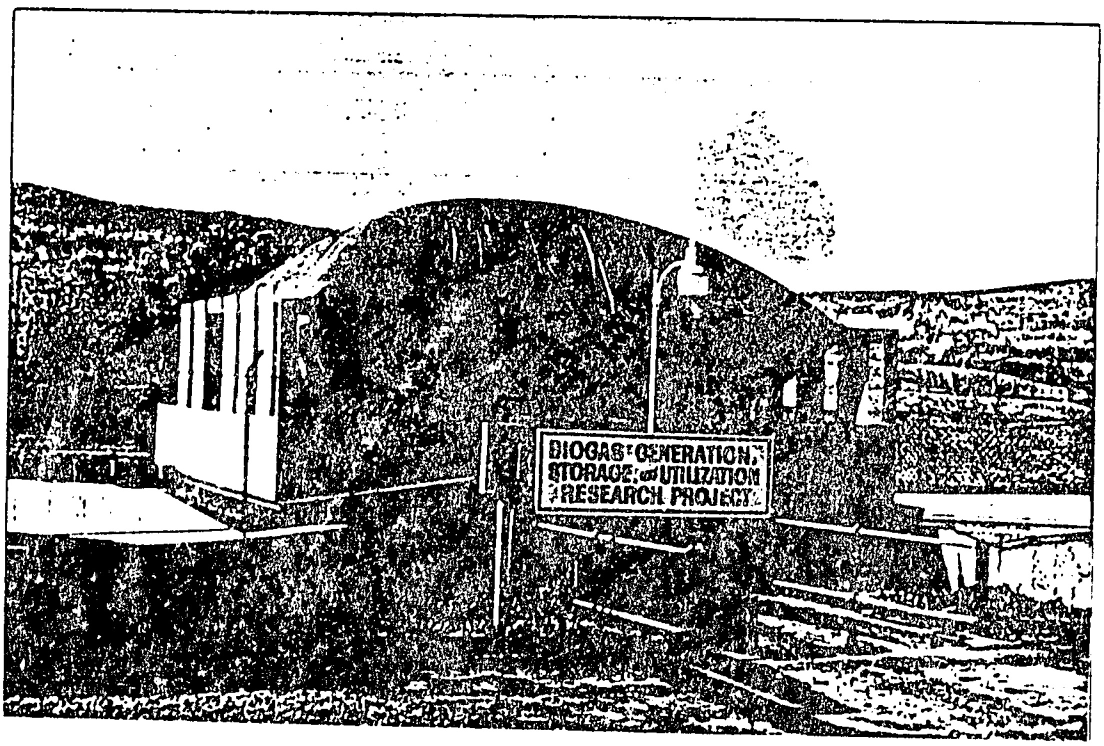
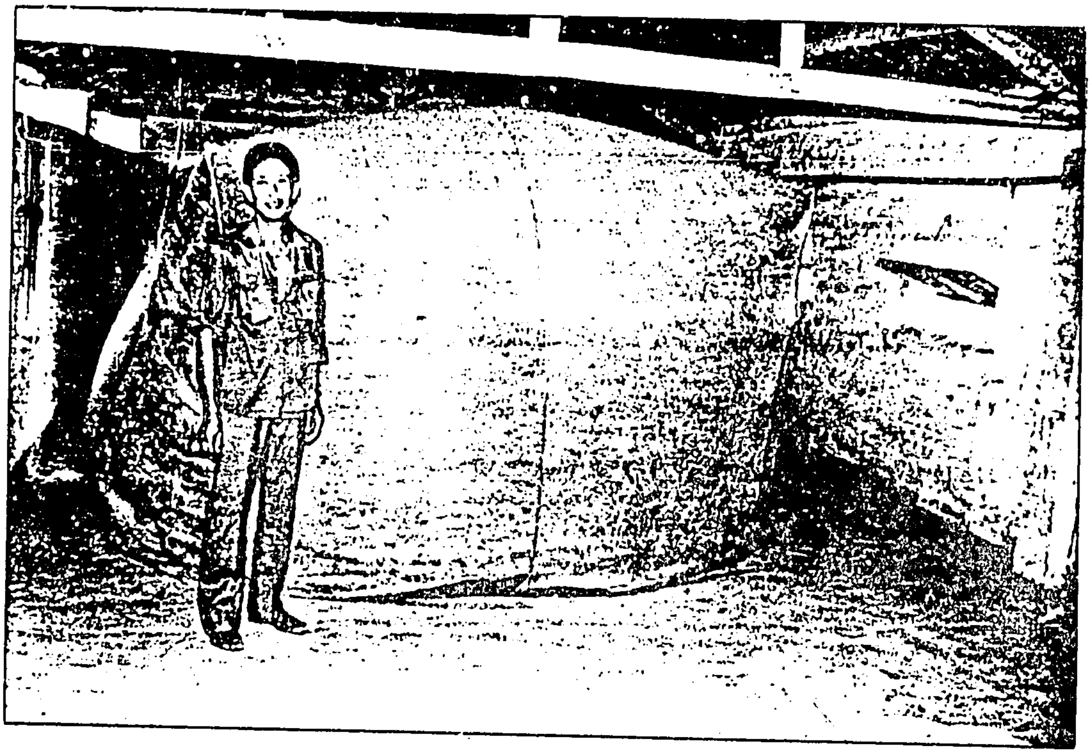


Figure 10. Horizontal 50 m^3 Digester with Heating Pipes and Stirrers, in Egypt [11]

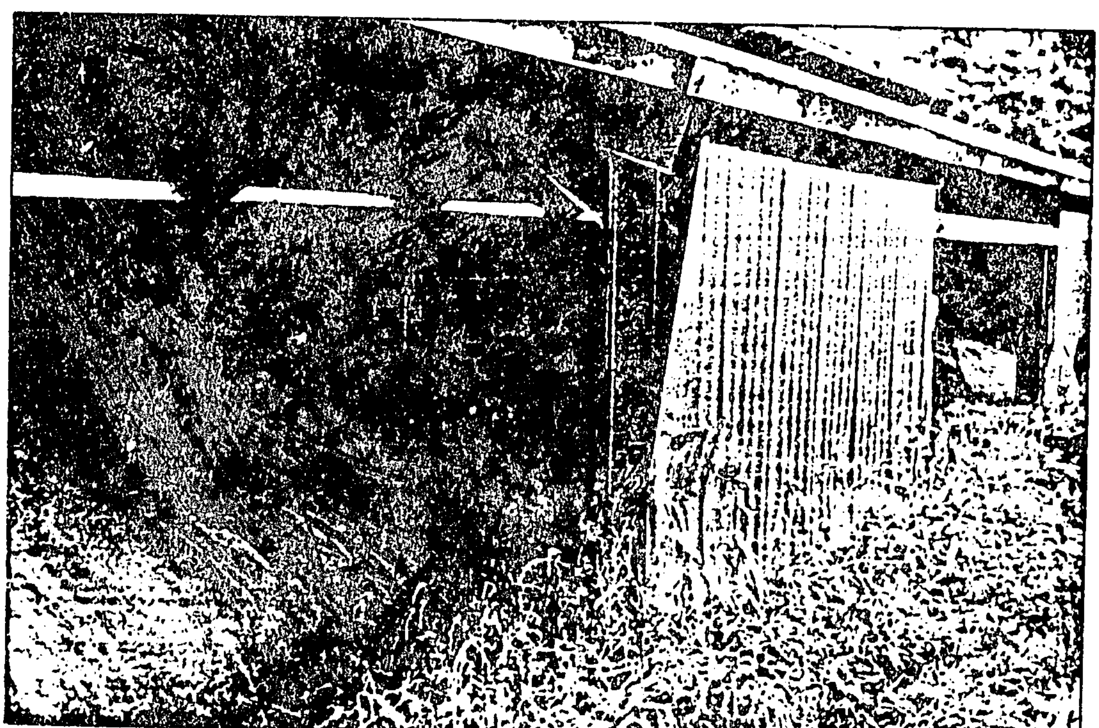


Above: horizontal biogas unit at a dairy operation in the US. Below: bag storage for biogas.





Gas bags used to collect the biogas from horizontal digesters. The photograph above is from China. The large bag shown below is from a biogas plant in the US.



Alternative Designs

There is a large variety of anaerobic digesters in operation around the world. Part of the reason for this is that the technology is extremely simple in technical terms; all that is required is an airtight vessel and some way to store the gas. Since efforts have been largely directed to introducing small digesters into the rural areas of developing countries, there have been many attempts to design the digesters in such a way that locally-available materials, techniques, and technologies can be used in the fabrication of the units. For instance, in Thailand, cement water jars with a volume of 1.2 m^3 are readily available in most parts of the country at a cost of about $30 (1982). A novel biogas system using these vessels is shown below.

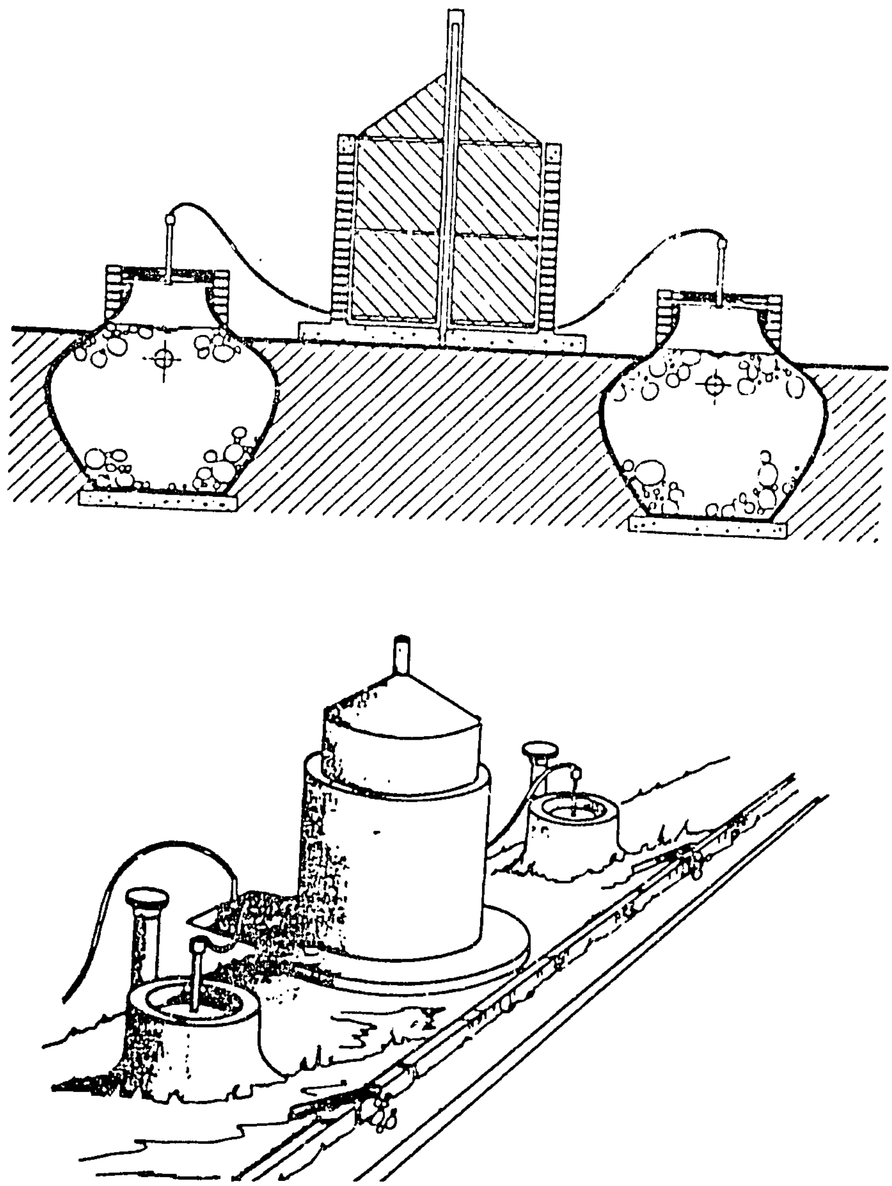


Figure 11. Cement Water Jar Digester Developed by the National Energy Administration in Thailand [26]

Digester Design

The basic design of a biogas system involves 3 steps. These are:

1. Estimate the quantity and the characteristics of the feedstock available for digestion.
2. Fix a residence time, based on a consideration of both digester temperature and volatile solids loading rates; this gives the size of the digester required.
3. Select a design configuration, and then proceed with the detailed design.

Feedstock

There are two considerations here. First, the C/N ratio of the digestible portion of the waste materials should fall in the range 20 - 30 to 1; and second, the slurry must be of a consistency that does not cause operating problems with the digestion. If the waste is too dilute, solid material may settle or float and digestion will be impeded; the digester will also be oversized and therefore more expensive than it needs to be. If the slurry is too thick, the digester may clog, and the system may become literally constipated. As a rule of thumb, the total solids content of the slurry should be about 8%. More graphically, the proper feedstock consistency has been described as being like "cream".

As an example, take cow dung. The C/N ratio for cow dung is just about in the acceptable range (Table 1), so it is not necessary to add supplementary material with a high C/N ratio, such as straw, in order to raise the C/N ratio (although one can, and it may well increase gas production), but the total solids content of the dung, 16 percent, is too high. Cow dung is usually mixed with an equal volume of water to give a slurry with a total solids level of about 8 percent, which is fine for digestion.

As another example, consider pig manure. The C/N ratio for this dung is given as 13.7. This is too low, and pig wastes should be mixed with some digestible material with a high C/N ratio to bring the C/N ratio of the mixture within acceptable limits. If we mix 1 kg of pig dung with 1 kg of rice straw the C/N ratio of the mixture is calculated as follows [Table 1]:

Available carbon is	0.383 + 0.357	=	0.74 kg
Available nitrogen is	0.028 + 0.007	=	0.035 kg

So the final C/N ratio is 0.74/0.035 = 21.1, an acceptable figure.

Now, we look at the total solid (TS) content. The mixture (2 kg) contains 0.25 kg TS from the pig manure, plus 0.89 kg TS from the rice straw: a total of 1.14 kg TS; hence 1.14/2 = 0.57 or 57 percent total solids.

This is too high; the mixture will be too thick and will have a tendency to clog the digester. To bring the mixture to the desired consistency it is necessary to dilute it with water--about 12 kg of water (12 liters) added to 2 kg of the dung-straw mixture to give a final TS content of 1.14/(12 + 2) = 0.081, or 8.1 percent.

The calculation or estimation of the quantity and quality of the digester feed can be difficult. One must take into account all the liquids and solids that may get mixed up with the basic waste material. Rainwater, washwater, and any ot - waste fluids (urine, for example) or solid material such as bedding, musu all be included in the calculation if the C/N ratio and the total solids content of the digester feed is to be set correctly.

Residence Time

The influence of temperature on residence time has been discussed earlier, and the relationship is shown graphically in Figure 2. The curves shown there suggest that residence times should be about 20 days when the slurry temperature is held at 30° C, and it should increase to about 60 days as the temperature falls off to 10° C. As a rule of thumb, the following relationship between residence time and temperature is recommended.

Table 3. Digester Temperature and Residence Time

Digester temperature ° C	Residence time days
10	50
15	42
20	35
25	28
30	20
35	12

These figures are only intended as guidelines, but they provide a convenient check on the digester size.

Perhaps a more scientific way of calculating both the residence time and the size of the digester is based on loading rates. The loading rate is the amount of volatile solids (VS) entering the digester each day, divided by the volume of the digester (the pit volume): it is measured in kg VS/m^3 day.

For standard municipal digesters, the loading rate is between 0.5 and 1.6 kg VS/m^3 day and the residence times can vary from 30 to 90 days [8]. Studies based on dairy cattle wastes in India revealed loading rates as high as 6.7 kg VS/m^3 day [8]. Other authors suggest that a range of 0.8 to 3.2 kg VS/m^3 day is appropriate, and recommended a design value of 2.8 kg VS/m^3 day [14].

The problem with using loading rates as design criteria is that the published figures [8, 13, 14, 15] do not indicate the digestion temperature appropriate for the recommended rates. And, as we have noted, the effects of temperature are absolutely critical to the design and operation of the digester.

The procedure recommended here is for the designer to set an approximate residence time based on the guidelines indicated in Table 3. The volume of the digester is then calculated (knowing the volume of slurry entering the digester each day). Then the loading rate is calculated and this should fall in the range of 1 - 4 kg VS/m^3 day.

For example, consider again the cow dung digester mentioned earlier. Assume we have about 20 kg/day of dung, and that this is mixed with water 1:1 to give the correct total solids content. The digester feed is therefore 40 kg of slurry per day. Assume also that the average temperature at the site is 20° C (ignoring seasonal variations for the moment). Table 3 suggests a residence time of 35 days. The volume of the digester pit is therefore estimated as

$$40 \frac{\text{kg}}{\text{day}} \cdot 1 \frac{\text{liter}}{\text{kg}} \cdot 35 \text{ days} = 1400 \text{ liters}$$

or 1.4 cubic meters. What is the loading rate? Table 1 gives a volatile solids content of 0.77 x 0.16 = 0.123 kg VS/kg dung. Each day the digester is fed 10 kg of dung and 10 kg of water; the loading rate is therefore

$$10 \times 0.123 \frac{\text{kg VS}}{\text{day}} / 1.4 \text{ m}^3 = 0.9 \text{ kg VS/m}^3 \text{ day}$$

This is on the low side, but is not that much out of line. It suggests that a slightly smaller digester might prove adequate. The prudent biogas system designer, however, will be careful not to size digesters too small.

The same approach can be taken with the pig dung-straw feedstock looked at earlier. Assume there are pigs in numbers sufficient to produce 50 kg dung per day. To balance the C/N ratio and the total solids content, it was calculated previously that 1 kilogram of dung needs to be mixed with 1 kg of rice straw and 12 kg of water.

The daily feed to the digester is therefore 50 kg dung, 50 kg straw, and 600 kg of water--a total of 700 kg of slurried biomass residues delivered to the digester each day.

It is necessary to estimate the volume of this amount of slurry. It is usually accurate enough to assume that the density of the slurry, even when it contains material such as straw, is close to the density of water since the fraction of total solids is low--less than ten percent. The volume of the digester feed is therefore approximately 700 liters a day.

Designing once more for a temperature of 20° C, Table 3 suggests a residence time of 35 days as before. The volume of the digester should therefore be 700 liters/day x 35 days = 24,500 liters or 24.5 cubic meters.

A quick check on the loading rate gives for the volatile solids content:

for the dung: 50 kg/day x 0.25 x 0.807 = 10.1 kg VS/day
for the straw: 50 kg/day x 0.89 x 0.79 = 35.2 kg VS/day

So the loading rate is (10.1 + 35.2)/24.5 = 1.85 kg VS/m^3 day which is an acceptable figure.

Manure Production

One question that remains unanswered is: How much manure will an animal produce? Again, this is not an easy question to answer. Data for the U.S. are unlikely to apply to the developing countries. Feed material may be different, the body weights may not compare, dung collection systems may collect different amounts of dung even if similar animals produce identical amounts. The table below gives some average values.

Table 4. Volumes or weights of excreta produced per day by different animals

Animal (type of food)	Body Weight Kg.	Volume of Excreta/day Liters	% faeces	% urine	Ratio of total daily waste/Body Weight, %
Cattle					
Dairy cow (silage & concentrates)	454+	32-45	70	30	7.2
Fattener (silage & barley)	454	27			6
Beef fattener	203	11			6
Pigs					
(Dry meal fed)	45.4	4.5			
(Pipeline fed)	45.4	6.8-9	45	53	10
(Whey fed)	45.4	9-13.5			
	18-36	2.7			9
	36-54	5.4			12
	54-72	6.8			10
	72-90	8.2			10
Poultry					
Layers	2.3	0.11 kg			5
Broilers	1.4	0.05 kg			3.3
Geese/Turkeys	6.8	0.22 kg			3.3
Horses	383	23	70	30	6
Sheep	30	2.3	66	34	7.5
Humans	68	1.4	20	80	2

Adapted from reference 14.

One point to note is that the ratio of total daily waste to body weight is nearly constant for each species. The amount of dung produced by lighter animals than those indicated in the table can therefore be estimated using the ratios shown in the last column of the table.

Other Feedstock

Besides animal dung--from cattle, horses, pigs, or chickens--there are other waste materials and biomass materials that can be digested.

Nightsoil. Human wastes have a high nitrogen content, so material such as straw must be added to the digester if the digester is to produce good quality gas. Most of the digesters in China run on a mixture of nightsoil, pig manure, and plant material. However, some digesters appear to run quite well on nightsoil alone. It has been suggested that in the developing countries, where diets may be low in protein, the C/N ratio of nightsoil may not be so low as to make it unsuitable as a feedstock material.

Reports from India indicate that nightsoil may be difficult to keep in suspension, with some material settling to the bottom of the digester while other substances float on the surface. Corrosion problems with metal gas holders may also occur due to the higher levels of sulphides in the slurry.

Water Hyacinths. Many research groups have experimented with the use of water hyacinths in digesters, and it is possible to produce good gas from this fast growing aquatic weed.

Food Processing Wastes. The waste streams from food processing plants can very often be digested and biogas produced. For instance, in California the wastes from a fruit juice production facility is digested and produces about 57 m^3/day of gas. The gas is burned in boilers that generate steam for the plant.

The Bacardi Corporation in Puerto Rico operates an enormous digester system to safely dispose of about 1.2 million liters a day of rum distillery wastes. The 12,600 m^3 digester is packed with plastic sheeting which provides a very large surface area for the methanogenic bacteria to attach themselves to. The plant generates nearly 29,000 m^3 of gas each day which is used to generate steam for the distillery. Smaller plants generating biogas from distilleries are in operation in Thailand [30].

The wastes from a cheese-making plant are added to the dung from a large dairy herd in New York State and fed to a 910 m^3 digester. The biogas runs a 225 kW diesel engine driving a generator.

Gas Production

It is perhaps surprising that for a technology subjected to so much scientific scrutiny, there is remarkably little agreement on just how much gas is to be expected from the operation of an anaerobic digester. The rate of methane generaton is a function of many variables--temperature, volatile solids content, residence time, carbon-nitrogen ratio, pH level, among others; it has proved difficult if not impossible to accurately predict the quantity and quality of the gas production merely by analyzing the chemical and physical characteristics of the biomass feedstock.

The NAS study found that gas production, when related to the volatile solids content of the digester feed, could be anywhere from 0.06 to 1 m^3/kg of volatile solids [16]. But since loading rates will range from 0.8 to 3.2 kg VS/m^3 of digester per day, daily gas production as a fraction of the pit volume (which is the common way of expressing the amount of gas generated by the digester) could conceivably be anywhere from 0.04 to 3.2 m^3/day of gas per m^3 of pit volume--almost 2 orders of magnitude difference.

The missing analytical factor in these calculations is, once again, the influence of temperature. Low temperatures sharply curtail the rate of digestion of volatile solids and hence the rate of biogas generation.

Based on a wide reading of reports from the field on the operation of biogas digesters in developing countries, the following guidelines are suggested: Table 5 presents approximate values for gas production.

Table 5. Digester Temperature and Gas Production

Digester temperature °C	Gas production m3/day (of gas) per m3 (of pit)
10	0.15
15	0.2
20	0.5
25	1.0
30	1.5
35	2.0

It should be emphasized that these estimates are only approximate, and that they are applicable only to digesters that operate with due regard to the residence times recommended in Table 3, and with total solids content and loading rates suggested as appropriate in the previous discussions.

Gas Utilization

Biogas from a properly functioning digester should consist of about 50 - 70 percent methane; the remainder being carbon dioxide with a trace of hydrogen sulphide--usually not enough to cause problems. The calorific value of pure methane is close to 38 MJ/m^3; biogas therefore has a calorific value between 20 and 27 MJ/m^3 depending on the amount of methane contained in the mixture.

Biogas is a good quality fuel gas, and a versatile source of energy. It can be used directly for heating, cooking, lighting and refrigeration, or as a fuel in spark-ignition engines and in compression-ignition (Diesel) engines, although in the latter case biogas cannot substitute totally for the diesel fuel.

Table 6 indicates the amount of gas required for these and other tasks which are discussed in more detail overleaf.

Table 6. Biogas Consumption in Specific Applications

End-Use	Descriptor	Gas Required
Cooking	2 inch burner	330 liter/hr
	4 inch burner	470 liter/hr
	6 inch burner	640 liter/hr
	per person/day	340-420 liters (1)
Gas lighting	per lamp (100 candlepower)	130 liter/hr (2)
	per mantle (64 candlepower)	70-80 liter/hr
Engine	per hp	450-510 liter/hr
Engine-generator	per kW	600-1100 liter/hr
Refrigerator	per ft^3 capacity	28-34 liter/hr
Incubator	per ft^3 capacity	13-20 liter/hr

Adapted from reference 8.

Notes 1. The gas required for cooking in China are generally quoted as being higher than for India. The Chinese texts suggest that for cooking 500 liter per day per person is required [18].

2. The figures quoted for the consumption of biogas for lighting vary considerable. Chinese sources quote rates of 100 liter/hr for a 200 candlepower lamp [18]; also 140 - 170 l/hr for a lamp equivalent to a 60 W electric light [4]. An average figure for an electric lamp would be 1.6 candlepower (20 lumens) per Watt.

Cooking

Biogas is a good fuel for cooking; nearly all the small family-sized biogas plants throughout the world are used to provide fuel for this purpose. Methane burns in air according to the formula

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

generating heat at a rate of 37 MJ per cubic meter of methane burned. A unit volume of methane requires therefore 2 volumes of oxygen, or about 10 volumes of air, for combustion. Since biogas is about 60 - 70 percent methane, approximately 6 - 7 volumes of air are required for combustion; the energy released is about 20 - 22 MJ/m^3 of biogas.

Many difference kinds of burners can be made to burn biogas. In developing countries burners are simple and inexpensive. A variety of burners and stoves are shown below and overleaf.

