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Biogas Systems for Rural Development

Report of the Training Workshop on

MONITORING AND EVALUATION OF BIOGAS SYSTEMS

29 AUGUST - 1 SEPTEMBER 1983, LUSAKA, ZAMBIA

AFRICAN ENERGY PROGRAMME

COMMONWEALTH SCIENCE COUNCIL
COMMONWEALTH SECRETARIAT
Marlborough House, Pall Mall, London SW1Y 5HX

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SUMMARY

This report contains the proceedings of a training workshop on monitoring and evaluation of biogas systems held in Lusaka, Zambia from the 29 August - 1 September 1983. The workshop, organised under the African Energy Programme of the Commonwealth Science Council, reviewed the progress of the regional overseas research project involving scientists from Kenya, Mauritius, Seychelles, Tanzania, Uganda, Zambia and Zimbabwe. The workshop, co-sponsored by the National Council of Scientific Research of Zambia, was funded by the UK - Overseas Development Administration, and reviewed progress on the projects as well as considering techniques and methodologies of monitoring and evaluating biogas systems.

Country papers from each of the seven participating countries were presented and discussed. A set of four technical background papers on monitoring an devaluation were presented, followed by discussions which let to the drafting of a set of guidelines on monitoring and evaluating biogas systems. Finally there was a discussion of the future of the projects after the end of the current ODA grant in March 1984.

1. INTRODUCTION

The Workshop on monitoring and evaluating biogas systems was convened by the Commonwealth Science Council, hosted by the National Council of Scientific Research ofZambia at their offices in Lusaka, Zambia and sponsored by the Overseas Development Administration of the United Kingdom. The workshop reviewed the progress of the ODA-funded biogas research project, which is part of the CSC's African Energy Programme, and considered techniques and methodologies of monitoring and evaluating biogas systems, with particular reference to the AEP projects.

The review session of the workshop was convened as a routine part of the CSC's procedure for managing research projects, in which both scientific findings and operational progress are regularly reviewed. The more detailed technical discussions on monitoring and evaluation were considered to be necessary in view of the differing and sometimes inconsistent approach to monitoring, evaluation and scientific reporting among the various national project co-ordinators. While the reports produced by the co-ordinators were generally sound in the context of their respective projects, their differences in approach frequently hindered exchange of experience between different projects. The workshop therefore aimed to develop a basic methodology and a set of techniques which could be applied in all the projects.

Country papers from each of the seven participating countries were presented and discussed. A set of four technical background papers on monitoring and evaluation were presented, followed by discussions which let to the drafting of a set of guidelines on monitoring and evaluating biogas systems. Finally there was a discussion of the future of the projects after the end of the current ODA grant in March 1984.

2. PROCEEDINGS

The workshop participants were welcomed to Zambia by Dr S M Silangwa, Secretary-General of the National Council for Scientific Research. He expressed his pleasure on behalf of the Council in hosting the meeting. He expressed the hope that the meeting would make a fruitful contribution to the progress of the Biogas Project.

He welcomed the opportunity to expose a number of Zambian Scientists to the discussions of work on biogas being conducted elsewhere in Africa. Dr Silangwa invited the Prime Minister of Zambia to open the Workshop.

In his opening remarks the Right Honourable Prime Minister of Zambia, Mr Nalumino Mundia, extended the greetings of the Government of Zambia to the workshop participants. He pointed out how relevant the technology of biogas was to Zambia in its efforts to develop its indigenous energy resources, in order to reduce its dependance on imported fuels. While efforts to exploit hydroelectric energy and coal reserves were providing energy for industry and the urban population, it would require a massive effort to distribute this energy to the rural population. The Zambian Energy Policy therefore now included the development of renewable energy sources which would be more cost effective in rural areas. Biogas production was one of the technologies under consideration, and offered the potential to solve several problems in addition to providing energy - it could relieve the environmental pressure of deforestation, offer hygenic rural sanitation, and provide a valuable fertiliser to replace imported artificial products. Prime Minister Mundia pointed out that while Africa was well endowed with energy resources, both renewable and non-renewable, the continent's major problem was the lack of local skills, technology and investment to exploit those resources. He therefore welcomed the opportunity of hosting the workshop and expressed the hope that all participants, including Zambians would benefit from exposure to the experience of researchers in other parts of Africa.