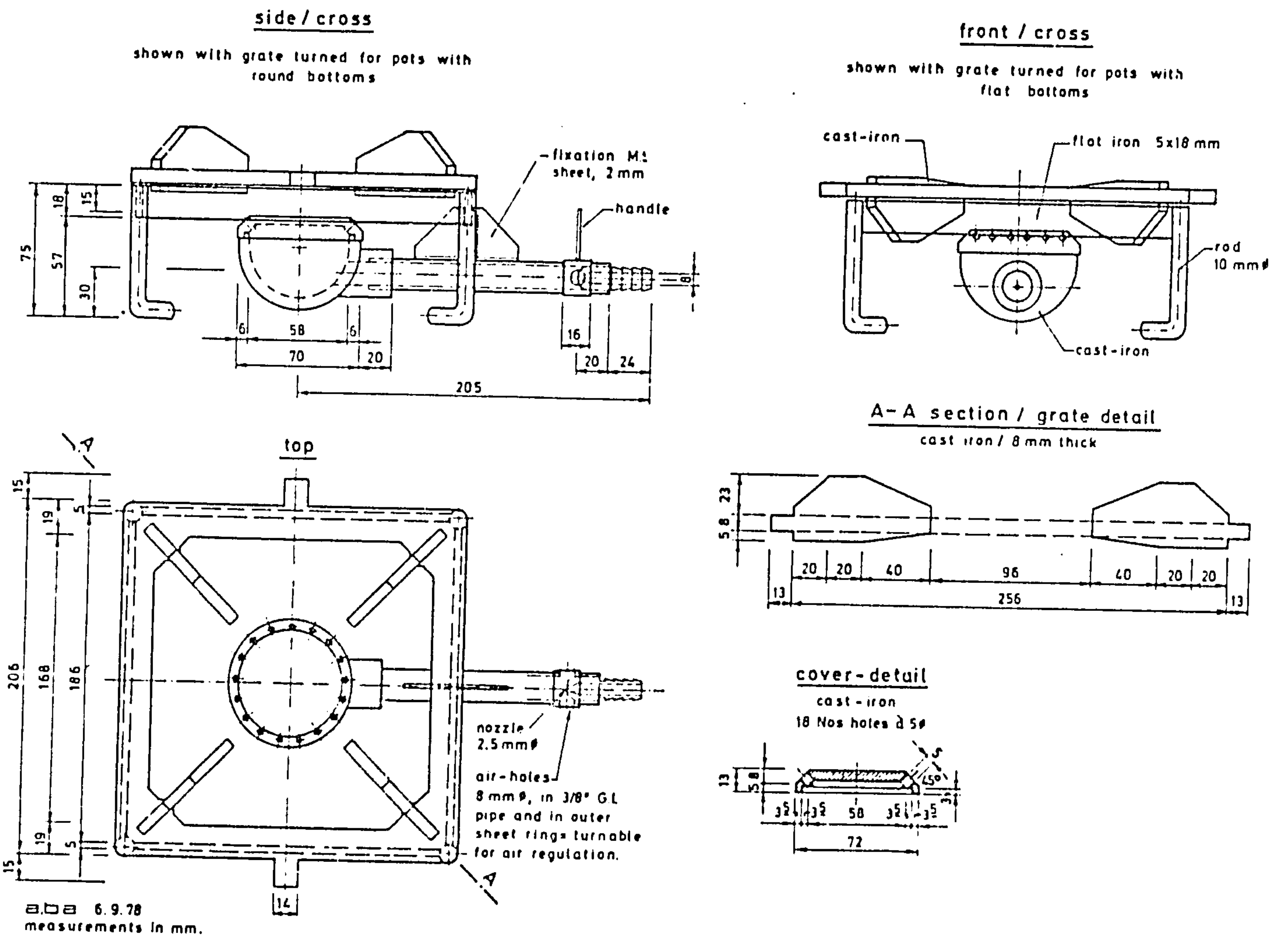
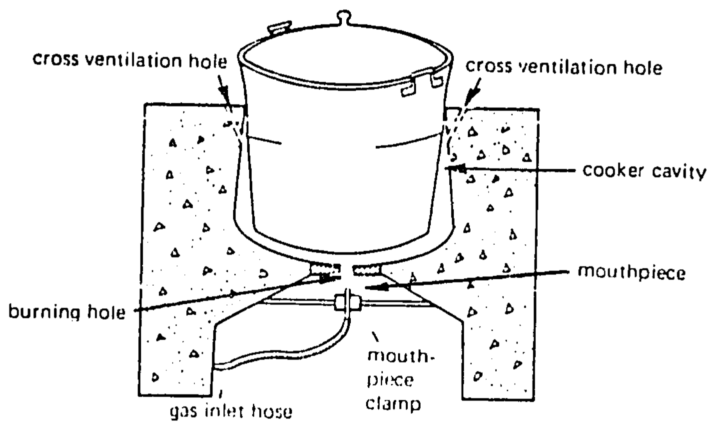
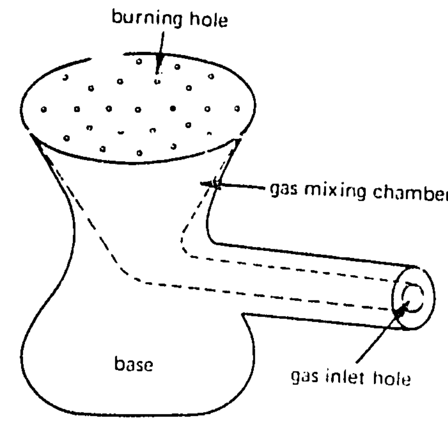


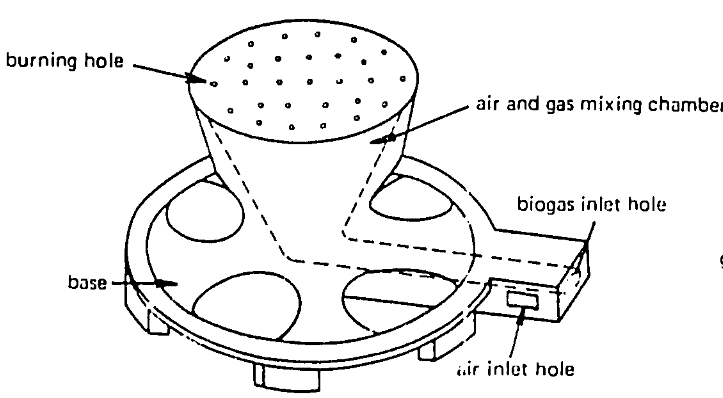
Figure 12. Burner Design (Nepal) [6].



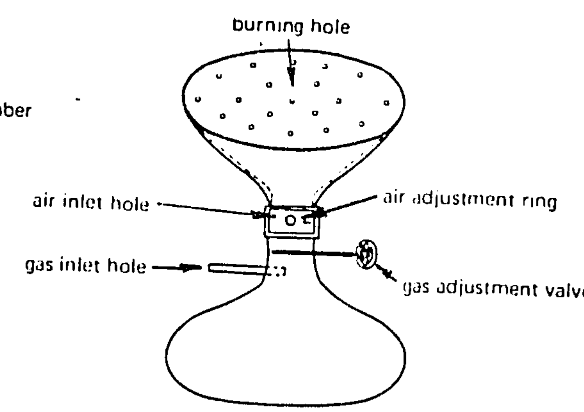
Biogas stove



L-shaped burner

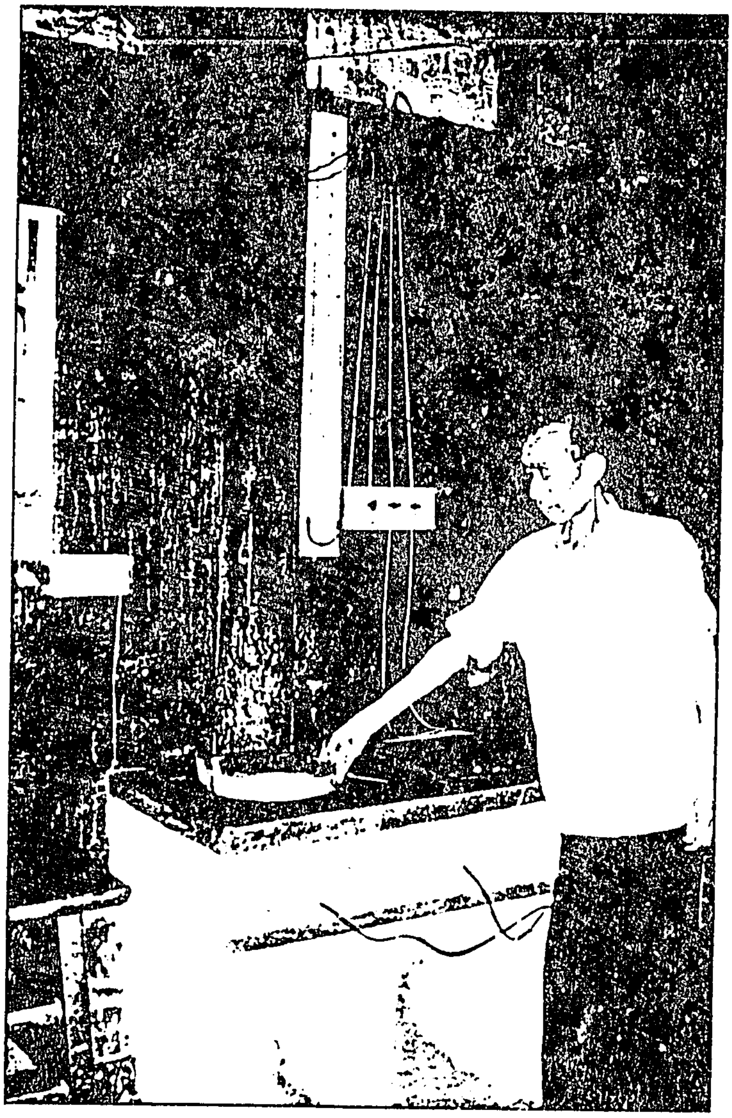


Showerhead burner

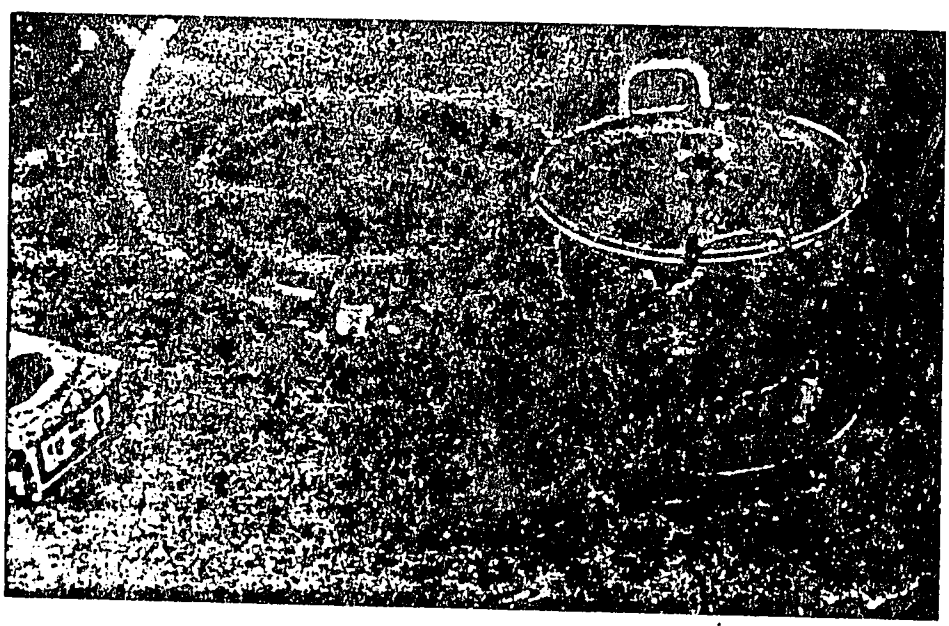


Hourglass-shaped burner

Figure 13. Chinese Burners for Biogas [4]



Cooking with biogas: photographs from China. Note the manometer shown in the photograph above.



Lighting

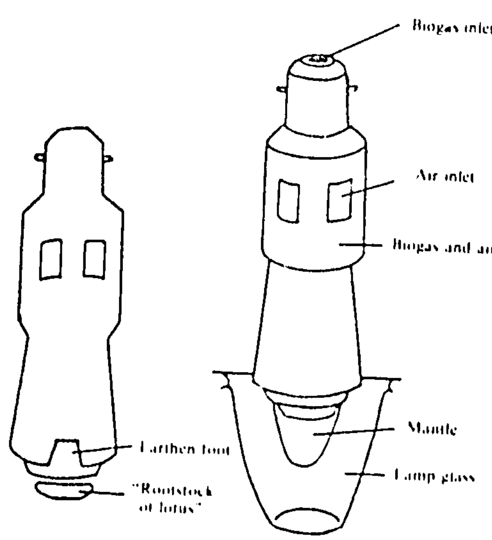
Biogas gives a soft white light when burned with an incandescent mantle. Lamps of various styles an sizes are manufactured in both India and China for use with the gas. Gas lamps require approximately 0.1 liter/hr of biogas to provide 1 lumen of light, an overall efficiency of 0.24 percent. There are more efficient ways to produce illumination using biogas, as shown below.

Table 7. Biogas for Illumination

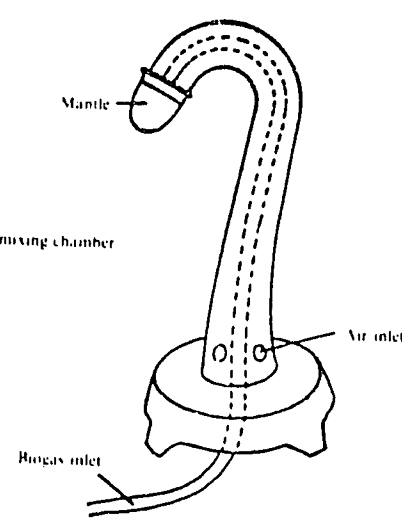
System	Gas required to produce 1 lumen ml/hr	Overall Efficiency light/thermal input percent
Incandescent mantle	100	0.24
Generator & incandescent lamp (20 lumen/W)	37.5	0.65
Generator & Fluorescent lamp (80 lumen/W)	9.4	2.61

Notes: Biogas is assumed to be 22 kJ/liter, and that it takes 750 liters of biogas to produce 1 kWh of electricity; 1 lumen is 1.5 mW of power.

However, a biogas-powered electrical system designed to produce illumination for a few houses would be hopelessly uneconomic. The load would need to be about 4 kW (about 100 lamps) before such a system would be practical. The advantage of the incandescent mantles is that they match the scale of the application when only a few lamps are required. Some typical biogas lamps are shown in the figures below and overleaf.



Hanging biogas lamp



Standing biogas lamp

Figure 14. Chinese Biogas Lamps [18]

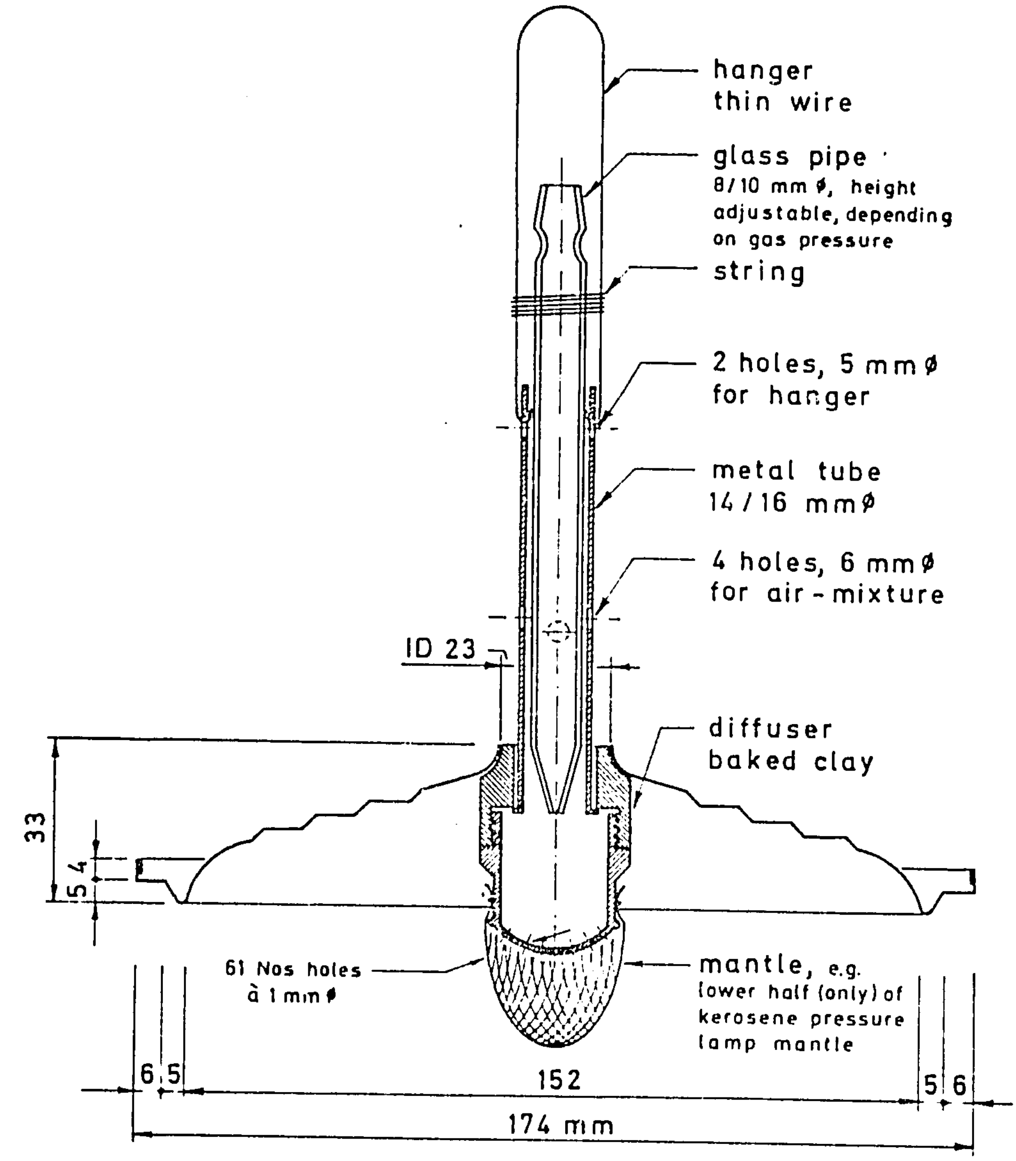


Figure 15. Biogas Lamp from Nepal [6]

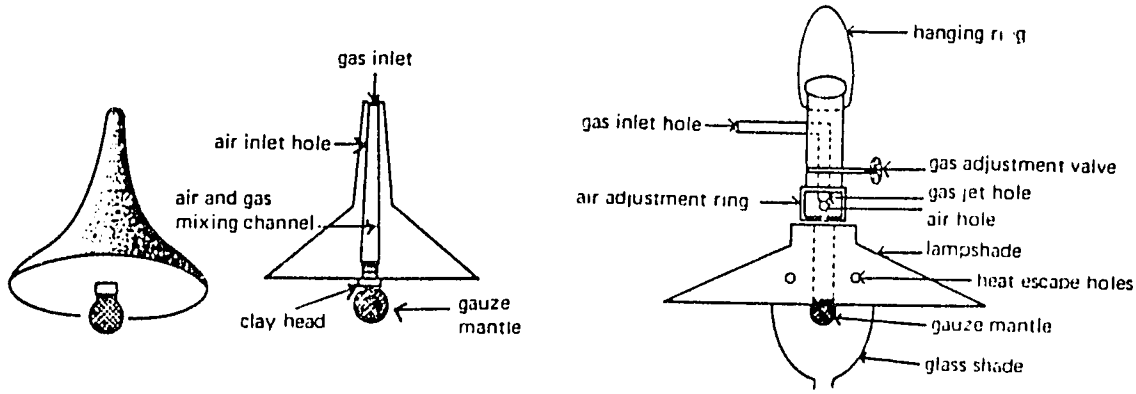
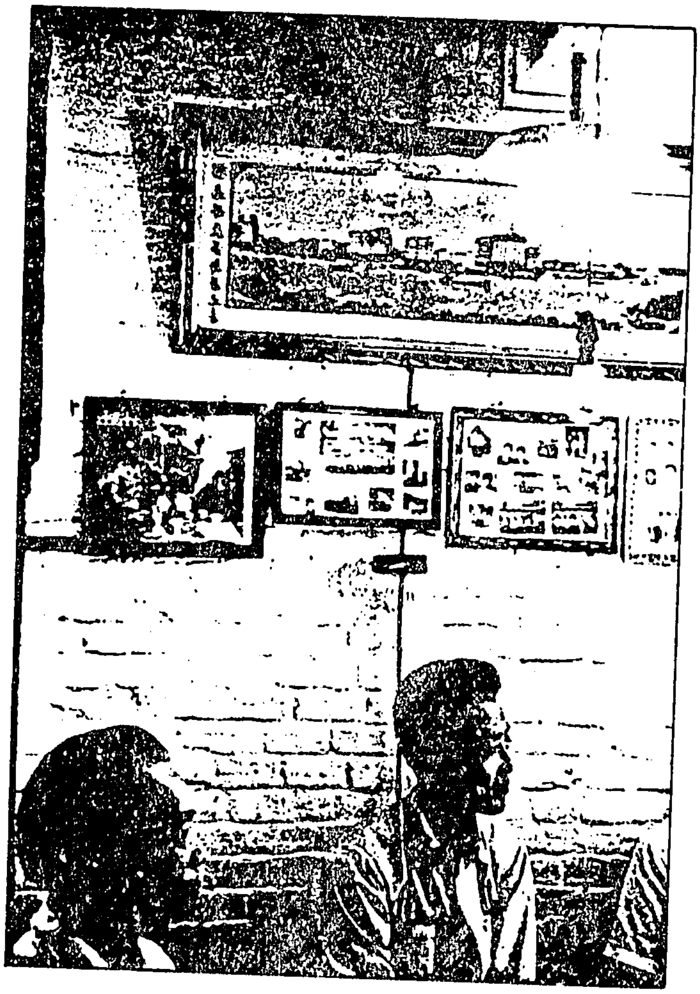


Figure 16. Biogas Lamps from China [4]



Biogas illumination in China. Note that a biogas lamp and an electric light hang side by side. Only the biogas light is turned on here.

Refrigeration

A vapor absorption refigerator of the type once common in the U.S., and still available in many developing countries, can be run on biogas without difficulty. The burner shown below has given good results in Nepal where a 12 cubic foot refrigerator was run for 8 months on biogas. Gas consumption was 100 liters per hour at a pressure of 8 cm water gauge [6].

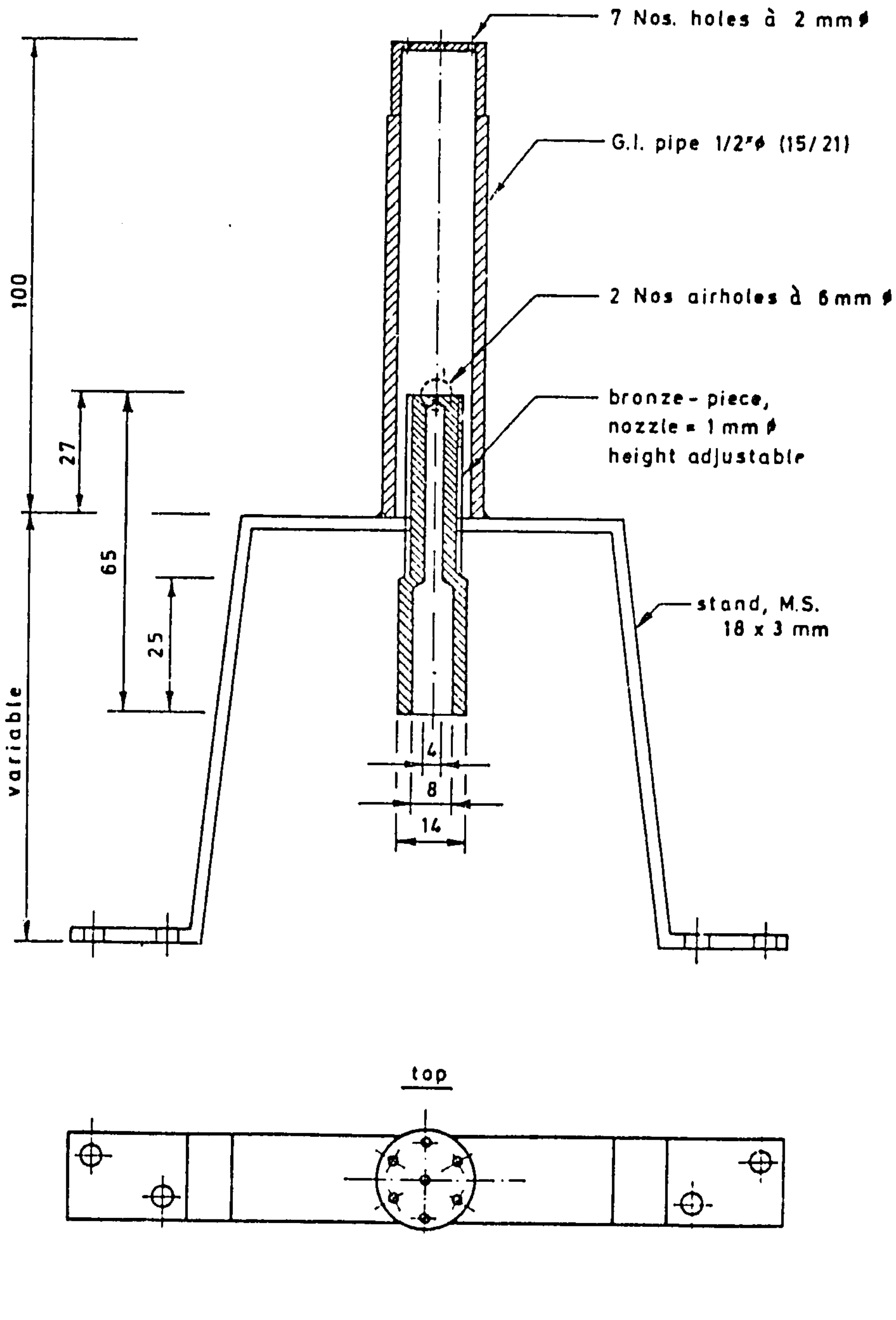


Figure 17. Biogas Burner for Absorption Refrigerator [6]

Shaft Power

As mentioned earlier, biogas can be used to power both spark ignition and compresstion ignition (diesel) engines. In the latter case, a small amount of diesel fuel, typically about 20 percent, must also be supplied because a diesel engine will not fire on biogas fuel alone. The engine therefore runs on two fuels--biogas plus diesel fuel--and is called a dual fuel engine.

The engines must be modified for use with biogas. With gasoline engines, the procedure is to drill a small hole near the choke and attach a 1/4 inch (7 mm) tube supplying biogas through a control valve. The engine is generally started on gasoline and then switched over to biogas while running. Several Indian companies now manufacture engines designed to operate on biogas.

Dual-fuel engines are modified diesel engines which induce a mixture of biogas and air into the cylinder together with a small charge of diesel oil, as shown in the diagrams below. One advantage of dual-fuel engines is that the higher compression ratios improve both output power and thermal efficiency. At a compression ratio of 12:1, a diesel engine is about 30 - 35 percent efficient [22]. Diesel engines can be converted, with a little more effort, to spark-ignition engines. The injectors are replaced by spark plugs, the compression ratio is lowered to 9:1, and an electrical system is added [23].

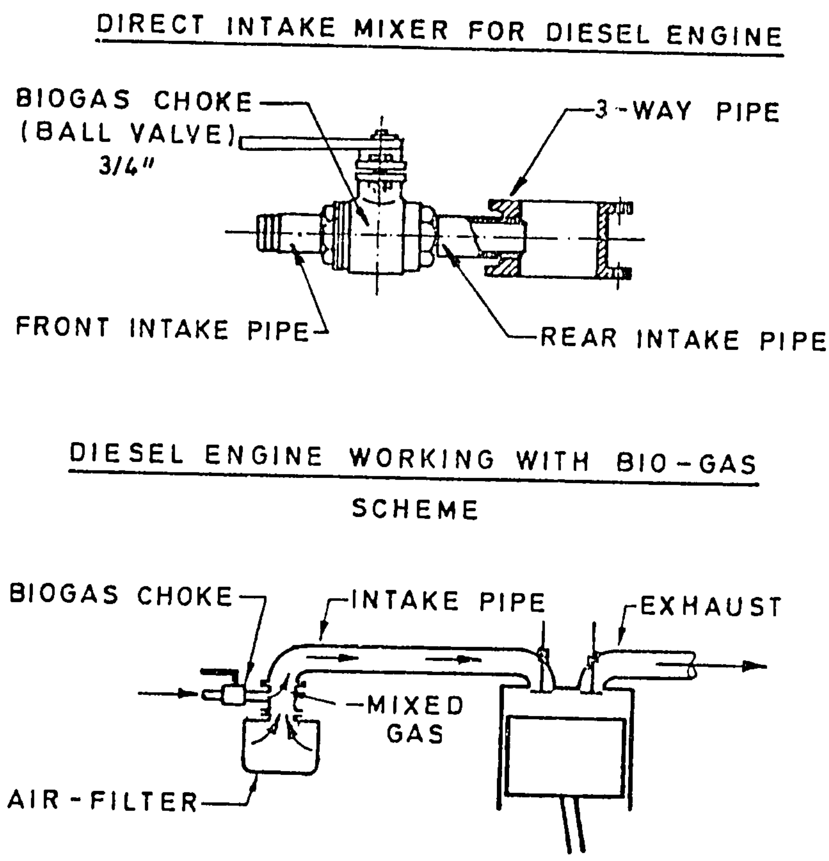


Figure 18. Piping Arrangement in a Dual-Fuel Engine [6]

Power Generation

There is increasing interest in biogas systems large enough to generate power in the low kilowatt range. China has pioneered in the use of biogas to generate electricity. In the province of Sichuan alone, there are over 300 small power stations running on biogas with an installed capacity of 1500 kW. Biogas fuel consumption is generally in the range of 600 - 1000 liters per kilowatt hour.

The world's largest power station is also in China--at Forshan, Guangdong. There are two generators in the station. One is a diesel generator set rated at 50 kW; the other is a gasoline generator set rated at 40 kW. Both sets are spark ignition--the diesel engine was converted. A flow sheet of the process is shown below. An interesting feature of the system is the gas holder, which consists of two balloons, each with a volume of 120 m^3. The balloons are made of PVC film with a thickness of 0.28 mm [24]. The biogas is held at very low pressure; when full, the pressure in the balloons is 3 cm water gauge. The plant runs on nightsoil: 170 tons per day is fed to 28 interconnected 47 m^3 digesters.

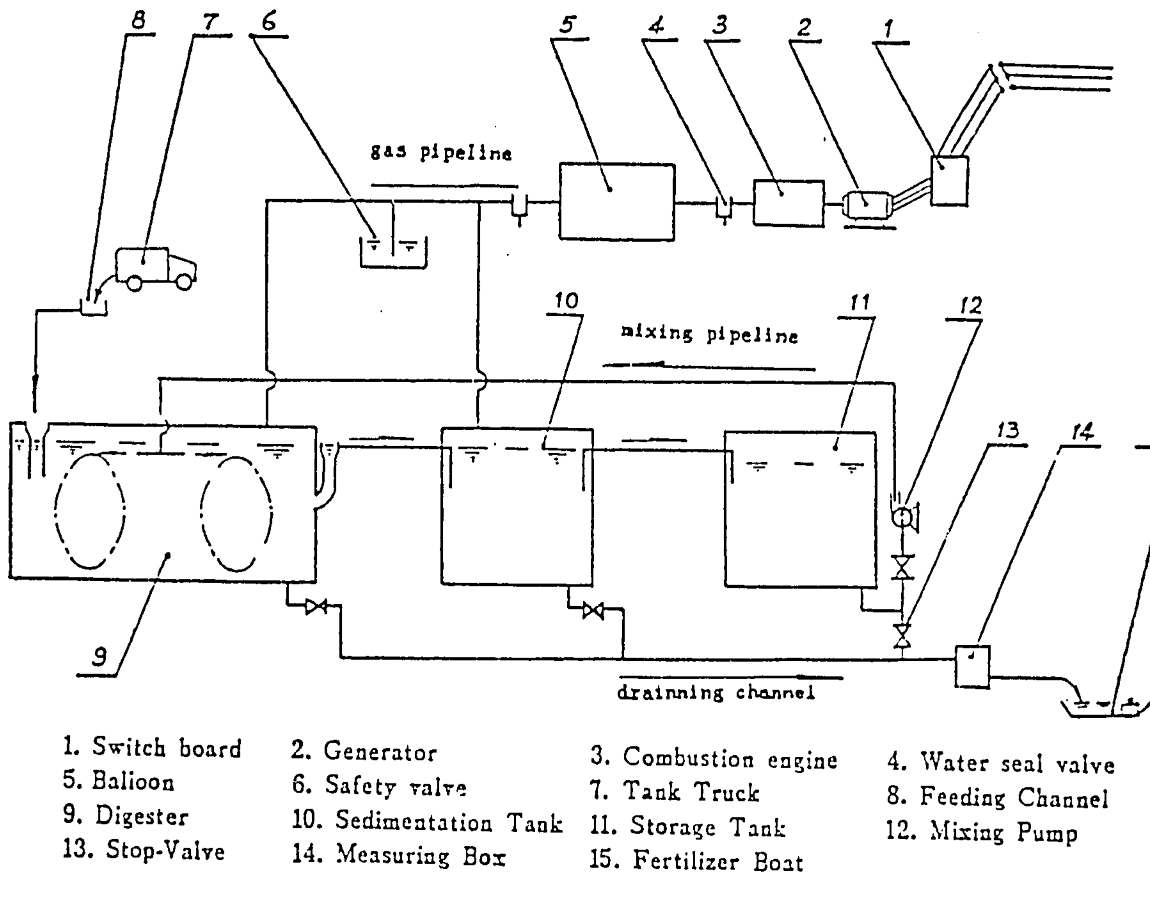


Figure 19. Diagram of Jun Qiao Biogas Power Station in Forshan, Sichuan [24]

Waste Heat Recovery

Although the efficiency with which biogas may be used to generate shaft power and electricity may appear low, being roughly 15 - 25 percent in the case of electricity generation, there is one very important factor that needs to be taken into account. The waste heat from the engine can easily be used to warm the digester, an operation that can drastically improve biogas production. Anytime that biogas is used in engines and generator sets, consideration should be given to using the waste heat to warm the digester.

Sludge Utilization

The composition of the sludge produced by anaerobic digestion is determined by both the operation of the digester and the composition of the raw material used as feedstock. It is commonly assumed that in a well-functioning digester about 70 percent of the organic constituents are decomposed. The organic fraction of the sludge produced from the digestion of plant and animal waste may therefore be expected to contain about 30 percent of the original weight of the organic material in the feedstock. This organic component of the sludge consists of three types of material: undecomposed organics protected from digestion by lignin and cutin, newly synthesized bacteria, and small amounts of volatile fatty acids. The amount of bacteria is generally small because anaerobic cultures typically convert only about 10 - 20 percent of the carbon substrate to cell mass.

Anaerobic digestion of plant residues and animal wastes conserves the nutrients needed for the continued production of crops. The only materials removed from the mixture are the gases generated--methane, carbon dioxide and a trace of hydrogen sulphide. In particular, it is a major advantage of the anaerobic digestion of plant residues and animal wastes that practically all the nitrogen present in the feed material remains in the slurry.

The distribution of total nitrogen in the sludge, between organic and ammonium nitrogen, depends on the distribution in the raw material. The greater the nitrogen content of the material fed to the digester, the greater will be the concentration of ammonium nitrogen in the sludge. However, this form of nitrogen can volatize and will be lost if the digested sludge is not stored under cover, or injected beneath the soil surface during cultivation. To minimize these losses, the sludge should be stored in deep lagoons or tanks that present a minimum of surface area for ammonia volatilization. The nitrogen content of several different types of digested sludges is given in the table below

Table 8. Nitrogen Content of Sludges

Sludge	Nitrogen, % dry wt
Raw sewage	1.0 - 3.5
Activated sludge	4.0 - 7.0
Digested sludge	1.0 - 4.0
Digested manures	
Hog	6.1 - 9.1
Chicken	5.3 - 9.0
Cow	2.7 - 4.9

Adapted from Woods [15].

In a study for the Indian Institute of Science [7], Rajabapaiah found that the sludge from an Indian-type digester running on cow dung had a nitrogen content of 2.2 percent (dry weight), and a total solids content of 6.67 percent. The effect of strong fresh sludge and raw dung in the open air was also studied. On standing, the nitrogen content of cattle dung fell from an initial value of 1.7 percent to a final value of 0.9 percent over a 10-day period, after which it stayed constant. In contrast, the sludge effluent decreased from 2.2 percent to a constant 1.9 percent in 3 days.

The result of applying anaerobically digested sludge on soils is the same as for any other kind of compost: the humus materials formed improve soil properties such as aeration and moisture-holding capacity, and increase cation-exchange capacity, water-infiltration capacity, etc. Moreover, the sludge serves as a source of energy and nutrients for the development of microorganism populations that directly and indirectly favor the solubility --and thus the availability to higher plants--of essential nutrients contained in soil minerals. [8].

It is interesting to note that although most people regard anaerobic digestion as primarily a source of fuel gas, and believe that the greatest benefit of the technology is to be derived from the utilization of this source of energy, a number of experts dispute this view. For instance, S.K. Subramanian states flatly, "The greatest benefits from biogas digesters are to be derived from the manurial value of the slurry; however this fact is not well known outside India and China." [17]

Health Benefits

The anaerobic digestion of organic material for biogas production provides a public health benefit greater than that of any other treatment likely to be used in the rural areas of developing countries.

Survival data for some of the more important enteric microorganisms are given in the table below.

Table 9. Die-off of enteric microorganisms of public health significance during anaerobic digestion

Organisms	Temperature (° C)	Residence Time (1) (days)	Die-off (%)
Poliovirus	35	2	98.5
Salmonells ssp.	22-37	6-20	82-96
Salmonells typhosa	22-37	6	99
Mycobacterium tuberculosis	30	Not reported	100
Ascaris	29	15	90
Parasite cysts	30	10	100 (2)

Adapted from reference 8.

Notes 1. Time indicated is time of digestion
2. Does not include Ascaris.

These examples clearly show the importance of anaerobic digestion in the treatment of human wastes. With few exceptions, pathogenic enteric microorganisms are effectively killed off if the digestion time is 14 days or longer and if the temperature is close to 35° C.

Studies of viruses typical of those hazardous to man show that anaerobic digestion at 35° C for 14 days will result in a 99.9 percent die-off [8].

In Chinese investigations of 19 operating biogas plants, a comparison of the digested slurry with the incoming fecal liquid showed that the total number of parasite eggs was reduced by 93.6 percent, the average number of hookworms was reduced by 99 percent, no schistosome flukes were found, and the number of dead ascarid eggs was high. Tests showed that parasite eggs could survive in the digesters for 14 days in autumn and 37 days in winter (when the slurry temperature is lower) [18].

Once the sludge has been removed from the digester, microorganisms continue to die off because of the lack of nutrients and the hostile environment. This die-off continues both during storage of the sludge and after the sludge has been applied to the soil.

The magnitude of the health hazard created by the use of digester sludge as fertilizer depends on the concentration of pathogens entering the digester, the rate of die-off during digestion (whicn increases with higher digester temperatures), and the rate of die-off during sludge storage and when in the soil. However, there is no other practical method of treating human excreta--whether for disposal or to return nutrients to the land as fertilizer--that will reduce the burden of pathogenic organisms as much as anaerobic digestion [8].

Biogas Economics

The economic analysis of biogas systems is a complicated task. It is difficult to evaluate the worth of the inputs to the system, and of the outputs from it. For instance, the dung used to feed the digester has a value as a fertilizer, a different value when used as a fuel. The biogas produced can be valued as a substitute for kerosene, wood fuel, or electricity, and each option gives a different result.

There are other less tangible benefits. There is a benefit derived from the slurry which has a greater efficacy than might be expected by simply measuring its nitrogen content. The digester improves the health of the family or community by disposing of unsanitary and potentially hazardous excreta, and also by providing a clean fuel gas in place of dung fuel--a fuel that produces an acrid smoke that can cause inflammation and disease of the eye and lung. How is this benefit to be evaluated? Biogas can substitute for wood fuel, thus freeing children and women from the time-consuming task of collecting wood, leaving them time for other productive tasks: this benefit is also difficult to assess.

There have been many analyses carried out on the costs and benefits of biogas plants. An excellent review of a number of case studies, as well as a good discussion of the theory and limitations of cost-benefit analysis, with particular reference to biogas plants in developing countries, is provided by Barnett in the IDRC review [17]; Lichtman [9] also gives an interesting analysis of the situation in India.

The approaches taken to the analysis of biogas system economics include the following:

(1) Biogas can be seen as providing a fuel and can therefore be evaluated in terms of its ability to meet some of the villages' energy needs in comparison with other sources of energy. The comparison might include: (a) firewood, which in many areas is becoming increasingly time-consuming to collect because of its scarcity; (b) electricity. which is not usually used for cooking but can have very low marginal costs where there is surplus capacity in existing generating capacity, and the village is close to existing power transmission lines; and (c) at a different level, the comparison can be legitimately made with alternative practices associated with the use of existing fuels; for instance, considerably less wood might be consumed if the design of stoves were made more efficient.

(2) Biogas plants provide fertilizer in the form of the spent slurry and might therefore be compared with aerobic composting processes or the provision of chemical fertilizer.

(3) Biogas has been advocated as a substitute for other activities that are considered harmful or wasteful, such as the burning of dung and wood. The dung might be better used as fertilizer, and the burning of wood has resulted in deforestation of some areas, which in turn, has led to erosion and flooding. The comparison here might be with composting or the growing of trees and other plants (such as water hyacinth) for fuel.

(4) Another function for the biogas plant is the safe disposal of human and animal (usually pig) manure; here the alternatives for comparison might again be composting processes or more conventional waste disposal through lagoons and septic tanks.

(5) Investment in biogas might alternatively be seen as a means of utilizing village resources that are currently going to "waste" (or at least being underutilized). This way of looking at the problems provides certain insights, and is another formulation of the more general economic problem of optimum use of all resources.

Capital Costs

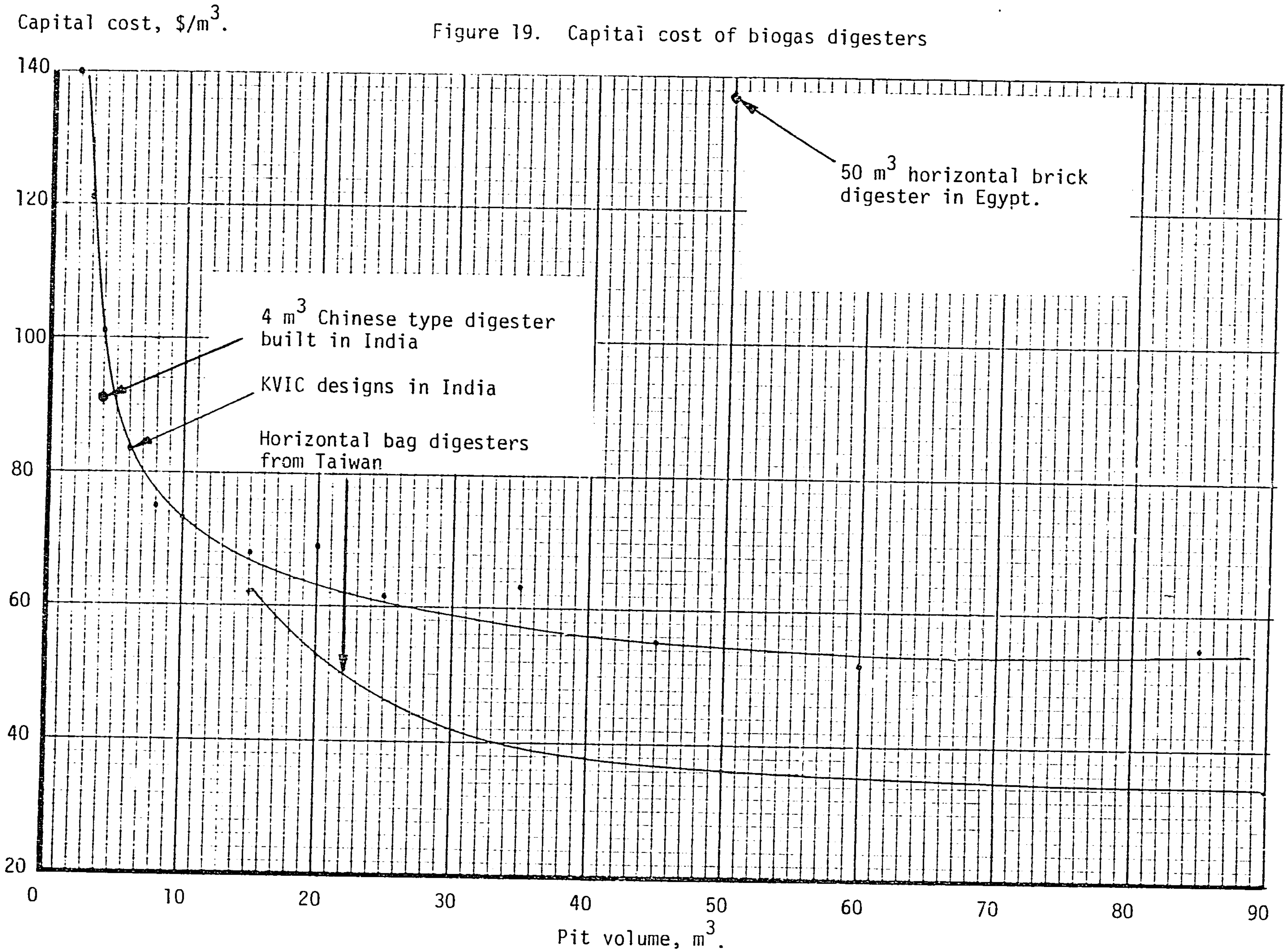
The capital costs of the digesters vary enormously. At the very low end of the scale there are the digesters built in China, which can reportedly be constructed for less than $30 for a family-size unit (8 - 10 m^3). But this cost does not include the opportunity cost of labor which may be considerable; a team of 3 - 5 workers may take 8 - 10 working days to build the digester [4].

At the other end of the scale, there is the cost of large digesters (160 m^3) built in the U.S., and very small digesters (2 m^3) built in India, which both have capital costs of about $140/$m^3$ [10, 21]. In between these extremes, there are a multitude of designs and sizes with capital costs generally in the range of $40 - $140/$m^3$. The variation of costs on a unit volume basis is considerable; there are significant economies of scale as the chart overleaf shows.

The curve for the red mud plastic bag digesters does not include civil works and installation costs which, when included, could well raise the cost of such a system to about the same level as for the KVIC design. In addition, a separate gas holder is required with horizontal digesters; this raises the total system cost still further.

The 4 m^3 Chinese-type digester data point is based on a system constructed in Pondicherry in 1981 (see Appendix 1); the Egyptian system is based on the data given in reference 11. Rupees have been converted at Rs 10 = $1, Egyptian pounds at $1 = 0.7 pounds. The KVIC prices are for 1978; the prices for the red mud plastic bag digesters from Taiwan were quoted in June 1983 [25].

Figure 19. Capital cost of biogas digesters



Financial Analysis

As an instance of a simplified analysis of a small biogas digester, we take the example given by the KVIC in their small booklet [21] which also forms the basis of the cost/income analysis presented in the NAS book [8]. A description of the plant, and some of the assumptions made in the analysis are given below.

Design	KVIC, metal floating gas cover
Size	6 m^3 (pit volume)
Gas production	1 m^3/day per m^3 pit
Dung feed	14.8 tons/yr
Dung value	40 Rs/ton as fertilizer
	57.8 Rs/ton as a fuel
Capital cost	Rs 5010 (incl. pipelines & civil works)
Operation & maintenance	100 Rs/yr
Gas value	0.744 Rs/m^3
Slurry value	50 Rs/ton
Slurry produced	22.32 tons/yr

The analysis then proceeds as follows:

Annual expenses	Rs/yr
Interest at 12% on capital to be repaid in 5 installments	360.72
Gas holder; depreciation over 10 yrs at 10%	200.00
Pipeline and appliances; depreciation over 30 years	24.75
Civil work; depreciation over 40 years	56.50
Operation & maintenance	100.00
Cost of dung:	
a) valued as fertilizer	592.00
b) valued as a fuel	or 855.60

Total expenses: 1333.97 Rs/yr or 1597.57 Rs/yr depending on the valuation of the dung.

Annual income	Rs/yr
Gas ($6 \frac{m^3}{day} \times 0.744 \frac{Rs}{m3} \times 365$)	1629.36
Slurry ($22.32 \frac{ton}{yr} \times 50 \frac{Rs}{ton}$)	1116.00
Total income	2745.36 Rs/yr

So based on the assumptions used in this analysis, it would appear that the biogas plant earns between 1148 and 1411 Rs per year. The value attributed to the dung (used as fuel) and the gas in this example is determined by the amount of kerosene used for cooking that would be displaced by using either the dung or the biogas instead.

It must be stressed however that the digester only pays for itself if the biogas actually substitutes for a commercial fuel; the value of the slurry is not enough to pay for the annual expenses of the plant. If the gas is used in the home for cooking, where the fuel previously used was obtained at little or no cost (wood, for instance) then the biogas plant will certainly not generate sufficient income to offset its expense.

The strong economies of scale demonstrated in the previous chart suggest that large biogas sytems might be a more attractive proposition than the smaller family-size digesters.

For instance, consider the horizontal digester recently built at Santa Center in the Nile delta and shown on p 14. This 50 m^3 digester operates on chicken manure from one of the many poultry rearing businesses in the area. The farms raise about 5000 chicks in a 65 day cycle.

The poultry farms have two major problems. The first is the difficulty of obtaining the butagas bottles needed for keeping the chicks warm. If the fuel is not available the chicks will die, so there is a strong incentive to ensure a reliable supply of this fuel by paying more than the official price; the cost of butagas is therefore about double for the farm.

Secondly, the accumulation of poultry droppings creates a problem. Sometimes they can be sold to land reclamation projects, but the disposal of the manure in this manner is not guaranteed. The manure is a source of pollution and is a potential health hazard for the chickens since diseases may be passed from cycle to cycle via contact with the droppings.

A biogas digester could help solve both problems; a unit was therefore designed and constructed in 1983 [11]. Details are given below.

Design	Horizontal, brick construction, separate gas holder
Size	50 m^3
Feed	167 kg/day (dry); 2 m^3/day slurry
Digester temperature	35° C
Gas production	1 - 1.2 m^3/day per m^3 of pit
Gas holder	separate unit, 20 m^3
Costs (Egyptian pounds)	
Digester	₤2000
Gas holder	₤1800
Heating system	₤1000
Gas distribution system	₤800
Solar green house	₤400
Operation and maintenance	₤180/yr
Gas used for heating	12 m^3 day (av.)

Assuming the biogas system is financed with a 10-year loan at 10% annual interest, which gives a capital recovery factor of 0.16275, the annual expenses incurred by the system are as follows

	LE/yr
Capital charges (6000 x 0.16275)	976
Operation and maintenance	180
	1156

The unit produces about 55 m^3/day of biogas of which 12 m^3 is used to heat the digester. The remainder of the gas substitutes for butagas purchased at LE1.25 per 12 kg bottle; 330 bottles are purchased each year.

On an energy basis 1 m^3 of biogas is equivalent to 0.433 kg of butagas, so the amount of butagas equivalent produced by the digester is 43 m^3/day x 365 x 0.433 = 6796 kg/yr. This is more than the total amount of butagas purchased over the year (330 x 12 = 3960 kg/yr), so the savings in purchased fuel are equal to 330 x LE1.25 = 412 LE/yr, only about one-third of the cost of running the digester.

This example is interesting because it illustrates one of the difficulties of introducing renewable energy technologies in competition with subsidized petroleum fuels. A 12 kg bottle of butagas has an energy content of nearly 600 MJ; at LE1.25 a bottle that works out to 2.1 LE/GJ or about 3 $/GJ--cheap energy!

The international price for a bottle of butagas in Egypt is reportedly closer to LE5 [11]. At that price, the biogas unit would save 330 x LE5 = 1650 LE/yr which more than covers the cost of operating the digester (1156 LE/yr).

It should also be noted that the biogas system produces, on average, about 18 m^3 more gas each day than is required to substitute for the butagas. This may be necessary in order to warm the poultry houses during the coldest part of the year when the amount of gas required will be higher. But during the summer months, and at other times of slack demand for biogas, it might be possible to utilize the gas for a task that provides additional income to the project.

Moreover, the analysis does not include any income or benefit arising from the sale or utilization of the slurry. Inclusion of this item would also improve the economics of the project.

Power Generation

The preceeding analyses enable one to estimate the economic viability of using biogas in stationary engines--either spark ignition or dual fuel diesel engines--as discussed earlier in the text.