Dr Silangwa thanked the Prime Minister for his interesting and encouraging remarks and invited the Commonwealth Science Council's representative Mr Robert Dewing to offer a vote of thanks.

Mr Dewing began by thanking the Government of Zambia for its hospitality in hosting the workshop. He then gave an outline of the CSC's African Energy Programme, and went on to describe the developments in the biogas project which has given rise to the present workshop. He expressed the hope that the outcome of the participants' deliberations would lead to some useful scientific conclusions as the end of the current ODA grant approached in

March 1984, and enhance the prospects for the project securing further funding for those elements of the research which need to continue beyond that data.

3.0 TECHNICAL SESSIONS

3.1 Technical Introduction

Dr Pyle began the technical sessions of the workshop by introducing his first paper (reference 1), which discussed the status of biogas in various parts of the Third World. The main interest in biogas in the Third World has been in Asia and the Pacific, with very little in Africa and Latin America. The most widespread use of biogas occurs in China and India. The principal problem encountered in popularising biogas among the low-income rural poor is the high capital outlay involved in setting up a digester despite the low marginal cost of the fuel and fertiliser which are produced. The paper discussed the experience of various Third World countries and pointed out that the major problems facing biogas are not purely technical, but involve social and economic factors. The paper is not reproduced in full in this report as it is about 30 pages long; it is cited as reference 1 in the bibliography.

Paper 2

Dr Pyle's second paper briefly describes some current developments in digester design and discusses the comparative advantages and disadvantages of various designs. The paper includes illustrations of a number of design configurations.

Paper 2: Developments and Trends in Biogas Technology, by Dr. L. Pyle

There already exists a range of biogas designs which can handle a variety of input substrates and operate more or less reliably and more or less efficiently. (Details can be found, for example, in Basnett et al, Pyle (paper 1)). However, there is a need to develop new designs and to refine the detailed designs of existing models to meet the following objectives in particular:

1. To improve technical efficiency (i.e. the yield and rate of production of gas);
2. To improve reliability;

3. To enable operation with a range of inputs (e.g. crop residues, effluents, human excreta, etc. etc.), and to minimise the use of expensive or scarce materials;

4. To reduce the costs of operation.

In practice, there will be no single 'best' design; in a particular location this will result from a trade-off between competing objectives and intelligent adaptation to accommodate local constraints. On the other hand, there is a lot to be learned from work across the world to improve digester designs to meet the listed objectives. Few radically new, tested designs have been developed since my survey (paper 1) a few years ago, but a number are very close to adoption. The need now is to collect and assess reliable and comparable data on the technical (and economic) operation of the range of designs.

Figure 1 illustrates schematically the range of digester types. Some examples of conventional single stage units are outlined and described briefly in paper 1. For example the familiar Indian KVIC and Chinese fixed dome designs fall into this category. Examples of plug flow digesters include the early Fry design, the large scale interconnected Chinese design (fig. 7, paper 1); the Taiwanese bag digester (figure 2); a similar and well-tested design has also been developed by Jewell and co-workers. Many local variants on these designs are known or being tested: there will always be a need to accommodate designs to local conditions, materials availability and price.

Surprisingly little serious attention has been paid to batch or semi-batch operation, despite the relative simplicity of such designs. One possible advantage is their ability to handle essentially solid or "dry" substrates (i.e. up to 40 to 50% solids concentrations): although little experimental data is available we do know that such designs can be operated. Apart from opening up a wider range of feed materials, operation at high concentrations should imply lower digester volumes (and therefore costs), and, of course, reduced water requirements.

It is now widely accepted that one of the intrinsic limitations in all these designs is the limited 'natural' hold-up of active micro-organisms in the digester. In any through-flow system a mixture of living and dead bacteria will be lost with the slurry. In practice the rate of gas production per unit volume of digester is directly proportional to the concentration or hold up of bacteria in the digester. Considerable attention has thus been devoted recently to increasing this concentration level. The recycle digester (3) in figure 1 is one example: this invariably gives rise to problems in the separator/concentrator and does not look a very attractive proposition for on-farm or small community applications.