We can simplify the analysis by assuming that the cost of dung to feed the digester is about equal to the income derived from the sale of the slurry as a fertilizer; an assumption which is not too far off the mark, and one which tends to overestimate the cost of the biogas produced by the system.

The first digester evaluated (the 6 m^3 KVIC design running on cow dung) had annual expenses of 742 Rs/yr. Gas production was estimated as about 2190 m^3/yr. So a cubic meter of biogas cost about 742/2190 = 0.34 Rs to generate. Converting that to dollars at Rs10 = \$1, gives the cost of biogas as 3.4¢ per cubic meter.

The second digester looked at (the 50 m^3 Egyptian design running on chicken manure) had annual expenses of 1156 £/yr. Gas production (net) was estimated as nearly 15700 m^3/yr. So the cost of the gas is about 0.074 £/m^3 and converting that at £1 = \$1.43, gives the cost of biogas as approximately 11¢ per cubic meter.

A diesel engine will consume fuel at the rate of approximately 0.4 liter per hour per kilowatt of shaft power. Biogas can substitute for at least 80 percent of this diesel fuel; gas consumption will be about 0.6 m^3/hr per kW of output. So 0.6 m^3 of biogas can substitute for 0.32 liters of diesel fuel which, at a price of say 40¢/L suggests a value for the biogas of about 21¢/m^3. This price is a good bit higher than the estimated cost of generating biogas calculated using the two case studies presented earlier. There is little doubt that biogas can compete with diesel fuel as a fuel for stationary engines.

Moreover, as mentioned earlier, the waste heat from stationary engines can be profitably utilized to warm the digester, increasing the volume of gas produced each day and improving the economics of the biogas system still further.

The same argument applies to diesel generator sets. A cubic meter of biogas can replace about half a liter of diesel fuel. If biogas costs less than 11¢/m^3 to produce, it can compete with diesel fuel costing as little as 22 cents per liter; in many countries diesel fuel, particularly in the rural areas, costs a good bit more than this.

Policy Considerations

The majority of biogas systems operating in the developing countries are small digesters generating small amounts of gas, 1 - 2 m^3/day, for use in the home, mainly for cooking. There are many advantages to using this technology. In providing a substitute fuel for kerosene or fuelwood--the common rural cooking fuels--biogas technology can help efforts aimed at slowing the pace of deforestation or reducing the level of imported petroleum. Moreover, the technology is good sanitary engineering practice--stabilizing potentially hazardous human and animal wastes, and minimizing the spread of infectious disease; the slurry is also an excellent soil conditioner and fertilizer.

In a few countries, notably China and India, there are many thousands of digesters in operation. But how successful are these programs and to what extent should biogas programs be promoted in other developing countries?

In China, the purpose of most of the digesters is to accomplish the sanitary treatment of pig and human waste; the fertilizer effect of the slurry is also recognized as important. The gas produced by the digester is considered to be of only secondary importance--a useful by-product. The digesters are built by "production teams" of workers, and involve very little capital expense. The digesters cost only about one-third the cost of the ubiquitous bicycle, and nearly every family in China has one of those [28].

Viewed in this way, as a farm waste treatment system which can be cheaply and easily installed, small digesters in China appear to be a successful technology.

In almost every other country, however, the technology is being promoted because of its ability to produce a fuel gas--biogas. Moreover, the digesters are considerably more expensive than those constructed in China. If money has to be borrowed in order to finance the construction of the digester, then for the system to be financially viable it must generate an income either by:

1. the sale of the gas or slurry

2. the sale of agricultural produce, the quantity or quality of which has been improved by the application of the slurry as a fertilizer

3. the substitution of the biogas for commercial fuels

A biogas system financed through a loan must be part of a cash economy if the loan is to be repaid. It should not be surprising then that in India it is generally the wealthier farmers who find biogas technology an attractive proposition.

This assessment has implications with regard to the assertion that biogas programs can significantly reduce the rate of deforestation in the developing countries. This seems possible only under two sets of conditions. First, in situations where the digesters can be built for almost nothing, as in China, the biogas will displace fuelwood, even if wood is available free of charge (although not of labor), because biogas is a much more convenient fuel to use than wood and the time-consuming task of obtaining the wood is avoided. Second, in situations where wood is purchased for cooking, then biogas from a digester financed with a loan might prove a cheaper proposition, and the demand for fuelwood might then subsequently diminish. However, this latter situation seems implausible; if people have the money to buy wood they will generally prefer to purchase kerosene for cooking, unless the wood is extremely cheap in which case, of course, the biogas cannot compete with the wood anyway. It is instructive to note that only in China is there any indication that the use of biogas in the home has reduced the demand for fuelwood.

Economies of Scale

It has been shown earlier that anaerobic digesters of all types enjoy considerable economies of scale. It is also apparent that biogas systems can compete effectively with commercial fuels. One area of application where the technology is therefore likely to be quite successful is in commercial agricultural operations that involve a large number of animals, and which require supplies of commercial fuels and electricity.

There are other advantages with larger biogas systems. Anaerobic digesters require a certain amount of skill to build properly. Small digesters in rural areas often suffer from structural defects caused by the use of inferior construction materials and poor workmanship. There have been reports that as many as one-third of China's 7 million digesters do not work properly because of leaking gas and leaking liquids. The digesters were simply not built properly.

It should be possible to avoid this problem with larger digesters. Since capital costs are higher with large systems, there is a much greater incentive to insist upon high standards of design and construction, and to more closely supervise the building of the digester.

It is often suggested that building larger digesters, which serve the needs of more than one family, is one way to bring the benefits of biogas technology to a wider socioeconomic group. However, many "community-scale" biogas projects have run into problems. A high degree of cooperation and trust is required of those that manage the digester and share its benefits. Not surprisingly perhaps, disagreements and disputes concerning the operation, maintenance, and management of the plant can quickly lead to a failed project, even if the project was technically sound and economically viable.

Social and Economic Issues

The experience with biogas technology in India has shown that the social and economic impact of the technology can sometimes give cause for concern. An anaerobic digester enables a very poor quality fuel--animal dung--to be transformed into a good quality fuel gas. The technology is therefore an attractive one for families that own several animals and which purchase commercial fuels. But gobar gas plants rely on a continuous supply of cow dung--a source of energy which is often available to the poorest families at little or no cost. Biogas technology raises the value of animal dung quite significantly--often to the point where the dung is no longer available to subsistence families who may depend upon it as a cooking fuel.

Data from India clearly indicate that it is the middle and upper classes that benefit most from the technology. A survey in Gujarat revealed that nearly 67 percent of digester owners were of medium socioeconomic status, and only 26 percent were from the low-income group. The individual families who owned biogas plants had, on average, 10 hectares of land and 10 head of cattle [17].

A survey in the State of Haryana, which has the highest number of biogas plants, revealed a similar pattern. In the five villages surveyed, the families who owned the plants were all in the upper third in socio-economic status. The situation is generally the same in the other Asian countries where biogas plants require a significant capital outlay.

Conclusions

1. Anaerobic digestion of biomass materials is an extremely useful technology, and one that can be benefically utilized in the developing countries. The technology improves sanitation, generates a good quality fuel gas, and produces a useful fertilizer; all of which are attributes of particular importance in the developing countries.

2. Countries unfamiliar with the technology should experiment with different digester designs, and should develop a system adapted to local socioeconomic, cultural, and environmental conditions.

3. Biogas technology is more likely to be economically viable on a larger scale than small family-size digesters. Commercial animal-raising operations and businesses appear to present immediate opportunities for financially sound investments in biogas technology.

4. Programs designed to disseminate the technology at the family level should be carefully considered. If digesters are sufficiently expensive that they require financing, then the wealthier families are likely to be the principal beneficiaries.

5. Biogas technology raises the value of dung. If dung is available for free to very poor families, the introduction of biogas technology may have the effect of causing the supply of free dung to come to an end. If poor families turn to fuelwood as a cooking fuel it is conceivable that the introduction of biogas technology into a region could increase the demand for fuelwood.

6. Only if the digesters can be installed at extremely low cost will biogas technology significantly reduce the demand for fuelwood.

7. Community-scale biogas systems require very careful social as well as technical management if they are to be successful. The record suggests that successful community-scale biogas systems are the exception not the rule.

8. Anaerobic digestion is a proven waste treatment technology. Any business or operation that generates large amounts of dung, sewage, or any other kind of degradable waste should be considered a potential site for a digester. Food processing operations, farms, slaughterhouses, schools, prisons are all candidates for the installation of an anaerobic digestion system. The benefits arising from the sanitary disposal of the wastes alone may be sufficient to justify the construction of the system.

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$4m^3$ DRUMLESS BIOGAS DIGESTER
(Erected at Cazanove Garden)

Base diameter 3m, dome base dia. 2.6m, dome height 60cm, cylindrical portion 170cm high. Total volume 12 m^3 and gas volume $4.0m^3$. (Using 80kgs of cow dung per day.)

CONSTRUCTION DETAILS, MATERIALS & COST

INTRODUCTION:

Biogas on farms is an autonomous means of obtaining power, and fuel from the animal and farm wastes and fertilizer as a byproduct. On an integrated farm, it is a distinct and effective possibility. A design has been tried with the following objectives:

1) To study the feasibility of replacing compost pit with a drumless biogas plant.

2) To study the feasibility of constructing a drumless biogas plant with village level expertise and suiting local conditions.

3) To explore the possibility of using slurry for growing animal food, fish, etc.

METHOD OF CONSTRUCTION

A. FOUNDATION:

1) Foundation is dug to a depth of 2m of 3.6m diameter. The bottom is rammed to make it approximately level. Over this brickjelly is laid.

2) Brickjelly: Use 2cm to 2.5cm brick bats. Mix with stone lime in proportion 2 brick bats 1 lime. Dry mix them first then add sufficient water to make it workable. Place this initially, 23cm to 24cm thick which when consolidated properly by ramming will settle to 20cm.

3) Cement concrete: This should be 1:2:4 proportion (1 cement, 2 sand, 4 pebbles). This should also be thoroughly dry mixed and water added approximately 25 to 27 litres per bag of cement. Place this mixture first in a layer of 3cm thick. Over this place the grid (6mm bars at 15cm centres both ways). Over this place the remaining 7cm concrete. Use 1% soap water for mixing instead of plain water (1kg of soap in 100 litres of water. The soap is easily dissolved in boiling water).

B. DIGESTER SUPERSTRUCTURE

4) Brickwork: It should be started after one day of laying the cement concrete. The base circle should be drawn first (3m inside diameter and 3.5m outside diameter). The brick layer should follow these circles. Usual english bond and 1:1:8 combination mortar with soap water should be used for the brickwork here. As the wall is sloping inside (for reducing the gas pressure on the dome and increasing earth pressure on the walls), which reduces the base diameter by 40cm at the

base of the dome, each layer of bricks should project inside by 8 mm. It would be better to make a template as shown which should be used for checking the slope of the brickwork. Over the openings for the inlet and outlet, 10cm deep R. C. lintel with three 6 mm bars should be provided. The inlet and the outlet chamber brickwork up to ground level should now be done and left till the last, i.e., till all inside work is over. This will provide easy access to the inside. At the base of the dome the brickwork is extended in the form of a cornice as shown in the drawing, this is for the rigidity of the dome at the base.

5) Construction of the dome: First build a small temporary pillar, 30 x 30 x 70cm high at the centre of the base. This should be removed after the dome construction. A nail should be driven exactly at the centre with a small projection where a nylon or cotton string can be attached. The string should be about 2 metres long and a mark should be prominently made at a distance of 160cm from the nail by tying, say a coloured thread. This is the radius of the dome. Next get 7 to 8 thin bamboo strips. The nail should be partly driven, i.e., it will project nearly 1" from the bamboo. This is for the support of freshly laid bricks on the dome. Now the construction may be started. The inner face of the cornice, which has been provided at the base of the dome, is now plastered at the proper angle in line with the centre, in 1:4 cement mortar, with soap water. Two 6mm bars should be laid all round in a circle at the outer edge of the base and embedded in this mortar. The brickwork for the dome should also be carried out in 1:4 cement mortar, but here add 200 gms of washing soda per bag of cement for quicker setting. Ordinary bricks should be laid in this mortar and during laying each brick should be first checked with the mark of the string for its correct position and then should be supported by the bamboo strip, the projecting nail supporting the brick.

After laying 5 to 6 bricks in this manner it will be found that the cement has set sufficiently for the second brick to carry its own weight. The bamboo support may be removed and may be used for there seventh brick. The support for the first brick should not be removed until the ring is complete. If there is some difficulty experienced regarding the setting then some more time should be allowed for the cement to set before removing the support. Obviously, it would be much better if the bricks are cut to shape and size beforehand to follow the curvature of the dome. (Shown in the drawing). But it may be rather laborious to do it, so one can use two or three ordinary bricks and then cut one brick to shape and size for the layers near the base of the dome. It will make the curvature slightly undulating and which can be corrected by plastering. Thus each layer of brick will be concentric circle following the dome curvature. The dome construction can be carried out like this without preparing any form-work beforehand. It takes nearly 2 days to complete the dome of this size with one mason and two helpers. Of course, as the radius of the opening of the dome becomes smaller and smaller, the bricks will require shaping more frequently. The nail on the ba-boo should support the freshly laid brick so the bamboo may have to be placed on bricks to obtain the correct height. The 2 1/2" G.I. pipe for stirrer should be fixed at the centre of the dome. 2cm thick plaster in 1.4 cement mortar with Accoproof should be applied on outside of the dome. Then one layer of chicken wire mesh should be placed over the whole area and another layer of 2cm thick, 1:4 cement mortar should be applied over it. Over this, one layer of acchakal bricks should be laid, not in layers but in a criss-cross way, in combination mortar (1:1:8) and plastered over it with the same combination mortar, using soap water instead of plain water. It is understood that scaffolding should be provided wherever it is necessary. No weight should come on the dome until it is set and complete.

C. FINISHING & SEALING

6) Plastering: Before starting inside plastering of the digester, all joints should be raked with a thick nail to a depth of at least 1cm all over, including the dome. Then 1:4 cement mortar with Accoproof should be used for plastering the inside including the walls and the dome and a neat cement finish should be given all over. The plastering should be cured for at least 3 days with frequent spraying of water all over. It should then be allowed to dry for 3 days and then hot bitumen in liquid form should be applied to the dome and the walls. This will make it fully gas and water-tight. Now complete the inlet and the outlet chambers in combination mortar. Inside plastering should be finished in neat cement. The outside of the digester need not be plastered and should be filled with excavated earth and the dome also should be covered with 15cm of earth. Now loading may be started if it is ten days after completion of the dome. Otherwise allow at least 10 days after completion of dome.

Note I: The digester is designed to take gas pressure of 100cm water head. Although the pressure will be released from the digester if the slurry level goes down, it would be better to provide additional safety arrangement.

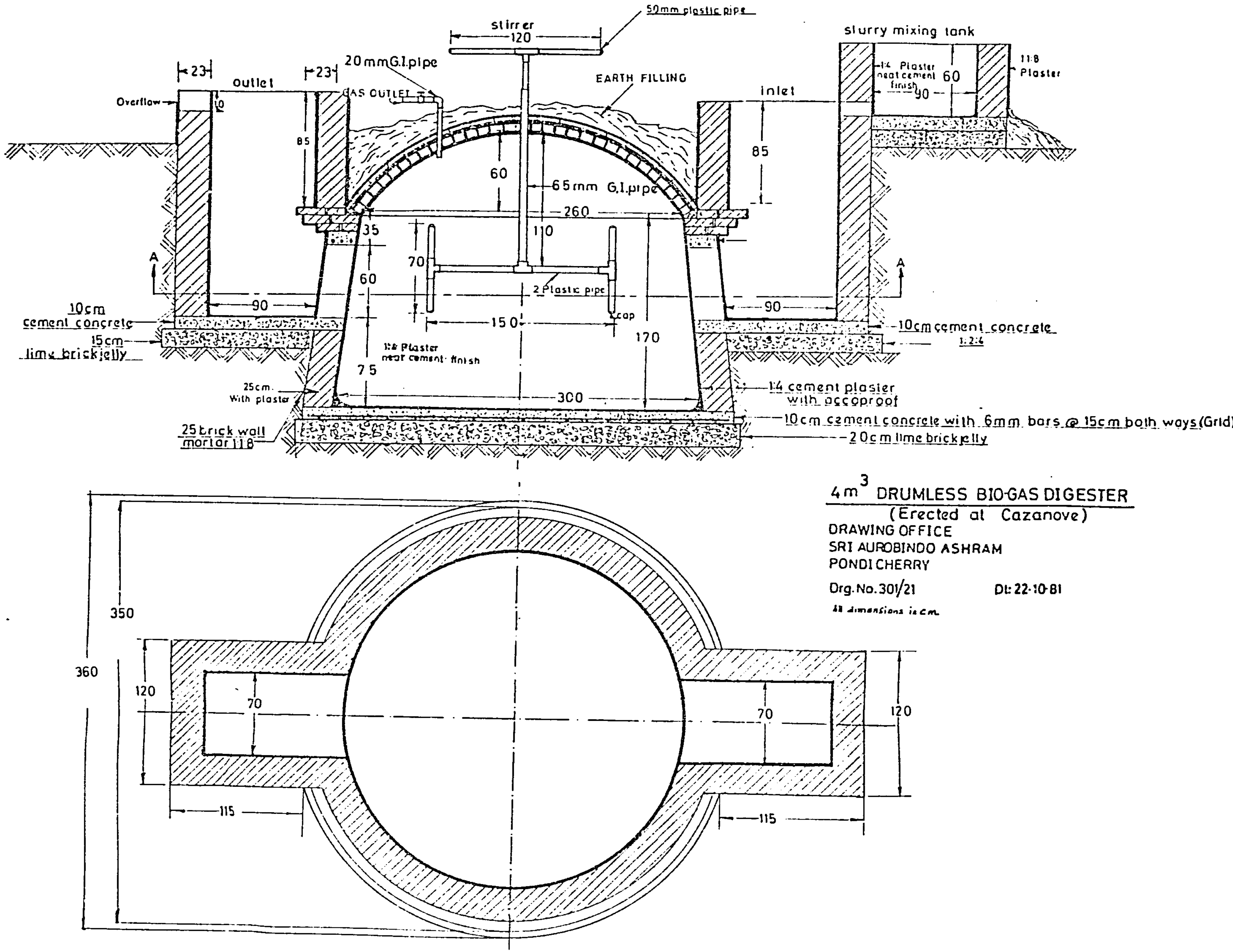
For this purpose, there should be one water manometer provided to check the gas pressure inside the digester and it should be so designed that it also acts as safety valve.

The design shown in the drawing may be adopted and connected at any convenient point on the gas line, where it could be observed easily.

Note II: Gas is likely to leak slowly and continuously if there is the slightest crack or porosity in the space where gas is collected. This, obviously is most undesirable as the output of the digester will be reduced and even it may become nil. All masonry and plastering work should therefore be done properly under good supervision so that there is no chance of having any porous area or cracks.

Drawing Office
Sri Aurobindo Ashram, Pondicherry

Date: 28.10.81

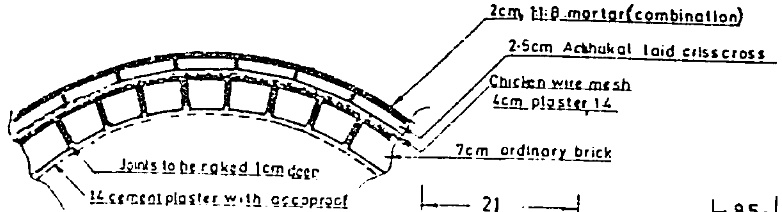


4 m³ DRUMLESS BIO-GAS DIGESTER
(Erected at Cazanove)

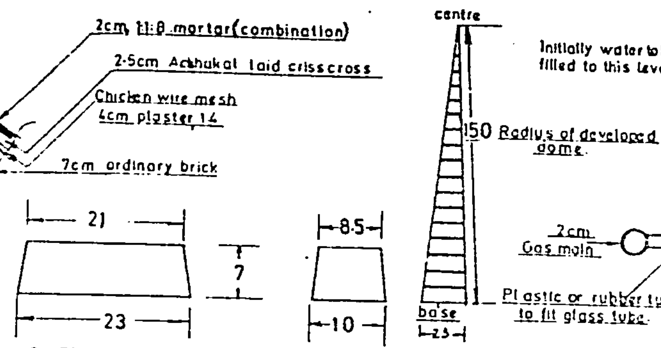
DRAWING OFFICE
SRI AUROBINDO ASHRAM
PONDICHERRY

Drg. No. 301/21 Dt: 22-10-81

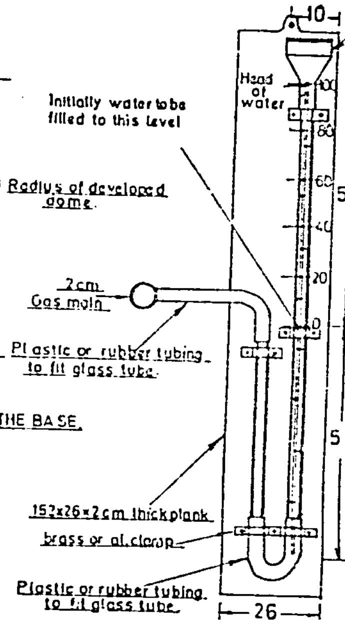
All dimensions in cm.



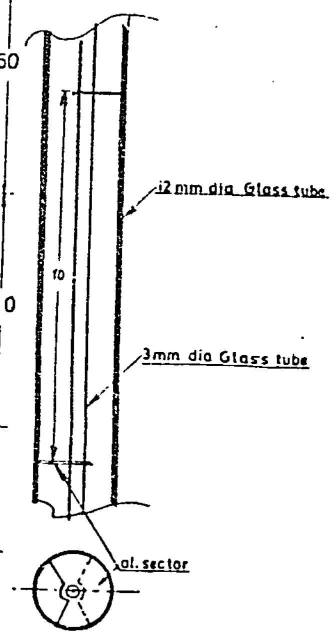
DOME DETAIL (1:10)



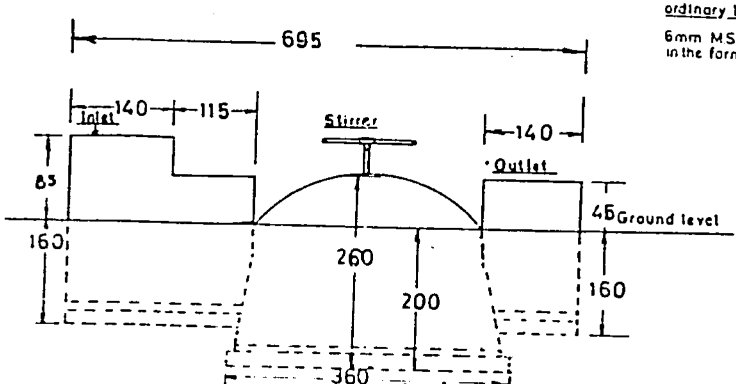
SHAPE OF THE BRICKS TO BE CUT FOR THE LINE AT THE BASE. FOR OTHER LINES THE ANGLE WILL DIFFER (1:5)



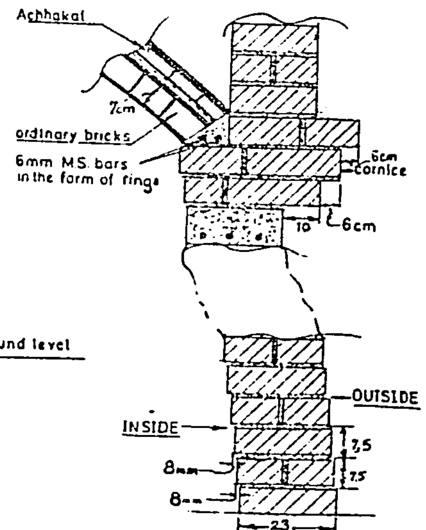
MANOMETER (1:7·5)
(cum safety valve)



GLASS TUBE DETAIL



ELEVATION (1:50)



WALL DETAIL (1:10)

$4m^3$ Drumless Biogas Digester Cost as on July 1981

A. MATERIALS

1.	Bricks	- -	- 4300 nos	= Rs. 623.50
2.	Achhakal	- -	- 400 nos	= Rs. 32.00
3.	Cement	- -	- 32 bags	= Rs. 900.50
4.	Sand	-(8.5m^3)	- 1.5 lorry	= Rs. 120.00
5.	Lime	-(2.3m^3)	- 3 carts	= Rs. 288.00
6.	Pebbles	-(1.5m^3)	- 2 carts	= Rs. 50.00
7.	Accoproof	-	- 12 pkts	= Rs. 84.00
8.	6mm M.S. bar	-	- 120 m	= Rs. 145.00
9.	Binding wire	-	- 1 kg	= Rs. 7.50
10.	Chicken wire mesh		- 10m x 1m	= Rs. 50.00
11.	Washing soap	-	- 10 kgs	= Rs. 30.00
12.	Bitumen	- -	- 3 kgs	= Rs. 13.50
13.	"Araldite"	-	- 1 pkt	= Rs. 16.00
14.	G.I. pipe - size 2 1/2"		- 1.5m	= Rs. 50.00
15.	Plastic pipe 2" dia.		- 6m with fittings	= Rs. 235.00
16.	Sundries	- -	- - -	= Rs. 10.00
				Rs. 2655.00

B. LABOUR

1.	Excavation	- -	20m^3	= Rs. 100.00
2.	Mason	- - -	25 man days	= Rs. 375.00
3.	Helper	- - -	80 man days	= Rs. 400.00
				Rs. 875.00

A. Materials	- - - -	= Rs. 2655.00
B. Labour	- - - -	= Rs. 875.00
		Rs. 3530.00
Manometer cost	- - - -	= Rs. 100.00
	Total	Rs. 3630.00

- - - - - - - - - - - -

Drawing Office,
Tata Energy Research Institute
Field Research Institute
Sri Aurobindo Ashram,
Pondicherry 605002

Date: 29.10.81

Biomass Gasification

Modern mechanized transport relies almost exclusively on petroleum fuels. This single sector absorbs between 20 and 40 percent of the petroleum used in developing countries. For the oil-importing developing countries, the transportation sector is obviously one area where efforts to reduce oil imports should be focused. Is there a way to fuel the gasoline and diesel engines without using costly imported petroleum?

There are a number of technologies that show promise in the effort to reduce the hydrocarbon energy consumption of the transportation sector. One of these technologies is biomass gasification.

Gasification is the thermochemical breakdown and the partial oxidation of biomass materials, usually wood or charcoal, to produce fuel gas. This gas, commonly called producer gas, while not a particularly high quality fuel, is quite capable of powering either gasoline or diesel engines. Moreover, the gasifier although somewhat bulky is portable, and can easily be carried by the vehicle to which it supplies fuel.

Like most renewable energy technologies, biomass gasification is not a new idea at all. In fact, only 30 to 40 years ago gasifier units for trucks, buses, and other vehicles were being produced by the thousands in Europe. And the circumstances that caused this sudden surge in popularity bear some similarity to the energy situation that the developing countries find themselves in today.

The war in Europe in the late 1930's completely and totally disrupted oil supplies. By the early 1940's petroleum supplies for many European countries had almost run out. The technology that came to the rescue was gasification. In 1938 there were perhaps 10,000 vehicles running on producer gas world-wide: by 1942 the number had risen to almost a million! Sweden converted 40 percent of its entire motor vehicle fleet to gasifiers. Germany alone had 350,000 vehicles running on biomass at this time, including at least 50 Tiger Tanks [1].

After the European war, with cheap petroleum once again available throughout the continent, people turned back to the more convenient gasoline and diesel fuels. The bulky and awkward gasifiers were thrown out and discarded. Only in Sweden, a country with plentiful supplies of wood, and where people are perhaps more prudent, did research continue on the principles of gasification and the development of improved gasifier systems.

Basic Principles

The gasification of solid fuels is accomplished by high-temperature thermochemical processes, similar to combustion, that convert the fuel to a gas with only a small loss of the energy of the solid fuel. Complete combustion is not permitted to occur since the supply of air is limited; gasification takes place with excess carbon present. Solid fuels are gasified by placing them in a sealed, closed chamber. The fuel is ignited at one point and exposed to a controlled blast of air. The gas is then drawn off from the chamber. A simple gasifier chamber is shown below.

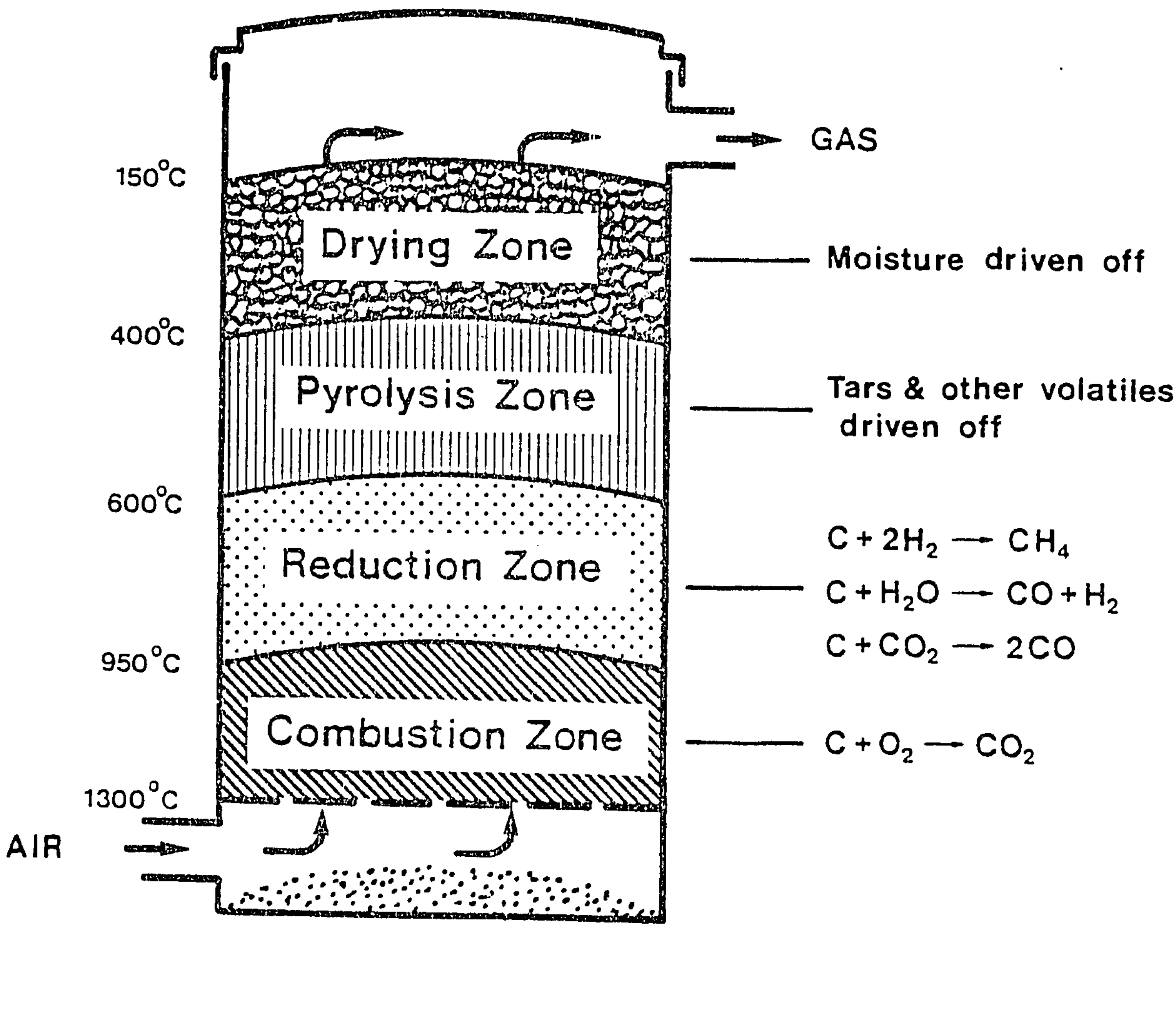


Figure 1. Schematic Diagram of Gasification Process Showing Principal Thermochemical Zones [4].

As shown above, a number of thermochemical zones can be identified, distinguished by both the type of chemical reactions taking place and the temperature of the material within the zone.

In the immediate vicinity of the air blast the fuel, now in the form of carbon is undergoing combustion. This zone is called the hearth zone or the combustion zone. The exothermic reaction taking place is

$$C + O_2 \longrightarrow CO_2 + 393.8 \text{ kJ/mol}$$

This zone is the hottest part of the gasifier; the temperature typically reaching 1000° C or more.

Above the combustion zone is the reduction zone, where the carbon dioxide gas is reduced to carbon monoxide; hydrogen and a small amount of methane are also produced. The principle reactions can be represented by

$$C + CO_2 = 2CO \quad - 176.6 \text{ kJ/mol}$$
$$C + H_2O = H_2 + CO \quad - 131.4 \text{ kJ/mol}$$
$$CO + H_2O = CO_2 + H_2 \quad + 41.2 \text{ kJ/mol}$$
$$C + 2H_2 = CH_4 \quad + 75 \text{ kJ/mol}$$

The water (steam) that takes part in these reactions is present in the biomass fuels.

Above the reduction zone is the distillation or pyrolysis zone where the biomass fuel is being broken down thermochemically at temperatures between 200° C to 600° C to yield gases, pyrolytic oils, and char. This is a necessary first step for the gasification process to proceed.

Finally the drying zone is that part of the gasifier chamber where temperatures are too low for thermochemical decomposition, but high enough (>100° C) to drive off water from the biomass fuels.

The gas leaving the gasifier, commonly called producer gas, will contain carbon monoxide, hydrogen, carbon dioxide and methane. Nitrogen from the air supply passes through unchanged; also present is water vapor and traces of other hydrocarbon gases. Typical volumetric compositions are indicated below [3].

Table 1. Typical Composition of Producer Gas

Constituent	Percent (vol.)
carbon monoxide	18-25
hydrogen	13-15
methane	3-5
other hydrocarbons	0.2-0.4
carbon dioxide	5-10
nitrogen	45-54
water vapor	10-15

The energy content of the gas is about 5 MJ/m^3. However, producer gas is not a clean gas; it generally conains a fair amount of fly ash, soot, condensible tars, and oils that would play havoc with an internal combustion engine. The gas must therefore be carefully cleaned if it is to be used in a gasoline or diesel engine. If the gas is to be burned directly to generate process heat, such cleaning equipment is generally not required.

Gasifier Types

A gasifier is basically a cylindrical or rectangular metal container with a grate at the bottom which supports the fuel. Part of the biomass is combusted in the vicinity of the grate, in the presence of a controlled amount of air, to generate sufficient heat to maintain the temperature necessary to effect the reactions indicated above.

In practice, gasifiers come in a number of different shapes and sizes, but 3 basic configurations are common. The most simple gasifier is called an updraft gasifier. Figure 2 below shows schematically the general structure of the device.

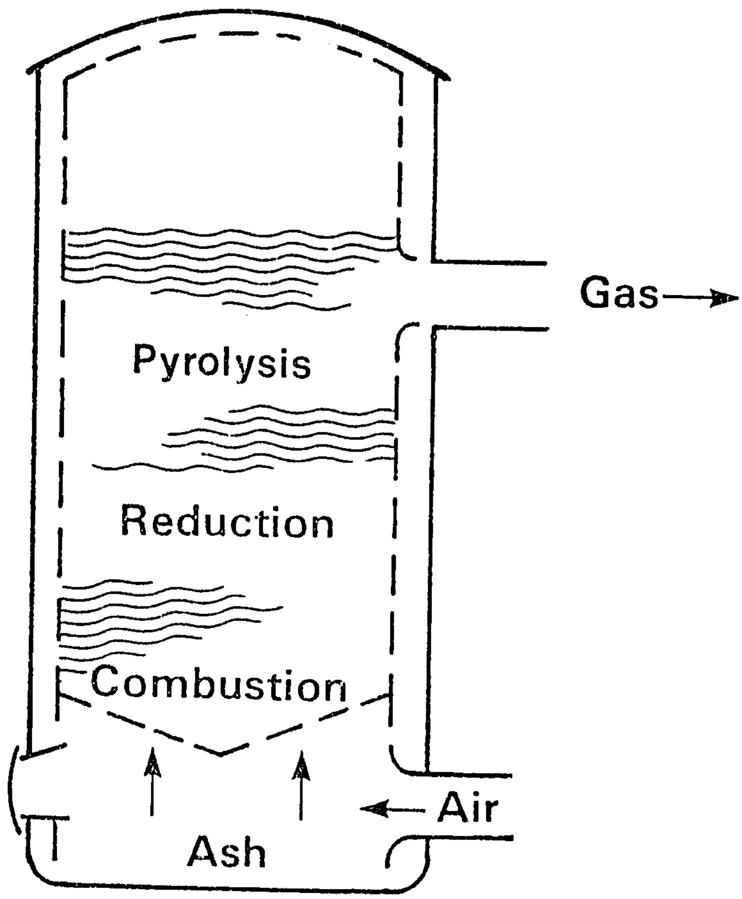


Figure 2. Schematic Diagram of an Updraft Gasifier [5].

Air enters the gasifier through the bed of hot biomass resting on the grate. At the level of the grate, combustion of biomass and char gasification occur. As the gases pass upwards through the gasifier (hence the name updraft), the temperature continues to fall and the gases leave the unit containing a significant amount of pyrolytic oils and water vapor. Because of the high content of vaporized tars and oils that are present in the gas produced by updraft gasifiers, this type of gasifier is not recommended for vehicle propulsion unless low tar fuels such as charcoal are used. However, updraft gasifiers operate without problems in direct combustion systems where the hot gas is burned for process heat.

In downdraft gasifiers, problems with oils and tars can be largely eliminated. The diagram below shows a typical arrangement.

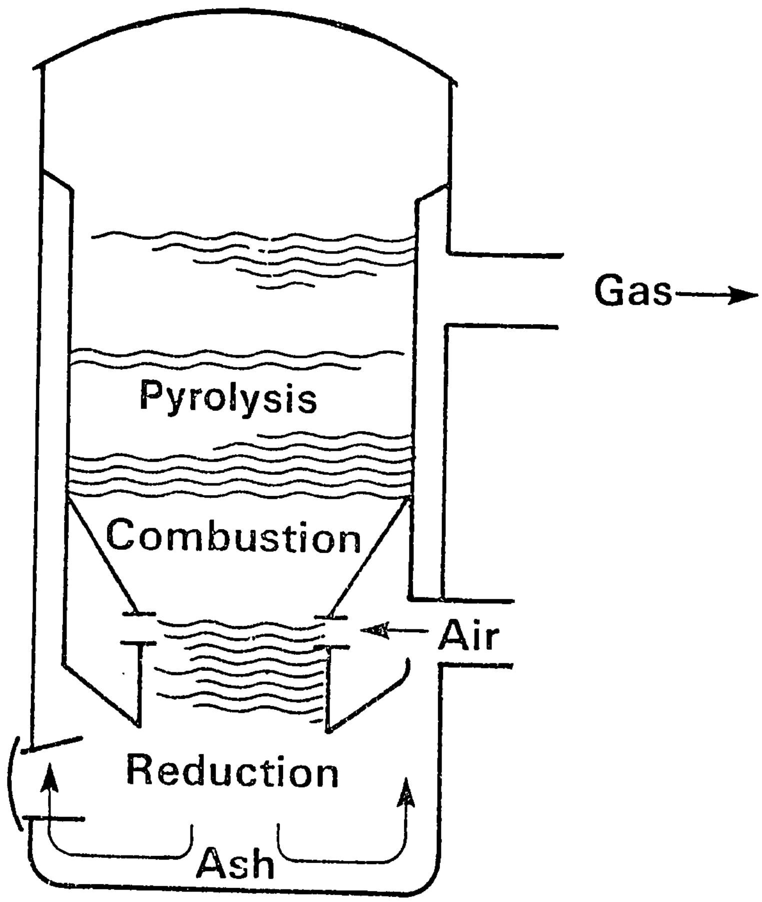


Figure 3. Schematic Diagram of a Downdraft Gasifier [5].

In downdraft gasifiers, air is typically introduced just above the grate. Heat from the reduction zone pyrolyzes the biomass above, but the tars and oils produced must pass through the very hot reduction zone where they are broken down and reduced to hydrogen and carbon monoxide. The downdraft gasifier therefore produces a gas relatively free of oils and tars, and this type of gasifier is the type most commonly employed to power motor vehicles.

A third type of gasifier is the cross-draft gasifier in which, as its name suggests, air is introduced on one side of the gasifier and gas is withdrawn from the other. Its principal advantage is that it is relatively simple. It is also a good system for vehicle propulsion and in Brazil, particularly, a considerable number of cross-draft units are in operation.

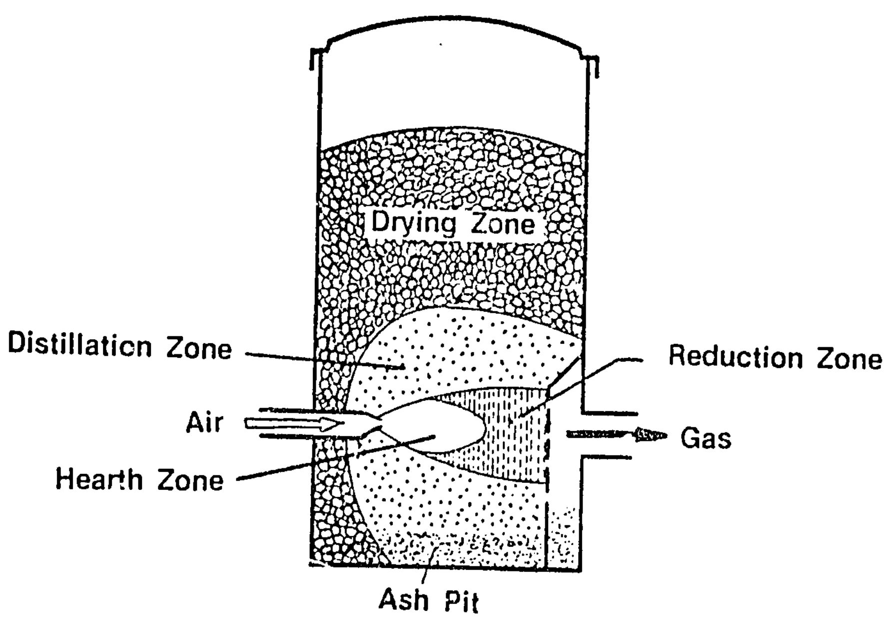


Figure 4. Schematic Diagram of a Cross-Draft Gasifier [12]

Gasifier Systems

If the producer gas is to be used in an engine, it is imperative that the gas is cleaned before being induced into the cylinders. Raw producer gas contains ash, soot, oils and tars that can scour cylinders, foul up valves, clog spark plugs, and quickly ruin an engine.

A typical producer gas cleaning system consists of three parts. The gas first enters a cyclone separator to take out fly ash and other small particles, the gas is then cooled by passing it through a heat exchanger, and finally the gas is run through a cloth filter to remove any fine soot or fly ash before entering the engine.

There are many variations on this theme, but the objectives are always the same:

1. To remove particulates
2. To cool the gas
3. To remove tars, oils and other condensible components

It should be noted that cooling the gas will condense much of the tars and oils; provision must therefore be made to collect these liquids. However, it is best to try to minimize the production of tars and oils in the first place, by using good quality fuel, and by using a gasifier design that breaks down these compounds into hydrocarbon gases and carbon monoxide.

A typical system of Swedish design is shown below.

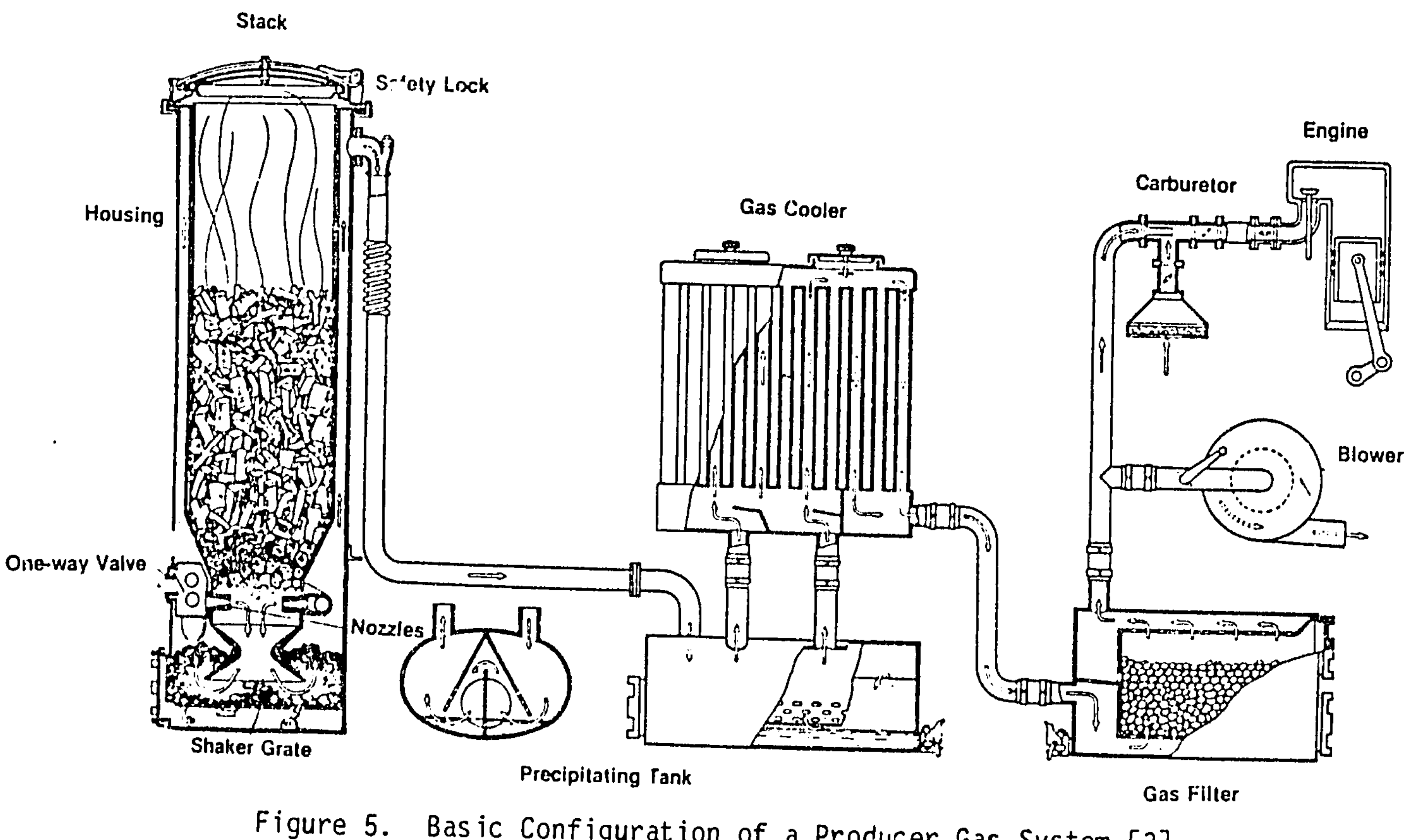


Figure 5. Basic Configuration of a Producer Gas System [3].

Gasifier Fuels

Gasifiers require solid fuels that are available in pellets or small pieces, more less uniform, free of dust, dirt, and other detritus. The fuel should not contain too much moisture particularly if the gasifier is updraft, and should not contain excessive amounts of ash--one of the problems with husks, for example.

The most common fuel is wood, and the majority of the one million vehicle gasifiers in operation in the early 1940's were run using this fuel. The second most popular fuel was charcoal, which has some advantages in terms of gasifier operation--it is less likely to produce tars and oils--but at some economic penalty. Nevertheless, many experts currently favor charcoal as a gasifier fuel over wood, particularly in the developing countries where system reliability and simplicity are regarded as a paramount consideration. In both the Philippines and Brazil, where the world's largest gasifier programs are underway, the fuel used is charcoal.

In principal, however, any biomass fuel can be used. Among those that have been successfully gasified are peat, seaweed, corn cobs, and rice husks. Fossil fuels such as lignite and coal can also be used.

Wood

Air-dry wood, with a moisture content of about 25 percent or less, is an excellent fuel for gasifiers. Because of the volatile compounds that wood contains, a downdraft or crossdraft gasifier is essential if the gas is to be used in an engine. Even so, the gas must be cooled and filtered to ensure that no tars, oils or particulates reach the cylinders.

Wood fuel must be chipped into small pieces (generally not more than about 5 cm on any side), not necessarily cubic, and air dried. Almost any tree species would appear to be suitable, although some woods have a higher energy content than others, the variation being between about 17.5 MJ/kg (Black Oak) to 24.2 MJ/kg (Pitch Pine), both kiln dried, i.e., with a moisture content of less than 10 percent. As a rule of thumb, an effective heating value of 19 MJ/kg may be used for mixtures of spruce, pine, and birch [7]; this value is then reduced according to the moisture content, F, (wet basis) to give the energy content of the wood fuel H_w, as

$$H_w = 19 - 21.46\,F \quad \text{MJ/kg} \tag{1}$$

Green wood has a moisture content of about 30 - 50 percent depending on the relative humidity and season rainfall patterns. Air dried wood has a moisture content of 15 - 25 percent.

Charcoal

When wood is charred, most of the volatile components are driven off. Air dried wood should be used to make charcoal. Depending on the technology used, a cubic meter of firewood will give 0.4 - 0.5 m^3 of charcoal. The heat content of charcoal at 10 percent moisture is approximately 28 MJ/kg.

Because tars and oils are not present in gas produced from charcoal, the generator can have a more simple and lighter construction, which generally means a cheaper gasifier. It is not necessary, with charcoal, to use a downdraft system or to constrict the hearth since there is no tar to catch or crack. Charcoal yields a cleaner gas without the pungent odor that accompanies wood gas.

Charcoal, however, is hygroscopic and friable; some care in handling this fuel is necessary. Moreover, the overall efficiency--wood to producer gas--is lower when charcoal is manufactured as an intermediate fuel.

Table 2 lists a number of possible fuels suitable for gasification, and shows the bulk density of the biomass material when it is in the form of a fuel.

Table 2. Bulk Density of Various Fuels

Fuel	Grading	Bulk Density kg/m^3
Saw dust	loose	177
Saw dust	briquets, 100 mm long, 75 mm dia.	555
Peat	dust	350-440
	briquets 45x65x60 mm	550-620
	hand cut	180-400
Charcoal (10% moisture)	beech	210-230
	birch	180-200
	softwood blocks	150-170
	softwood slabs	130-150
	mixed 60% hard/40% soft	170-190
	Swedish charcoal	175
Wood	hardwood	330
	softwood	250
	mixed 50/50	290
	Swedish car wood	325
	round wood	390
Straw	loose	80
	bales	320
Alfalfa seed straw	cube 30x30x50 mm, 7% moisture	298
Barley straw	cube 30x30x50 mm, 7% moisture	300
Bean straw	cube 30x30x50 mm, 7% moisture	440
Corn cobs	11% moisture	304
Corn stalks	cube 30x30x50 mm	391
Cotton gin trash	23% moisture	343
Peach pits	11% moisture	474
Olive pits	10% moisture	567
Prune pits	8% moisuture	514
Rice hulls	cube 30x30x50 mm	679
Safflower straw	cube 30x30x50 mm	203
Walnut shells	cracked	336
	8 mm pellets	599
Wood, blocks	17% moisture	256
chips	10% moisture	167
Coal	anthracite	830-900
	bituminous	770-930
Coke	hard	380-530
	soft	360-470
Brown coal	air dry lumps	650-780

Data are from Kaupp and Goss [6] and from reference 7.

Fuel Consumption

The energy content of wood is approximately 14.7 MJ/kg, as indicated by Equation 1 with F = 0.2. For charcoal, with a moisture content of 10%, a figure of 28 MJ/kg is an average value.

Gasifier efficencies are about 80 percent for both wood and charcoal. So if V_g and H_g are the volume of producer gas, m^3 and heating value, MJ/m^3, respectively; and if M_f and H_f are the mass of fuel and its heating value (MJ/kg), then we have:

$$\frac{V_g \cdot H_g}{M_f \cdot H_f} = 0.8$$

or $V_g/M_f = 0.8 \times H_f/H_g$ $\quad m^3$ gas/kg fuel

Using an average heat content for producer gas of about 5.44 MJ/m^3, we therefore have for wood

$$M_g/M_f = 0.8 \times 14.7/5.44 = 2.16 \text{ m}^3 \text{ gas/kg wood}$$

and for charcoal:

$$V_g/M_f = 0.8 \times 28/5.44 = 4.12 \text{ m}^3 \text{ gas/kg charcoal}$$

The efficiency of the engine is about 22 percent, that is to say

$$\frac{E \times 3.6}{V_g \cdot H_g} = 0.22$$

where E is the energy delivered by the engine in kilowatt hours, so

$$V_g/E = 3.6/(0.22 \times H_g) = 16.4/H_g \quad \text{m}^3 \text{ gas/kWh}$$

The typical engine therefore consumes producer gas at the rate of 16.4/5.44 = 3.0 m^3/kWh. Therefore, the fuel consumption for wood is given by

$$\text{wood consumption} = \frac{3 \text{ m}^3 \text{ gas}}{\text{kWh}} \cdot \frac{1 \text{ kg wood}}{2.16 \text{ m}^3 \text{ gas}} = 1.4 \text{ kg wood/kWh}$$

and for charcoal

$$\text{charcoal consumption} = \frac{3 \text{ m}^3 \text{ gas}}{\text{kWh}} \cdot \frac{1 \text{ kg charcoal}}{4.12 \text{ m}^3 \text{ gas}} = 0.73 \text{ kg charcoal/kWh}$$

However, Swedish figures for the efficiency of fuel production indicate that typically 375 kg of wood fuel, or 80 kg of charcoal, can be produced from 1 cubic meter of round wood. Therefore, a cubic meter of forest wood could produce 375/1.4 = 268 kWh of energy from an engine if wood is the gasifier fuel, or 80/0.74 = 108 kWh of energy if charcoal is the gasifier fuel. Clearly, it is less wasteful of forest resources to use wood as the fuel, not charcoal.

The figure below, taken from the Swedish literature, expresses the same idea. Again, it can be seen that 2-1/2 times more energy can be delivered to the final user if wood is gasified directly rather than being carbonized first.

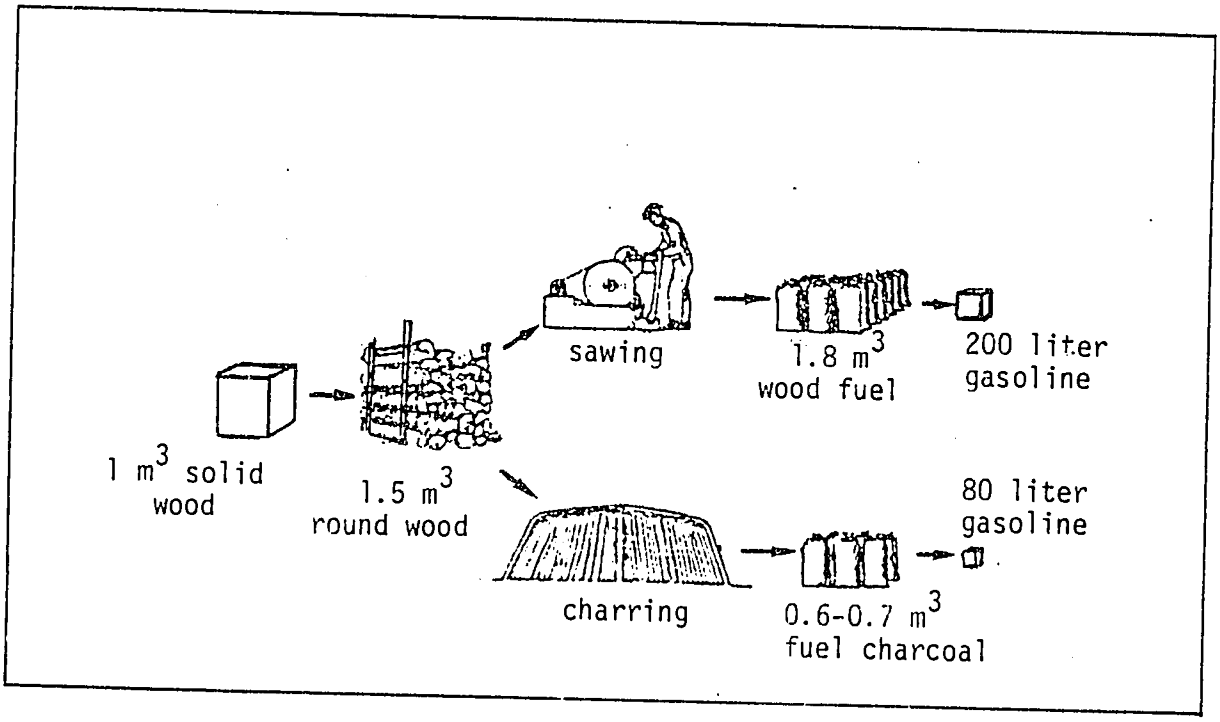


Figure 6. Comparison between the quantities of wood and charcoal gasifier fuels produced from 1 m^3 of solid wood. Adapted from [7].

It should also be noted that the efficiency of conversion from round wood to charcoal indicated by the figures given above in Figure 6, is about 36 percent (based on round wood at 390 kg/m^3 and 15 MJ/kg; and charcoal at 175 kg/m^3 and 28 MJ/kg). If charcoal is made by traditional methods, the conversion efficiency is likely to be only 15 - 20 percent.

Table 3. Fuel Consumption of Gasifiers

Gasifier Name	Fuel	Heating Value(1) MJ/kg	Consumption kg/hp.hr	Consumption kg/kWh
Malbay	Charcoal	-	0.53	0.71
	Low temperature coke	29.5	0.56	0.75
	Anthracite	32.4	0.46	0.62
Wisco	Charcoal	-	0.40	0.54
	Low temperature coke	33.7	0.45	0.60
Imbert	Air dry wood	-	0.8-1.0	1.07-1.34
Humboltz Deutz	Anthracite	32.6	-	
Gohin Poulence	Low temperature coke	-	0.47	0.63
Koela	Charcoal	32.2	0.45	0.60
	Low temperature coke	30.7	0.45-0.49	0.60-0.66
	Anthracite	34.5	0.45-0.49	0.60-0.66
Swedish model 1940's	Wood, 20% moisture	14.7	1.0	1.34
Swedish model 1957-63	Birch wood, 12% moisture	-	0.75-1.3	1.01-1.74

Table adapted from Kaupp and Goss [6].

Notes: 1. Base not specified.

Vehicle Fuel Consumption

Under normal conditions gasifiers will need about 2.5 - 3 kg of wood fuel or 1.3 - 1.65 kg charcoal to generate the same amount of energy as a liter of gasoline. However, fuel consumption figures measured in operating vehicles under realistic driving conditions vary widely, because of differences in the quality of the fuel, the efficiency of the gasifier and the engine, and the type of service the vehicle is in. For example, for delivery driving in city traffic the figures will rise substantially to about 2.75 kg charcoal or about 5 kg of wood equivalent to a liter of gasoline (where the gasoline engine is shut off at each stop but the generator is kept running). A gasifier continues to consume fuel when the engine is idling at a rate only 25% less than full load operation. For very discontinuous and interrupted driving patterns, fuel consumption per hour is a more reliable basis for estimating overall fuel consumption.

In 1940 the Royal Swedish Automobile Club ran an economy contest for gas powered trucks. A large number of mid-size trucks burning both charcoal and wood were monitored. The results are summarized below.

No. Vehicles	Average(1) load, kg	Average total wt., kg	Fuel	Fuel Consumption g/ton(load) per km	g/ton (total) per km
13	3180	6470	charcoal	130	65
8	3700	6900	wood	210	110
7	2620	5380	wood	220	110
7	3100	6510	charcoal	140	65
2	3070	6675	wood	220	100
4	4260	7430	wood	180	100
-	3500		charcoal	140	
-	3500		wood	240	

Adapted from reference 7.

Notes 1. Useful load - not including the gasifier

Fuel consumption in terms of distance (for steady driving) again shows a fair amount of variation. Using bulk densities of 325 and 175 kg/m^3 for wood and charcoal fuel respectively, the table above shows fuel consumption figures of about 2.4 L/km for charcoal and 2.2 L/km for wood.

Another study in 1941 on 82 charcoal-powered 2-1/2 ton trucks showed fuel consumption of about 3.25 L/km; and for 107 wood-powered trucks of about the same size the average figure was 3.2 L/km.

Studies in 1943, again in Sweden, reported these findings:

1 - 2 ton trucks	charcoal:	3.3 L/km	wood:	2.7 L/km
2 - 5 ton trucks		3.9 L/km		3.4 L/km
3 ton trucks		6.3 L/km		5.4 L/km

The last figures, which are higher, were for trucks delivering produce in Stockholm and frequently stopping and starting. This consideration is further illustrated by the data reported below for a 3.5 ton truck.

Driving distance, km	5	10	25	50	100	150
Gasoline, L/km	0.4	0.38	0.35	0.3	0.3	0.3
Wood, L/km	5.0	4.0	3.5	3.0	3.0	3.0

However, the average speed of the vehicle also affects these figures. As mentioned before, fuel consumption per hour may be a more reliable guide to the rate of fuel use. Consider the data reported below

Vehicle Class	Average Speed km/hr	Wood Consumption	
		L/km	L/hr
I	40	2.5	100
II	30	3.3	99
III	24	4.2	101
IV	15	6.7	100
V	10	10.0	100

Figures for Swedish buses between 1941 - 1942 are as follows

Number of buses	Maximum load, kg	Average distance, km/yr	Fuel Consumption, L/km	
			Charcoal	Wood
14	2210	11,900	5.1	-
29	3146	23,370	3.7	-
23	3620	33,800	3.5	-
30	3860	46,760	2.9	-
21	3060	23,120	-	3.7
31	3350	33,780	-	3.5
55	3730	50,000		3.0

For passenger cars, fuel consumption is lower. In normal highway driving a small passenger car should achieve 75 - 85 km for a 100 liters of wood or charcoal; a more practical estimate being 55 - 60 km from 100 liters of either fuel [7].

Sizing Gasifiers

It has often been said that gasifier technology is more art than science. Nevertheless, extensive experience with gasifiers in Sweden between 1957 and 1963 established some guidelines for dimensioning downdraft gasifiers for use with wood. The numbers shown in Table 4 are derived from road tests and laboratory data which is still applicable today. The critical design area is the combustion zone; the area of the throat, A_h, the number of tuyeres and their diameter, and the diameter of the combustion zone must be correctly dimensioned if the gasifier is to produce good quality gas when operating an engine of a particular rated power.

For reliable vehicle operation, the generator must provide the engine with good quality gas under idling conditions as well as full load. The turn-down ratio of a gasifier is defined as the ratio of maximum to minimum rates of gas production. Generally the ratio is between 6 and 8 (see Table 4) which is acceptable for most vehicles, where maximum to minimum rpm values will usually be less than this.

For downdraft wood gasifiers the maximum permissible rate of gas production per unit area of throat is about 1 Nm^3/cm^2. hr. This parameter is called the "hearth load" [7] or the "specific gasification rate" [6]. The minimum value depends on the design of the hearth. For V-hearths of the type shown in the sketch, satisfactory gas production at rates as low as 0.1 Nm^3/cm^2. hr has been observed.

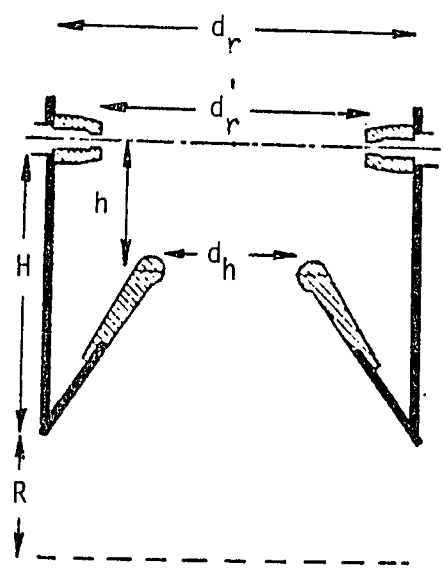


Figure 7. Nomenclature Used in Table 4 for Sizing Hearth and Throat of a Downdraft Gasifier of Swedish Design [6].

Table 4. Dimensions for Swedish Downdraft Gas Producers [6]

d_r/d_h	d_h mm	d_r mm	d'_r mm	h mm	H mm	R mm	N no.	d_m mm	$\frac{A_m \times 100}{A_h}$	$\frac{d_r}{d_h}$	$\frac{h}{d_h}$	Range of gas output max. Nm^3/h	Range of gas output min. Nm^3/h	Maximum wood consumption hg/h	Air blast velocity v_m m/s
268/60	60	268	150	80	256	100	5	7.5	7.8	4.5	1.33	30	4	14	22.4
268/80	80	268	176	95	256	100	5	9	6.4	3.3	1.19	44	5	21	23.0
268/100	100	268	202	100	256	100	5	10.5	5.5	2.7	1.00	63	8	30	24.2
268/120	120	268	216	110	256	100	5	12	5.0	2.2	0.92	90	12	42	26.0
300/100	100	300	208	100	275	115	5	10.5	5.5	3.0	1.00	77	10	36	29.4
300/115	115	300	228	105	275	115	5	11.5	5.0	2.6	0.92	95	12	45	30.3
300/130	130	300	248	110	275	115	5	12.5	4.6	2.3	0.85	115	15	55	31.5
300/150	150	300	258	120	275	115	5	14	4.4	2.0	0.80	140	18	67	30.0
400/130	130	400	258	110	370	155	7	10.5	4.6	31.	0.85	120	17	57	32.6
400/150	135	400	258	120	370	155	7	12	4.5	2.7	0.80	150	21	71	32.6
400/175	175	400	308	130	370	155	7	13.5	4.2	2.3	0.74	190	26	90	31.4
400/200	200	400	318	145	370	153	7	16	3.9	2.0	0.73	230	33	110	31.2

Variables not given in Figure 7 are defined as follows:

d_m = inner diameter of the tuyere

A_m = sum of cross sectional areas of the air jet openings in the tuyeres

A_h = cross sectional area of the throat

N = number of tuyeres

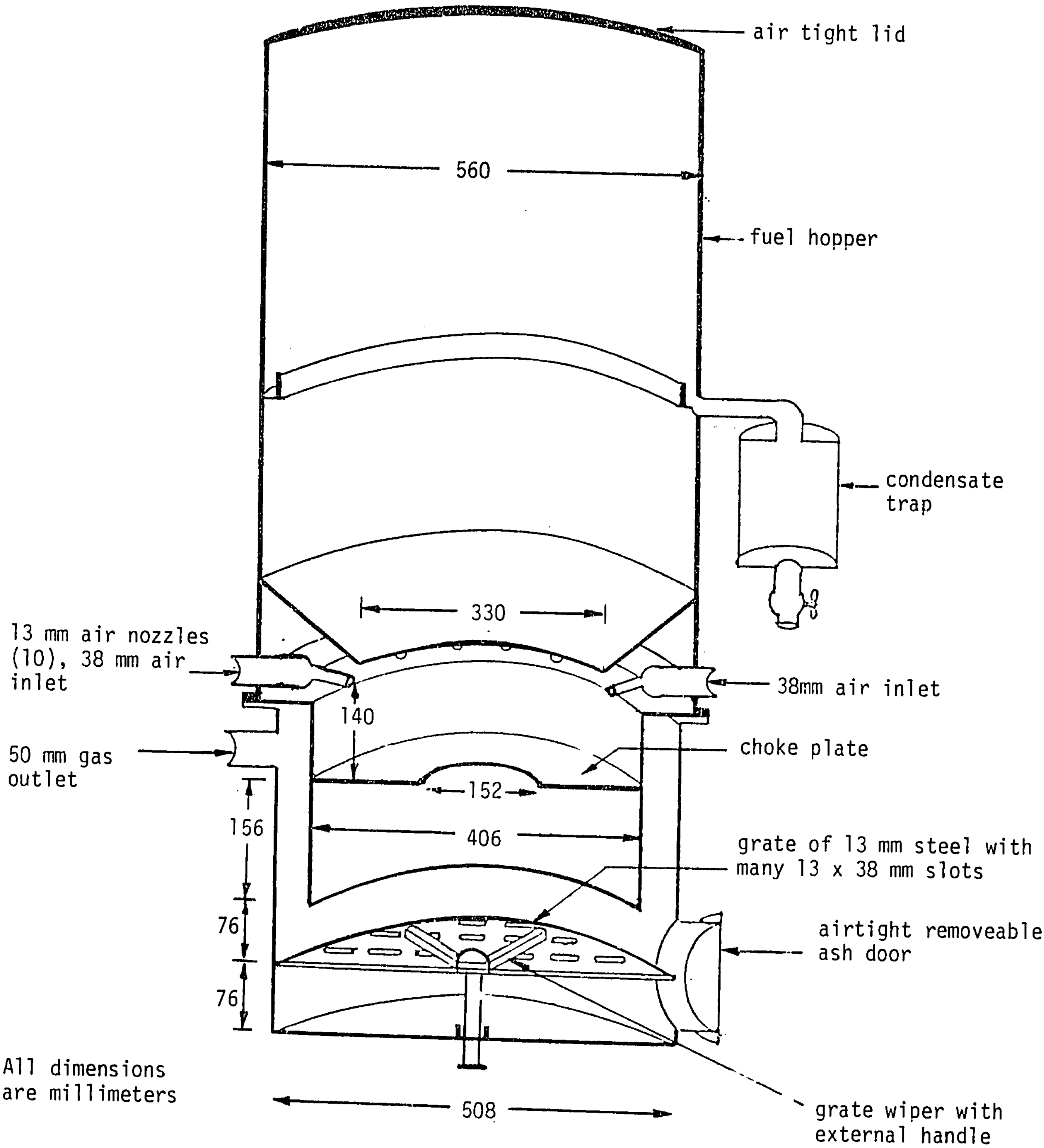
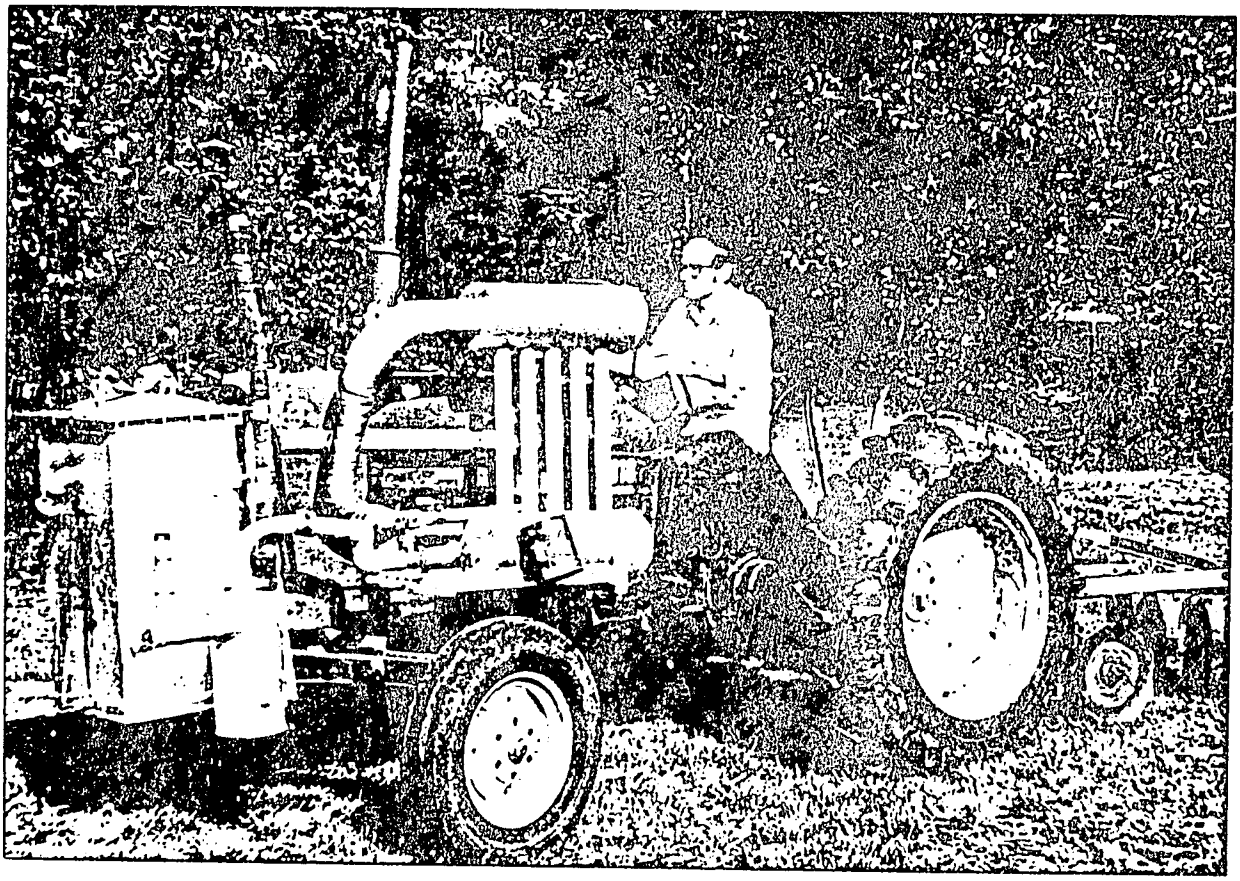


Figure 8. Dimensions of a Downdraft Gasifier Suitable For a 4 - 6 liter Engine [9]



Privately made gasifier unit powering a farm tractor in Florida. The square gasifier is mounted at the front. The gas passes through a cyclone filter, is then cooled and cleaned, and then flows to the spark ignition engine. The unit was built by Robert Hargrave of Rocky Creek Farm Gasogens, La Crosse, Florida.

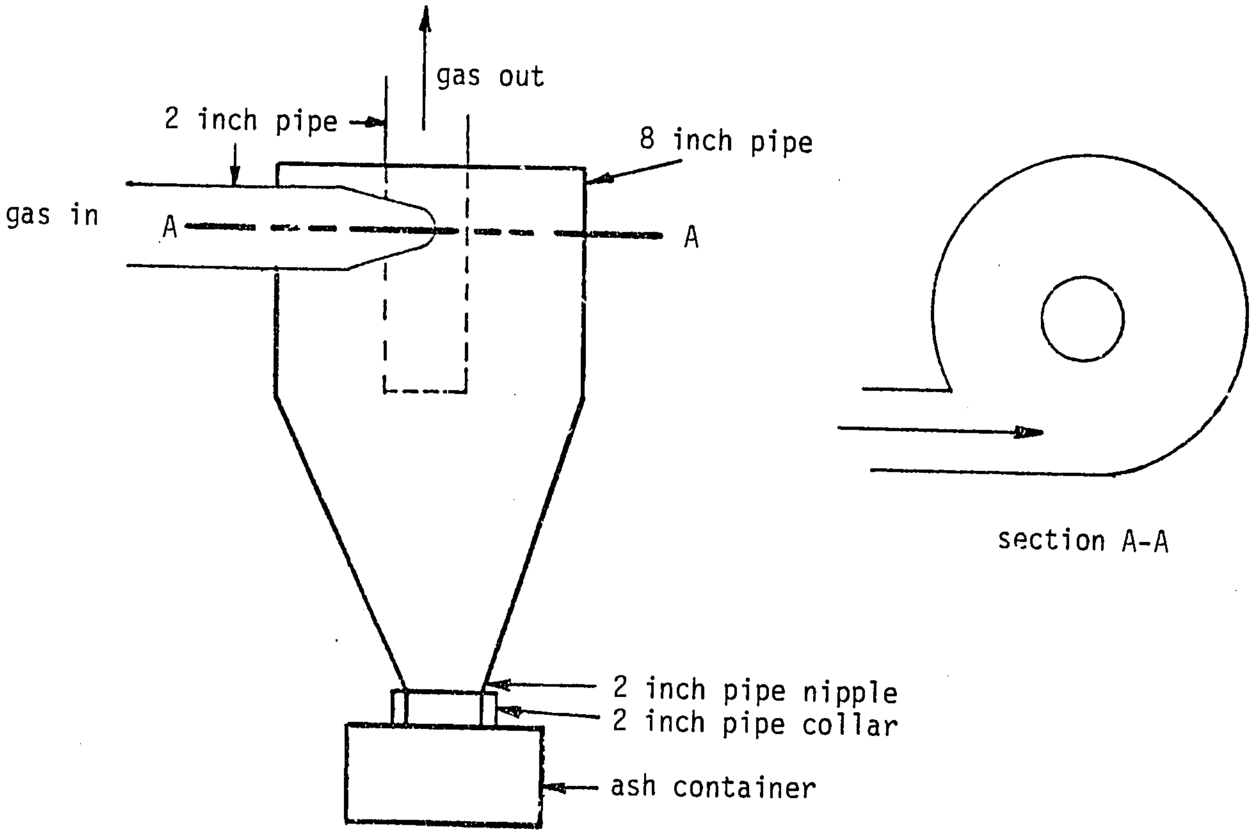


Figure 9. Cyclone seperator [9].

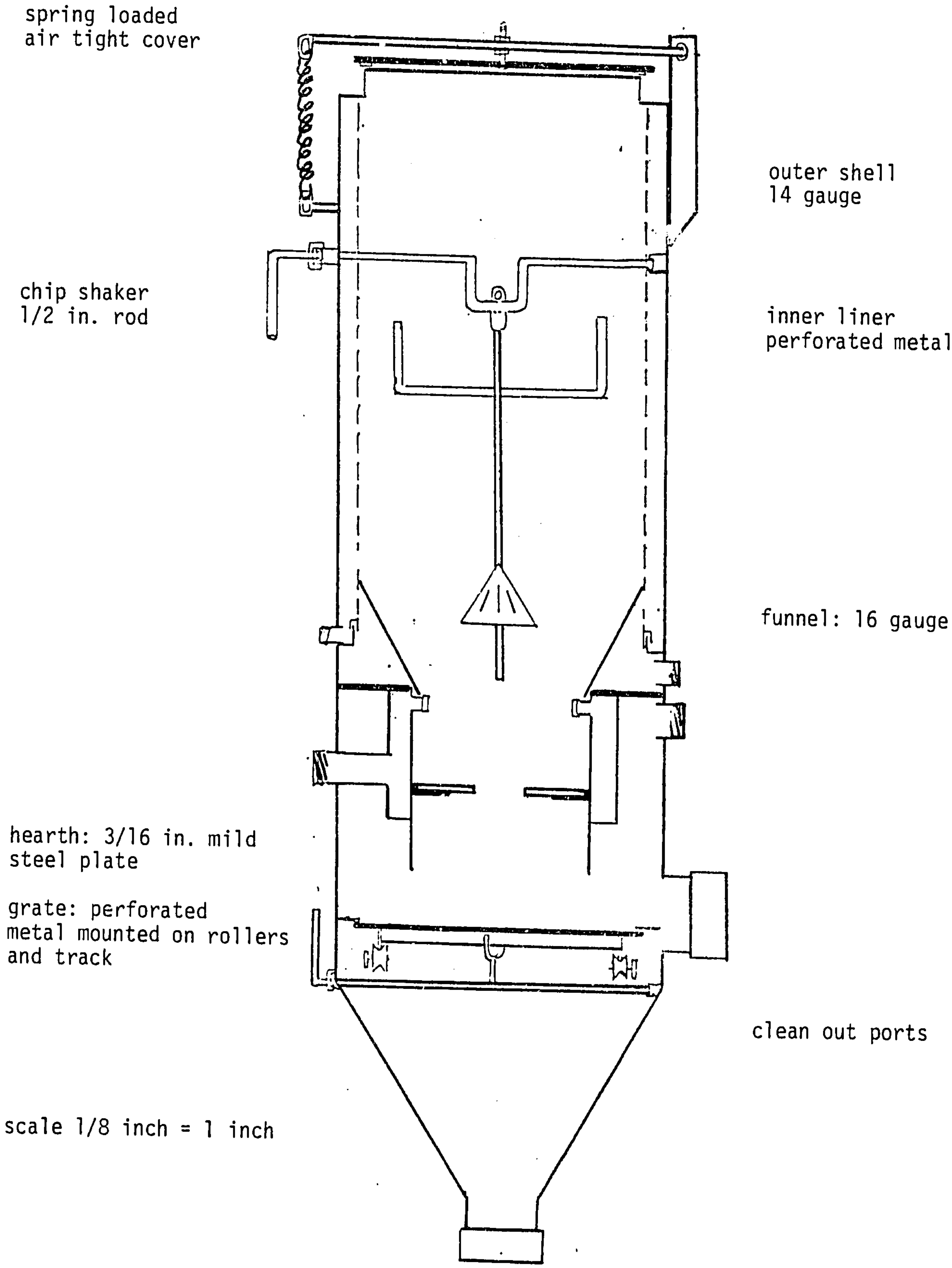


Figure 10. Downdraft gasifier--Rocky Creek Farm Gasogens, Florida [11].

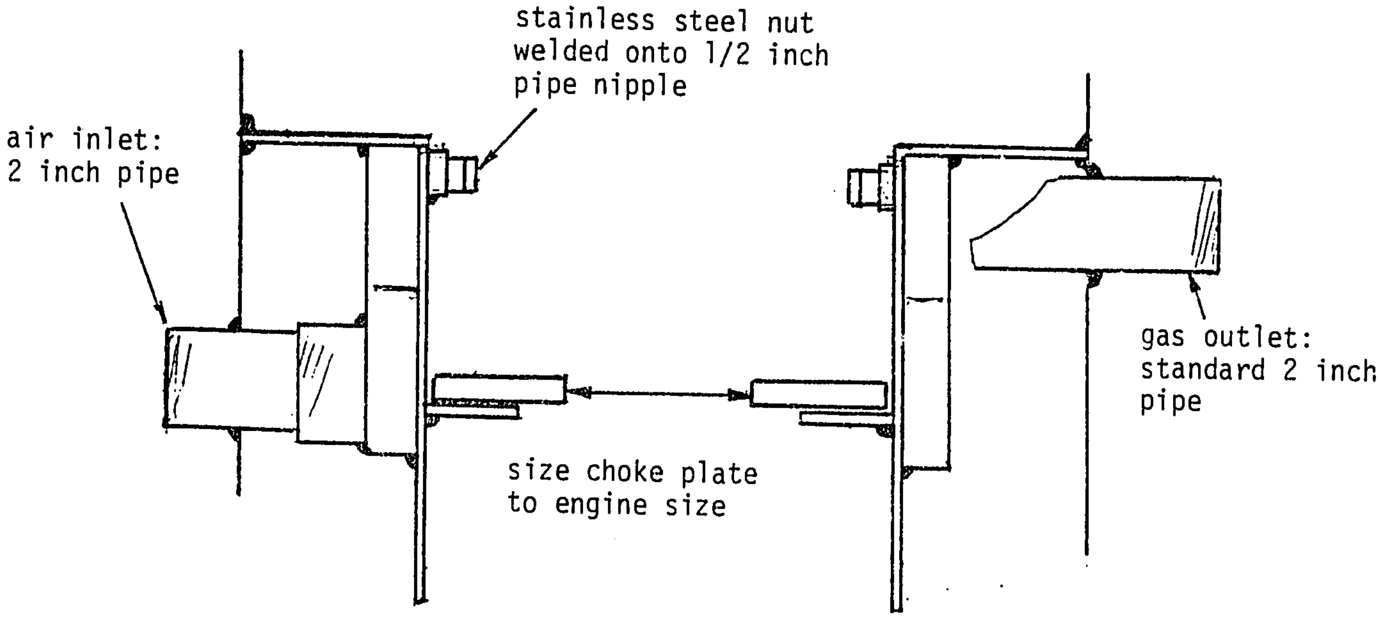


Figure 11. Details of hearth area of the gasifier shown in Fig. 10.

Choke plate orifice diameter should be within the shaded area in the figure below.

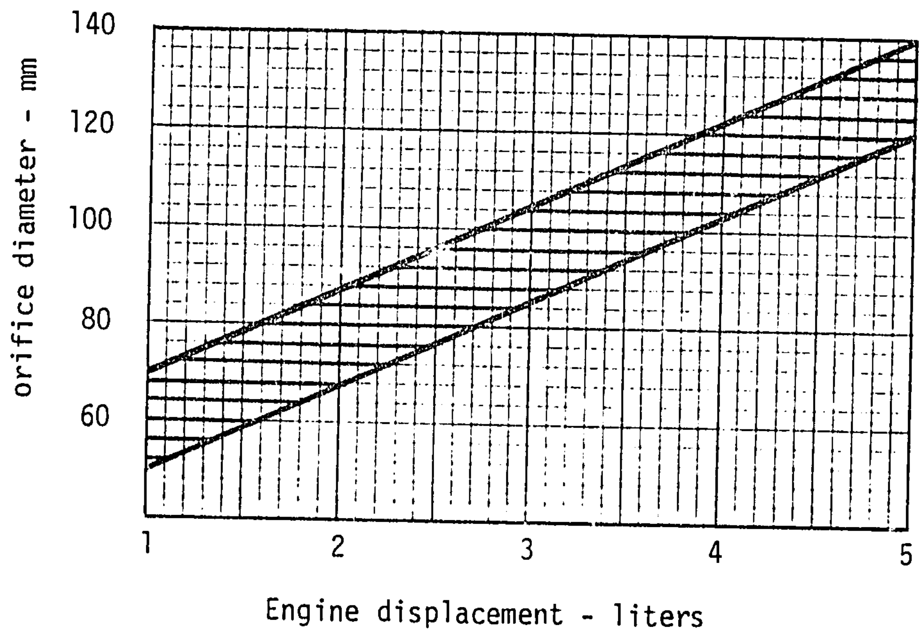


Figure 12. Choke plate diameter as a function of engine displacement. Adapted from [11].

Economics

The economics of gasifier systems have been explored in a number of recent publications--the NAS study [3], the USAID report [6], and the Earthscan report [4]. The Earthscan report presents the most detailed analysis for gasifier-powered stationary engines (50 kW), and for process heat applications. The results of these studies are summarized in this section.

Stationary Engines

One application of gasifier technology is to use gasifiers to power stationary diesel engines used to pump water or to generate electricity. The producer gas can substitute for 50 - 80 percent of the diesel fuel, depending on how the engine is run, often at significant cost savings. The Earthscan analysis took as it starting point a baseline case the assumptions for which are listed below.

Item	Assumed Value
Engine power	50 kW
Engine cost	300 $/kW
Maintenance	5% of capital cost/yr (includes labor)
Lubricants	5% of diesel fuel cost/yr
Interest rate	10%
System lifetime	6 years
Operating time	2000 hr/yr
Diesel fuel consumption	0.4 liter/kWh (diesel alone) 0.08 liter/kWh (with producer gas)
Diesel fuel cost	40¢/liter
Gasifier cost	$75, $200, & $800/kW
Maintenance	10% capital cost/yr
Lubricants	10% of diesel fuel cost/yr
Additional labor	$1000/yr
Wood consumption	1.4 kg/kWh (80% substitution)
Wood fuel cost	$20 per tonne (air dry)

The cost of energy (shaft power) produced by the diesel engine running entirely on diesel fuel and then using the gasifiers (at each price) can then be calculated. The results of this analysis are shown in Table 5.

Table 5. Cost of Energy from Diesel Engines with Gasifiers

Item	Diesel System (no gasifier)	Gasifier Cost/kW		
		$75	$200	$800
Capital Cost	$15,000	$18,750	$25,000	$55,000
Capital charges, $/yr (1)	3,440	4,310	5,740	12,630
Maintenance, $/yr	750	1,880	2,500	5,500
Additional labor, $/yr	-	1,000	1,000	1,000
Lubricants, $/yr	800	1,600	1,600	1,600
Diesel fuel, $/yr	16,000	3,200	3,200	3,200
Wood fuel, $/yr	-	2,800	2,800	2,800
Annual costs, $/yr	20,990	14,790	16,840	26,730
Energy produced, kWh/yr	100,000	100,000	100,000	100,000
Cost of energy, ¢/kWh	21.0	14.8	16.8	26.7

Notes: All data are based on the Earthscan report [4].
(1) Capital charges are calculated as capital cost multiplied by a capital recovery factor (CRF) defined as:

$$CRF\ (i,t) = \frac{i}{1 - (1 + i)^{-t}}$$

where i is the interest rate, and t is the loan period, 10% per annum and 6 years respectively.

A brief examination of this table shows, not surprisingly, the dominant effect of the capital cost of the gasifier. One is led to ask: How realistic are these cost data for the gasifiers? Commercial systems in the Philippines and Brazil, the only countries where gasifiers are being produced on any scale, cost between $50 - $100/kW. A 30 kW gasifier purchased in Florida in 1983 cost less than $2500, equivalent to about 80 $/kW; and a British commercially available 30 kW system (Seltec 50) was quoted (1983) at about 3000 pounds Sterling--roughly 150 $/kW. It may be that the upper range of installed costs used in the above analysis are unreasonably high, in which case, of course, the economic argument in favor of substituting producer gas for diesel fuel is further strengthened.

The effect of the prices of wood and diesel fuel on the economic viability of gasifier systems are indicated in the figure overleaf.

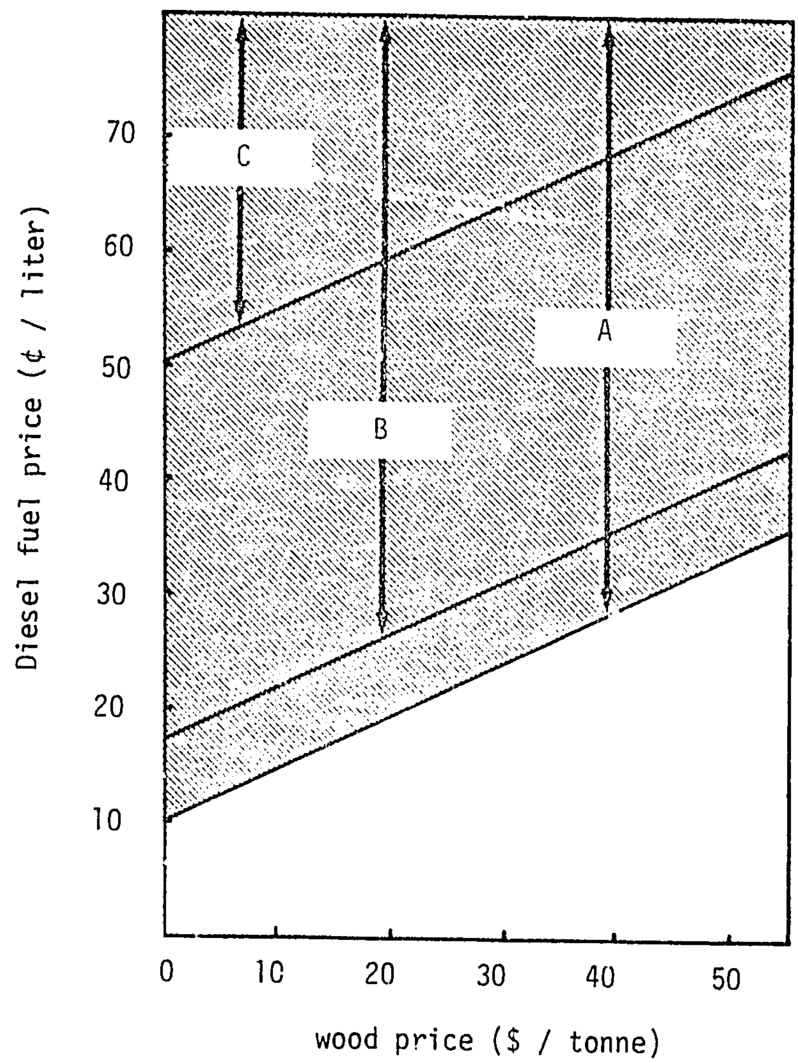


Figure 13. Economic feasibility of shaft-power gasifiers at different diesel fuel and wood fuel prices. Zone A shows economic feasibility for a gasifier costing $75/kW; zone B is for gasifiers costing $200/kW; zone C is the zone for units costing $800/kW. Adapted from Foley et al. [4].

Process Heat

A potentially important application of larger (>300 kW) gasification systems is the generation of high-temperature process heat by the direct combustion of the producer gas. For instance, gasifiers can be retrofitted to industrial boilers, and biomass fuel used to substitute for heating oil; this is the application examined here. Again, the Earthscan report [4] provides the fundamentals of the analysis.

Assume we have an industrial boiler with a rated output of roughly 10 million Btu/hr (or more precisely 10 GJ/hr), consuming 290 kg of fuel oil each hour in the process. Can this fuel be replaced by fitting a gasifier to the system and running the whole operation on wood? These are the basic assumptions:

Item	Assumed Value
Rated boiler output	10 GJ/hr
Average output	60% of rated power
Fuel oil consumption	29 kg/GJ
Interest rate	10%
System lifetime	12 years
Operating time	4000 hr/yr
Fuel oil price	$340/t (No. 6 fuel oil)
Gasifier cost	$25,000 per GJ/hr
Annual maintenance	10% of capital cost
Additional labor	$3000/yr
Electricity cost	24¢/GJ output
Wood consumption	100 kg/GJ
Wood fuel cost	$20/t air dry

First of all, consider the cost of running the system on fuel oil. Operating 4000 hours each year, and producing an average of 6 GJ/hr, the cost of the fuel oil will be:

6 GJ/hr x 4000 hr/yr x 0.029 t/GJ x $340/t = 236,640 $/yr

The following figures apply to the gasifier system:

Capital cost	$250,000
Capital recovery factor	0.14676 (10% pa, 12 yr)
Capital charges	36,690 $/yr
Maintenance	25,000 $/yr
Additional labor	3000 $/yr
Electricity	5760 $/yr
Wood fuel	48,000 $/yr
Total annual costs	118,450 $/yr

So the retrofitting of a gasifier system immediately saves over $118,000 each year and pays for itself in just over 2 years.

The clear economic advantage that the gasifier system enjoys over the conventional fuel oil burner is not seriously threatened until the price of wood fuel rises to over 80 $/t or until the cost of fuel oil drops down to around 100 $/t.

As a second example we look at a large gasifier installed by Florida Power Corporation at an electrical generating plant in Live Oak, Florida. Information and data pertaining to the gasifier system is given below.

Gasifier type:	updraft
Rated output:	25 Mbtu/hr
Maximum output:	32 Mbtu/hr
Fuel:	Wood chips
Fuel consumption:	3.2 t/hr

The system--including the wood handling system, ash removal system, liquid collection, air blower, flare, and controls--cost $1.07 million to install; operation and maintenance runs at $165,000 a year.

If the gasifier is operated for 6000 hours each year, it is expected to save about 1 million gallons of fuel oil annually [10].

If the system is financed over 10 years with a loan charged at 10 percent annually, then charges on the capital would run at about $174,000 a year. Together with operation and maintenance expenses of $165,000, annual costs are approximately $339,000.

The gasifier saves the cost of about 1 million gallons of fuel oil each year which at say $340 per tonne (the figure used in the Earthscan example [4]) works out to an annual saving of approximately $1.2 million. So installing a gasifier system saves more money in the first year than the capital cost of the system.

Florida Power Corporation estimates that energy from wood fuel gasifiers costs about $2 - 3 per million Btu, as opposed to approximately $6 for oil and $4 for natural gas.

The economics of retrofitting gasifiers to existing boilers has been examined by SERI in a recent publication [5]. Two large gasifiers were evaluated: one 4 MW system running on walnut hulls, the other, a 25 MW unit, using chaparral as a fuel. Details of the two systems are given below:

	Gasifier A	Gasifier B
Rated gas output (Mbtu/hr)	14.1	85
Fuel	Walnut hulls	Chaparral
Feed rate (ton/hr)	1.19	7.87
Capital cost	$125,000	$350,000
Fuel cost ($/ton)	4	10
Operation & maintenance ($/yr)	12,290	63,900
Operating time (hr/yr)	6000	8760

These cost data are suspect, however. The capital costs are equivalent to 30 $/kW and 14 $/kW for gasifiers A and B respectively which even for the late 1970s (which is when the data were published) must be considered much too low.

The SERI analysis went on to examine 3 options available to manufacturers considering switching from fuel oil or gas to biomass fuels:

1. Reconversion to solid fuel for an installation that was originally run on a solid fuel but had been converted to petroleum fuels. Where this is practical it may well be the most economical alternative; but it is likely that the solid fuel handling equipment will have been scrapped, new emission control equipment might be required, and the existing boiler is probably old and inefficient.

2. Replacement of the existing boiler unit with a new solid fuel installation burning coal or wood or other biomass. This will cost about $8 to $30 per lb. of steam per hour ($9 to $36 per MJ/hr) and will usually require installation of new emission control equipment.

3. Installation of a close-coupled gasifier to provide producer gas to the existing boiler. This will cost on the order of $4 to $9 per lb. of steam per hour ($5 to $11 per MJ/hr). Retrofitting a gasifier makes use of much of the existing installation. It also permits using fuel oil or gas where these fuels are available and economical, and permits use of biomass wastes that otherwise would not have value as fuels.

Figure 14 compares the costs of these options. It appears that the cost of adding a gasifier to an existing package boiler (option 3) is about two- thirds the cost of installing a new wood-fired boiler (option 2).

These cost curves also suggest that gasifiers coupled with inexpensive boilers cost about the same as conventional package wood-fired boilers for new installations. Adding the lower two curves gives prices for a complete gasifier-boiler system that are comparable with the cost curves for the wood-fired boilers. The factors which could favor the gasifier-boiler combination include the low price of conventional gas/oil boilers compared to wood burning boilers The turndown ratio of gasifiers may also be superior to that of wood fired systems.

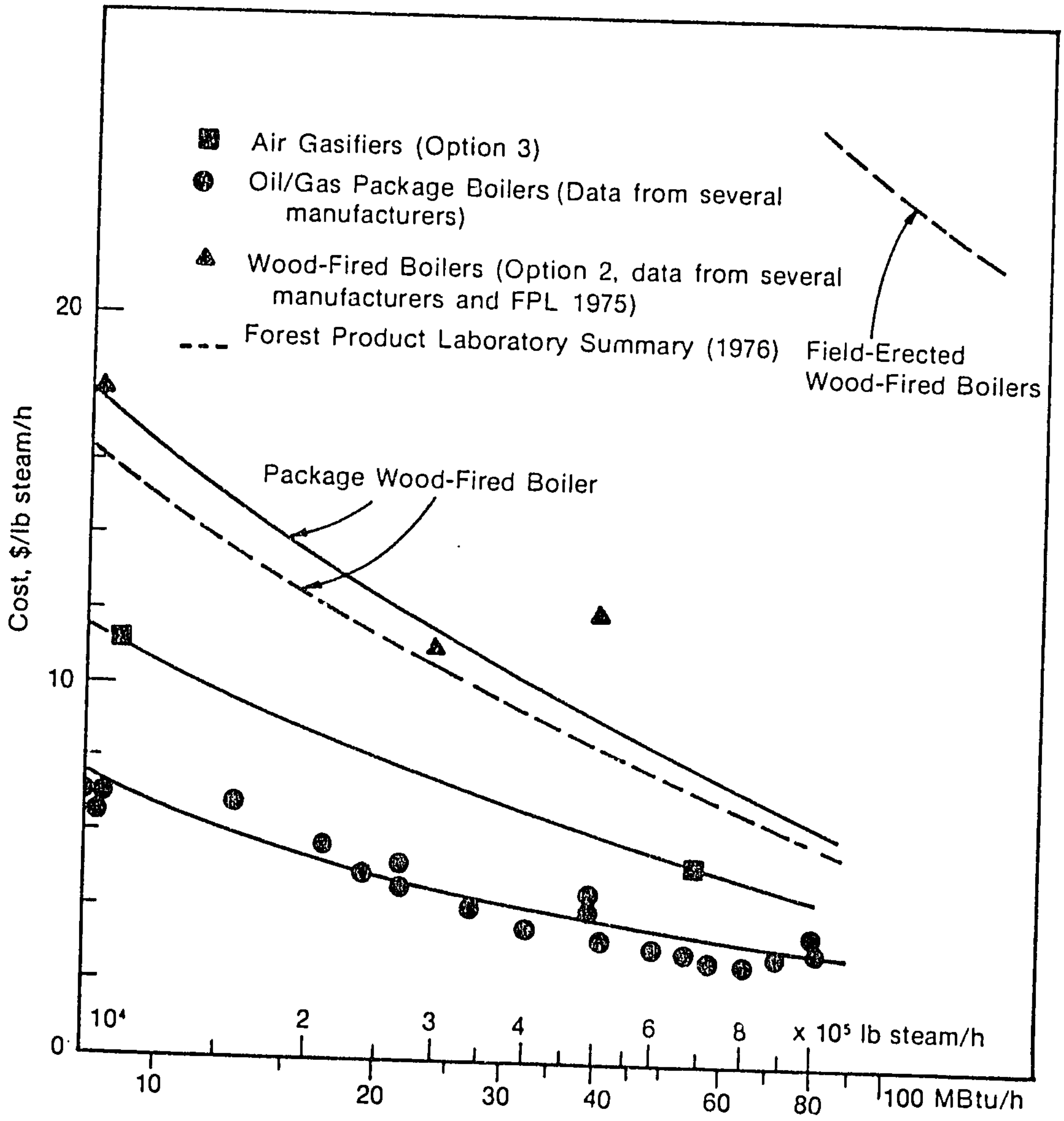


Figure 14. Cost comparison between retrofitting existing equipment and new installations. Adapted from SERI [5].

Electrical Power

The analysis of energy costs from gasifier-powered stationary engines presented earlier is a lower bound on the costs expected for generating electricity. It is obviously impossible to generate a kWh of electricity cheaper than it is to generate a kWh of mechanical energy.

If generators cost no more than 300 \$/kW the annual charges associated with a 50 kW generator, using the baseline data of Table 5, would be about \$3440. If the conversion efficiency of mechanical to electrical energy is 90%, the output of electricity is 90,000 kWh/yr; we therefore find:

System	Annual costs	Electricity costs ¢/kWh
Diesel generator	\$20,990 + 3,440	27.1
Gasifier (75 \$/kW)	\$14,790 + 3,440	20.3
Gasifier (200 \$/kW)	\$16,840 + 3,440	22.5
Gasifier (800 \$/kW)	\$26,730 + 3,440	33.5

Gasifier powered generator sets are therefore clearly competitive with diesel units although a careful economic analysis will always be necessary.

Vehicle Propulsion

It takes between 2.5 - 3 kilograms of wood or about 1.3 - 1.7 kilograms of charcoal to substitute for a liter of gasoline. Usually the biomass fuels are much cheaper than gasoline; however, the gasifier is an additional expense and the operating costs of a gasifier powered vehicle are higher. From the perspective of the vehicle operator, the gasifier is an attractive proposition if the annual costs of the gasifier system are less than the annual costs of running the vehicle on gasoline.

This decision can be represented algebraically by the inequality

$$P_b < gP_g/b - A/Db \qquad \$/\text{liter}$$

where P_b = price of biomass fuel, \$/liter

g = gasoline fuel consumption, liter/km

P_g = price of gasoline, \$/liter

A = annual charges for cost of the gasifier and the additional labor and maintenance, \$/yr

b = biomass fuel consumption, liter/km

D = distance driven, km/yr

If this expression holds true, then the gasifier system should save money. Consider the following case. Assume the vehicle can be powered by a 100 kW gasifier costing $10,000. The system is expected to last 6 years and the loan is repaid at 10% per annum.

The capital recovery factor CRF (i,t) = $0.1/(1 - 1.1^{-6}) = 0.22961$. Capital charges for the system are therefore $10,000 x 0.22961 = $2296/yr, plus say another $1000/yr for additional labor, to give total annual charges of $3296/yr.

Further assume:

g:	gasoline fuel consumption	=	0.2 liter/km
P_g:	price of gasoline	=	0.5 $/liter
D:	distance driven	=	40,000 km/yr
b:	biomass fuel consumption	=	3.0 liter/km

So with A = $3296/yr, we have

$$P_b = 0.2 \times 0.5/3.0 - 3296/(40000 \times 3)$$
$$= 0.00586 \text{ \$/L}$$

For wood fuel at 350 kg/m^3 this price is equivalent to $16.76 per tonne of wood fuel. If wood fuel could be purchased for a price less than this then the gasifier system is a financially viable proposition.

It is difficult to generalize, however, about the economic viability of gasifier powered vehicles. The Swedish experience was that gasifier powered vehicles could not compete with diesel engines; but they could compete with gasoline engines under some circumstances. Certainly, the longer the distance travelled annually the better the gasifier looks in economic terms; high mileage is required to offset the increased fixed expenses. A rough minimum was estimated at 30,000 km/yr for a car and 1000 hr/yr for a tractor [7].

A further consideration is the power loss experienced with gasifiers. A reduction of 40% - 50% during gasifier operation compared to gasoline operation is not unusual.

This decrease in power coupled with the weight of the gasifier system further undermines the economic viability of gasifiers used for vehicles. It should be remembered that Europeans had no choice in the 1940's when they switched to gasifiers--gasoline and diesel fuel were simply not available.

Deforestation Issues

Gasifiers run on trees. Although many alternative biomass fuels have been examined--and crop residues are a particularly appealing fuel from an environmental standpoint--only wood and charcoal have been shown to be reliable gasifier fuels. But considerable amounts of wood are required to supply a typical gasifier. The table below shows approximate wood consumption and the land area required to support typical gasifier applications.

Application (output)	Fuel Consumption	Fuel Required m^3/yr	Round Wood m^3/yr	Land Area ha
1. Generator Set (100,000 kWhe/yr	wood: 2.5 kg/kWhe charcoal: 1.3 kg/Kwhe	770 740	640 1,860	32 93
2. Dual-Fuel Pump Set (100,000 kWh/yr)	wood: 1.4 kg/kWh charcoal: 0.7 kg/kWh	430 400	360 1,000	18 53
3. Process Heat (10 GJ/hr; 4000 hr/yr)	wood: 100 kg/GJ charcoal: 54 kg/GJ	12,310 12,340	10,260 30,860	513 1543
4. Truck Haulage (40,000 km/yr)	wood: 3 liter/km charcoal: 3 liter/km	120 120	100 300	5 15
5. Farm Tractor (1000 hr/yr)	wood: 100 liter/hr charcoal: 100 liter/hr	100 100	83 250	4 13

Notes: Wood and charcoal are the only fuels accounted for in the table; diesel oil and electricity are not included. Calculations are based on the assumption that 1 m^3 round wood produces 1.2 m^3 of wood fuel or 0.4 m^3 of charcoal. Bulk densities of wood fuel and charcoal fuel are taken as 325 kg/m^3 and 175 kg/m^3 respectively. Wood yield is assumed to be 20 m^3/ha. yr.

It is clear that it takes a considerable amount of wooded land to support these gasifier applications. Utilized on any scale, gasifiers will obviously create a strong demand for fuelwood. If the supply of fuel wood is not carefully managed there is a risk of uncontrolled cutting and escalating deforestation.

In Europe, during the early 1940's, with hundreds of thousands of gasifier-powered vehicles in operation, the demand for fuel wood caused serious problems. In France and Denmark, for example, the construction of gasifiers was forbidden in July 1941 and wood was rationed; gasifier construction was also greatly restricted in Germany and Sweden. People were encouraged to switch to brown-coal, peat coke, anthracite, and low-temperature coke made from bituminous coal, but these fuels were never as popular as wood and charcoal.

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Kent
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Alcohol Fuels

Both ethanol and methanol can be used as fuels for internal combustion engines. Since both alcohols can be produced from biomass resources, they offer the possibility of substituting indigenous and renewable sources of liquid fuels for gasoline derived from imported oil.

Ethanol is generally considered to be the more appropriate fuel alcohol for production in the developing countries. There are several reasons for favoring ethanol over methanol as a substitute for gasoline.

- The production technology is well developed, commercially available, and economically viable over a wide range of capacities.
- A well-established feedstock is sugarcane--a biomass resource that is grown in over 40 developing countries.
- Sugarcase comes with its own source of fuel--bagasse; an important consideration for distilleries located in rural areas.
- Methanol technology is less well developed, unfamiliar in many developing countries, and is generally considered economic only if established on a significant scale.
- Ethanol from sugarcane provides an alternative market for the cane, helps to stabilize the sugar industry, and can provide employment for large number of rural workers.
- Ethanol production can be set up at existing sugar mills, with relatively low investment costs.

In Brazil, alcohol production began in the 1930's as part of an effort to rationalize and stabilize the market for sugar and molasses. The production of ethanol increased slowly until, in 1975, faced with a very low price for raw sugar and a high import bill for petroleum, the Brazilian government created the National Alcohol Programme (PROALCOOL). Production of ethanol then rose quickly: from about 0.6 billion liters in 1976 to 4 billion liters in 1980. There are now almost 400 distilleries; production in 1984 was approximately 6-7 billion liters, and substituted for about 15 percent of Brazil's demand for gasoline. All of Brazil's 7-8 million cars run on 17 percent alcohol blends, including about 700,000 vehicles which run on pure alcohol [1].

Ethanol can be manufactured from sugar crops (sugarcane, sugar beets, sweet sorghum, etc.), from grains (maize, barley, rice) from starchy root crops such as cassava and potatoes, and also from cellulose materials such as wood.

Cassava is considered to be a possible feed material in the developing countries, since the plant is well known, and it can be grown on poor soils ill-suited for food production.

Programs to produce ethanol are underway in about a dozen developing countries. A 240 m^3/day distillery is starting up in Costa Rica, and should substitute for 15 percent of that country's gasoline consumption. A large distillery is under construction in the Philippines. Argentina, which is almost self-sufficient in petroleum, diverted over 3 million tons of sugarcane to ethanol production in 1978. Other developing countries building distilleries include Kenya, the Sudan, Indonesia, Papua New Guinea, Thailand, Sri Lanka, and Zimbabwe.

Raw Materials

As noted above, there are a variety of biomass raw materials which can be used as feedstock for ethanol production. Table 1, below, shows alcohol yields from a range of raw materials. It should be noted that both sugarcane and cassava are among the most productive of these raw materials.

TABLE 1 Yields of Raw Materials Used in Ethanol Production

Crop	Yield (ton/ha/yr)	Ethanol (liter/ton)	Ethanol (liters/ha/yr)
Sugarcane	50-90	70-90	3,500-8,000
Sweet sorghum	45-80	60-80	1,750-5,300
Sugar beet	15-50	90	1,350-5,500
Fodder beet	100-200	90	4,400-9,350
Wheat	1.5-2.1	340	510-714
Barley	1.2-2.5	250	300-625
Rice	2.5-5.0	430	1,075-2,150
Maize	1.7-5.4	360	600-1,944
Sorghum	1.0-3.7	350	350-1,295
Irish potatoes	10-25	110	1,110-2,750
Cassava	10-65	170	1,700-11,050
Sweet potatoes	8-50	167	1,336-8,350
Grapes	10-25	130	1,300-3,250
Nipa palm			2,300-8,000
Sago palm			1,350

Note: These figures are derived from many sources and are included only as indications of possible yields [1].

Sugarcane

Sugarcane is an attractive raw material for ethanol production since, not only is its processing relatively simple, but its woody rind, bagasse, provides a source of fuel more than adequate for the generation of steam and electricity needed to run the distillery. A tonne of sugarcane, with a sugar content of 10-13 percent, will produce about 65-75 liters of ethanol by direct fermentation of the cane juice.

In many developing countries, sugar is produced for export. The diversion of sugarcane to ethanol manufacture reduces foreign exchange earnings which are often needed to purchase imported petroleum. The economic equation obviously varies with the market price of sugar and oil. In 1979-1980, the price of sugar was relatively high--about 80¢/kg--and the Brazilian alcohol program did not appear to economic. At the present time, however, the price commanded by sugar on the world market is low--less than 10¢/kg--and the economics favor the production of ethanol.

Cane Molasses

Molasses has traditionally been the most common biomass raw material for ethanol production - but for rum, not fuel alcohol. Molasses is a by-product of the production of sugar. A ton of sugar produced also gives about 190 liters of molasses. Molasses contains 50-55 percent of fermentable sugar, and yields about 280 liters of ethanol per ton of molasses.

There is a market for molasses; it has some value as an animal feed supplement, and also for human consumption. But the viscous fluid is difficult and costly to transport, and in many rural locations in the developing countries it is simply dumped. In some situations, therefore, it constitutes an extremely cheap raw material for ethanol production.

Sweet Sorghum

Sweet sorghum, like sugarcane, is an attractive raw material for ethanol production. The plant also has a woody stem which, after extraction of the sugar-laden juice, can be used as a fuel in the distillery. Yields per hectare are comparable to sugar cane. However, sweet sorghum is a new crop for most developing countries.

Cassava

Cassava is grown in many developing countries. It possesses the useful characteristic of being an extremely hardy plant - capable of thriving on poor quality soils. It does not, therefore, compete with food crops, a criticism sometimes voiced in regard to sugarcane.

However, because it contains starch, not sugars, cassava-based processing operations are more expensive; they require a pretreatment stage to convert the starch to sugar. In addition, Cassava residues do not provide a fuel source; commercial fuels must therefore be used to run the distillery.

Corn

The fuel alcohol program in the US is based on corn, a feed crop grown in very considerable quantities. However, in many developing countries corn (maize) is an important food; any diversion of corn fit for human or livestock consumption to alcohol production would directly reduce food suplies. Corn does not therefore find favor as a raw material for ethanol production in the developing countries.

Production Technology

A process flow diagram for an ethanol manufacturing operation based on cassava (manioc) is shown in Figure 1. Other sugar or starch crops would be processed in the same way, except that the saccharization step is omitted for sugar crops. Table 2 gives typical material and utility balances for ethanol production.

Table 2 Material Balance for Ethanol Production [2]

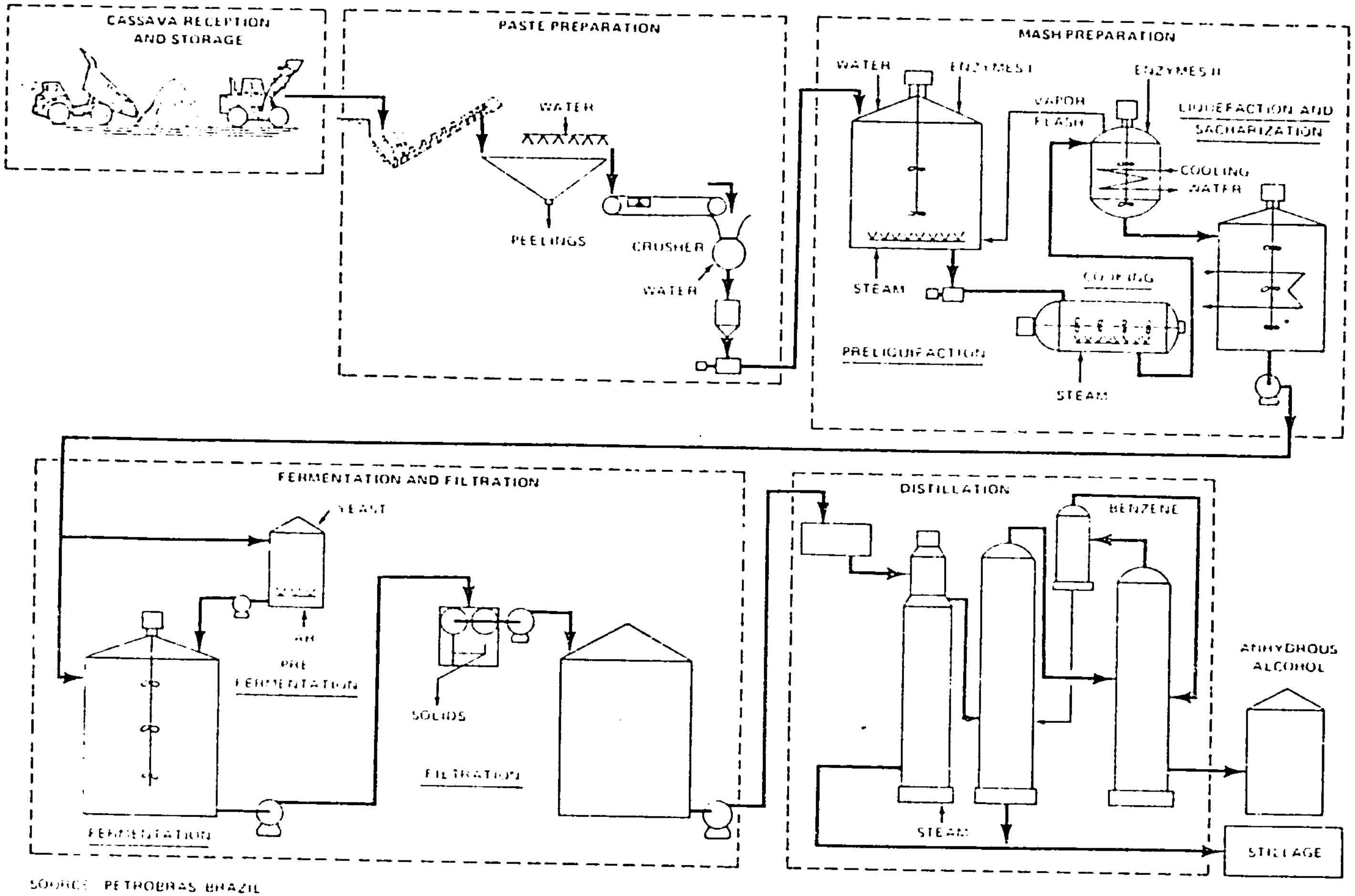
[Basis: per m^3 of ethanol]	Sugarcane	Cassava
Materials		
Raw material, tonne	15	6.8
Chemicals, kg.	46	55
Enzymes, kg	--	5
Fusel oil, kg	5	5
Stillage, tonne	12.5	10.5
Bagasse, tonne	3.8	--
Waste fibers, tonne	--	0.4
Utilities		
Steam, tonne	6.5	6.2
Electricity, kWh	--	450
Water, m^3	200	43
Fuel, (wood, tonne)	--	1.7

Note: Steam and electricity for the sugarcane plant are from bagasse fuel. The cassava plant requires an external supply of fuel, assumed here to be wood.

Sugarcane: The cane is crushed, washed, and the fibres filtered out from the sugar juice. The bagasse is dried and burned to generate steam and power for the plant. The juice is concentrated, sterilized, and then fermented for 1-3 days in a batch fermentation system with yeast, producing an 8-10% alcohol solution. The fermented mash (called beer) is filtered to remove the yeast, and then pumped to the distillation section. Conventional multistage distillation will produce ethanol containing about 6% water. If anhydrous ethanol is required, an additional processing stage is required to remove the last of the water.

The stillage from the distillation process contains about 10% solids and 1-2% nutrients. The disposal of stillage is generally considered to be a problem, but it is possible to anaerobically digest this waste and to generate biogas. The stabilized waste can then be returned to the sugarcane fields as fertilizer. If molasses is the feedstock, additional fermentation tanks are required since the fermentation normally take 4-5 times longer.

Figure 1. Process Flow Diagram for Cassava Based Alcohol Plant



SOURCE: PETROBRAS BRAZIL

From reference 2.

Cassava: The roots, which contain 25-30 percent starch, are washed, peeled, and hydrolyzed in a cooker. The liquified starch is converted to sugars by adding enzymes to the liquor. The process then follows the steps described above for sugarcane. Since cassava roots contain almost no cellulose, there is no woody residue available as a fuel source. An additional supply of fuel--wood, fuel oil, or perhaps biogas--must be made available to the distillery.

Stillage Digestion

A recent development in the operation of alcohol distilleries is the realization that the waste liquor from the the distillation columns can be anaerobically digested, and that substantial amounts of biogas can be produced. For instance, the Bacardi Corporation built a very large digester to treat the stillage produced by their rum distillery in Puerto Rico. The digester takes 1200 m^3/day of stillage, and generates about 28,600 m^3 of biogas daily [2].

The energy requirements for the conventional distillation of ethanol are about 5 MJ/liter to bring the solution up to 95% ethanol, and then a further 2.6 MJ per liter of ethanol to produce the anhydrous alcohol. If sugarcane is the raw material, there is more than enough energy in the bagasse to fuel the distillery. For example, sugarcane is 11-16 percent dry fibre [8]. If the bagasse fuel is about 50% moisture, then roughly 250 kg or so of bagasse fuel are produced from a tonne of cane. Assume further that:

Bagasse heating value:	15 MJ/kg
Ethanol yield:	65 liter/tonne cane

Therefore, a tonne of cane generates about 250 kg of biomass fuel which can be burned to release about 3750 MJ of heat. Since the energy required to distill the ethanol from a tonne of cane is at the most 500 MJ, it is clear that sugarcane provides sufficient fuel to run the distillation operation.

Processing that same tonne of cane will also produce about 800 liters of stillage. If the figures from the Bacardi plant are typical, then a liter of stillage will give approximately 23 liters of biogas. So the production of 65 liters of ethanol from a tonne of cane could simultaneously generate about 18 m^3 of biogas with a calorific value of 360-400 MJ. While this amount of fuel gas is not sufficient to run a conventional distillation operation, it would make a sizeable contribution to the energy demands of the process. Furthermore, improved distillation technology is likely to reduce the energy demands of the distillation step, thereby increasing the contribution that biogas generation could make to the process.

Ethanol distilleries based on cassava would require significantly less external energy if the anaerobic digestion of stillage, and the utilization of the biogas as fuel, were included in the process.

Ethanol Fuel

Table 3 compares the alcohol fuels with gasoline, and diesel fuel. The petroleum fuels are pure hydrocarbons containing no oxygen, while the alcohols ae partially oxidized hydrocarbons. The partial oxidation accounts for the lower calorific value of the alcohols. Methanol is 50% oxygen by weight and therefore has the lowest energy content. For the same reason, the stoichiometric air-fuel ratio is much less for the alcohols. Put another way, alcohol engines use much more fuel than conventional engines of similar size.

One of the most significant differences between the alcohols and the petroleum fuels is their vaporization characteristics. All liquid fuels have to be vaporized in order to burn, and one of the fundamental requirements of an engine fuel system is to deliver a vaporized fuel to the combustion chamber. Diesel engines mechanically vaporize fuels by using high-pressure spray nozzles as injector tips. The more volatile fuels are vaporized by heating them above their boiling points.

Since gasoline is a mixture of hydrocarbons and not a pure substance like methanol and ethanol, gasoline starts to vaporize at a low temperature (32°C) as low boiling point fractions are boiled off. This high volatility at ambient temperatures improves the starting ability of cold engines running on gasoline. The alcohols, on the other hand, while they exert a vapor pressure at ambient temperatures, are not excessively volatile until temperatures approach their respective boiling points.

Table 3 also shows a wide difference in the amount of energy rquired to vaporize the alcohol fuels. The range is 1.8 to 3.6 times the amount of heat needed to completely vaporize a similar amount of gasoline. If the alcohols contain water, even greater amounts of energy are required to vaporize the fuel because of the high heat of vaporization of water.

Self-ignition temperatures are high for ethanol compared with diesel fuel. It is very difficult, therefore, to ignite ethanol with the heat of compression alone. All the alcohols have high octane ratings; they all exhibit smooth, non-knocking engine performance in spark-ignition engines.

Ethanol can be blended with gasoline (gasohol), in which case the ethanol must be anhydrous; or ethnol can be used alone as a fuel, in which case the azeotropic proportion of water (5.5%) can be tolerated. The gasoline blend requires the ethanol to be anhydrous because gasoline-ethanol-water mixtures are not completely miscible; some phase separation occurs which can cause troublesome carburetor problems.

Table 3 Physical and Chemical Properties of Liquid Fuels

Property	Ethanol	Methanol	Gasoline	Diesel	Fuel Oil
Formula	C_2H_5OH	CH_3OH	C_4 to C_{12} hydrocarbons	C_{14} to C_{20} hydrocarbons	$C_{20}+$ hydrocarbons
Molecular weight	46.1	32.0	100-105 av.	240 av.	-
Composition (wt. %)					
Carbon	52.2	12.5	85-88	85-88	85-87
Hydrogen	13.1	12.5	12-15	12-15	10-11
Oxygen	34.7	50.0	neg.	Neg.	Neg.
Relative density	0.79	0.79	0.72-0.78	0.83-0.88	0.88-0.98
Boiling point, °C	78	65	27-225	240-360	360+
Flash point, °C	13	10	-43	38	66
Autoignition temperature, °C	423	470	257	-	-
Heat of vaporization, kJ/kg	920	1170	325	155	-
Lower heating value, MJ/kg	26.9	19.6	44.5	43	-
Flammability limits (vol. %)					
lower	4.3	-	1.4	-	-
higher	19.0	-	7.6	-	-
Octane number (research)	106-111	106-115	79-98	-	na
(motor)	89-100	82-92	71-90	-	na
Cetane number	0-5	na	5-10	45-55	na
Solubility in water	infinite	infinite	0	0	0

Note: na = not applicable. Source: American Petroleum Institute, adapted from references 2 and 5.

Gasohol

Internal combustion engines will run without modification on gasohol containing up to 20 percent ethanol. Although the energy content of ethanol is significantly lower than gasoline, the greater volumetric and combustion efficiency of the gasohol fuel offset this to the extent that fuel consumption is substantially the same as for gasoline.

The high octane number of ethanol permits it to be blended with low-octane gasoline to produce a high-performance fuel. Since low-octane gasoline is cheaper to manufacture at the refinery, ethanol actually has greater value as an additive to gasoline than it does as a substitute.

Straight Ethanol

To maximize performance with straight ethanol, spark-ignition engines need to be modified. The modifications include arranging a higher compression ratio, modifying the carburetor, employing different materials in certain parts of engine (ethanol will corrode certain metals and plastics); and building into the vehicle a small gasoline tank and fuel system to permit starting in cold weather.

The Brazilian car industry estimates that these modifications add about 5% to the cost of gasoline powered vehicles [2]. Other authors suggest the changes might cost $200-$400 per engine [3].

Diesel Fuel Substitute

Ethanol is a very poor fuel for diesel engines. Diesel fuel must auto-ignite under compression in the cylinders; none of the alcohol fuels possess this characteristic. Moreover, ethanol dissolves only sparingly in non-aromatic hydrocarbons; its solubility decreases with increasing temperature, and also in the presence of water.

One approach to diesel fuel substitution by ethanol is to add chemicals which improve miscibility and solubility; however this raises the cost of the fuel. Alternatively, a dual fuel system can be used where ethanol is aspirated directly into the cylinders without premixing with the diesel fuel. Neither approach, however, can be considered entirely satisfactory.

Production Costs

Capital Costs

The capital cost of an independent distillery in Brazil have been given as $11.5 - $15.5 million for a sugarcane operation, and $15.5-$17.0 million for a plant based on cassava. These are 1979 costs for a distillery producing 150m^3/day of ethanol, and operating for 180 days per year in the case of sugarcane, and 330 days per year for a cassava plant.

The World Bank in 1980 reported Brazilian costs as shown below in Table 4.

Table 4: CAPITAL COSTS OF ALCOHOL PLANTS IN BRAZIL
(late 1979 prices, in '000 US$)

Capacity, liters/day:	20,000	120,000	240,000
Engineering	135	400	680
Process Equipment	950	3,950	6,800
Utilities	220	925	1,620
Freight	60	225	300
Civil Works and Land	270	750	1,250
Erection	135	400	500
Sub-Total	1,770	6,650	11,150
Contingency	230	950	1,350
Installed Cost	2,000	7,600	12,500

These cost figures are for a conventional design (in which limited attention is paid to energy efficiency) developed for producing alcohol for potable and chemical purposes [2].

The data in Table 4 show that capital costs of distilleries show strong economies of scale. However, most developing countries would probably first build relatively small plants of around 120 m^3/day of alcohol production. The World Bank considered the optimum size to be 60 - 120 m^3/day for a cassava based plant, and 120-240m^3/day for a sugarcane/molasses based alcohol plant [2]. Estimated installed costs for a 120m^3/day ethanol plant were given as:

Sugarcane:	$7.6-$14.3 million
Molasses:	$6.8-$11.4 million
Cassava:	$9.1-$17.2 million

Again, these are 1979 figures [2]. Brought up date, 1985 capital costs would be expected to be 30 - 40 percent higher.

Operating Costs

The major cost component of a unit of ethanol is due to the cost of the raw material; typically this accounts for over half the cost of the alcohol. For example, data from Brazil were given as follows:

Table 5 Percent Operating Costs per Unit of Ethanol Output

	Sugarcane	Cassava
Raw material	57.0	60.1
Chemicals, utilities	1.7	15.8
Labor	4.2	3.4
Maintenance and other expenses	7.0	4.8
Taxes, depreciation, and net profit	30.1	15.9
	100.0	100.0

Note: Data from Yang and Trindade (1979) [6] cited by Rothman [3], assumes a 150 m^3/day distillery operating for 330 days/yr for cassava; 180 days/yr for sugarcane. Exchange rate Cr$18 = US$ 1.00 Based on sugarcane at $13.6/ton, cassava roots at $33.3/ton.

Feedstock Costs

Assigning a value to the raw materials used as feedstock is not always straightforward. The value of sugarcane as a feedstock for the production of raw sugar varies with the world price of sugar. This price reached 66¢/lb in late 1979, slumped to 5-10 ¢/lb between 1976 and 1979, rose briefly to 36¢/lb in 1980, and in early 1985 was again down below 5¢/lb [7].

As a rule of thumb, multiplying the price of sugar ($/lb) by 115 gives the price of a ton of sugarcane. The range of prices for raw sugar indicated above would therefore imply sugarcane prices of between $5.75 and $76 per ton of cane. The World Bank's assessment is that only relatively efficient cane producers, selling cane for between $10-$16/ton can produce ethanol at a competitive price [2].

Ethanol Costs

Based on the discussion above, it is possible to estimate the cost of ethanol produced from a typical distillery. The basis used is a cubic meter of ethanol produced. Capital costs can be reformulated on this basis by expressing them as dollars per m^3/yr of alcohol produced - rather like the dollars per "annual gallon" used in the US.

On this basis capital costs for a 120 m^3/day facility would be

Sugarcane:	352 - 662 $/($m^3$/yr)
Molasses:	315 - 528 $/($m^3$/yr)
Cassava:	276 - 521 $/($m^3$/yr)

in 1979 dollars. We will increment these by 35% to give 1985 capital costs for a sugarcane plant between $475 and $895 per m^3/yr. We further assume:

Cost of capital	10% p.a.
Loan period	10 years
Water and chemicals	$5/$m^3$ output
Operation, maintenace and labor	10% of capital
Ethanol yield	65 liters per tonne of cane

Case A: Cane at $10/ton

Capital costs, $/($m^3$/yr):	475	895
Capital charges (10%, 10 years)	77 $/yr	146 $/yr
Water, chemicals	5	5
Operation, maintenance, labor	48	90
Sugarcane (15.4 t/m^3 output)	154	154
	284 $/yr	395 $/yr

Ethanol costs are therefore between 28.4¢ and 39.5¢/liter.

Case B: Cane at $20/ton

Capital costs, $($m^3$/yr):	475	895
Capital charges	77 $/yr	146 $/yr
Water, chemicals	5	5
Operation, maintenance labor	48	90
Sugarcane	308	308
	438 $/yr	549 $/yr

Ethanol costs are therefore between 43.8¢ and 54.9¢/liter.

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