The anaerobic filter ((4), fig. 1) is a well-proven and old alternative, which has mainly been used in larger scale urban sewage disposal systems. The packing or support is an inert solid such as stone or coal. One limitation of this design is that it cannot handle inputs with high solids contents (because of blocking). It also must be cleaned and regenerated from time to time. Recent developments have however shown that simple filters may be suitable in developing countries, especially for liquid wastes - designs incorporating local materials are easily engineered and operation is relatively straightforward.

The fluidised bed digester takes the anaerobic filter a stage further. Here the support particles are suspended in the upflowing liquid and are thus free to move. This has a number of consequences. Blockage should be less of a problem; the digester contents are more-or-less mixed; it is possible to operate such a unit continuously since particles can be withdrawn and added without interrupting operation. Some of the advantages of such units are discussed by Mistry et al (1983).

Both these designs depend on the ability of the micro-organisms to stick to surfaces and to each other and thus to form films. This ability - or flocculation - is used in the upwards flow sludge blanket (U.A.S.B.) digester ((4) in figure 1; figure 3), which is suitable for soluble waste streams. Here a 'blanket' of active biomass forms in the digester and the substrate flows through it. Another design which depends on the flocculation/settling ability of the active biomass is shown in figure 4. This is an extension of the plug flow digester, and is presently being tested.

Sometimes it may be appropriate to hold the bacteria in position - for example, by trapping them inside a porous envelope: Mistry et al (1983) describe one such design where the biomass is immobilised in spheres of alginate gel. It is interesting to note that the process of immobilisation itself apparently accelerates the rate of gas production. Again, this design is more likely to be useful for soluble rather than insoluble substrates.

In all this set of designs, the retention time in the digester of liquid and solid biomass is different, and this is an important key to their improved performance.

Another key feature of anaerobic digestion relates to the microbiology. Although the overall process is complex and involves different types of bacteria (see paper 3) we can divide the process into two or three main stages (figure 5). When the starting material (i.e. the polymer) is insoluble (e.g. straw), it is likely that the rate-limiting stage is the rate of hydrolysis to simple sugars and intermediates (i.e. stage 1). When the starting materials are easily hydrolysed (e.g. soluble wastes, piggery wastes etc.) the limiting process is that of methanogenesis (stage 3). In any event (see paper 3) the implication is the same, since the optimum conditions for stages 1 and 2 do not necessarily coincide with those for the methanogenesis to flourish (stage 3): thus, why not separate out stages 1 and 2 and 3 from each other? This is illustrated by 5 in figure 1. The first example there outlines a configuration for a relatively soluble substance, in which the conditions in digester 1 are optimal for acid production (low pH); digester 2 operates at a higher pH and is the vessel where the acids are converted to methane and carbon dioxide. The second example refers to an insoluble substrate: this is converted to acids (again at low pH) in the first, concentrated, digester; the acids are recycled through the second digester where most of the methane production takes place.

Tables 1, 2 and 3 summarise some recent comparative information on, (a) continuous and plug flow digesters and, (b), two stage processes. These are also discussed in paper 3.

Conclusions

This review supplements paper 1, and indicates some recent developments at a process level, rather than at the level of detailed design, in anaerobic digestion. The designs described above are being developed in response to a variety of stimuli and also reflect the growing understanding of the basic process. They illustrate the wide range of alternatives available, and the need for careful definition of the problem and the objectives of biogas operation.

Although I have said little here about detailed design and the need to adapt basic designs to local needs and constraints, that does not imply that such processes are unimportant - quite the contrary. However, it is useful and instructive to separate out the principles of the basic design and the detailed and practical issues in developing any basic design into a working digester system.

TABLE 1: COMPARISON OF COMPLETELY MIXED DIGESTER WITH PLUG FLOW DIGESTER

	Completely	mixed	Plug	flow
HRT (d)	15	30	15	30
Gas production rate ($m^3m^{-3}d^{-1}$)	2.13	1.13	2.32	1.26
Specific gas production (m^3kg VS added $^{-1}$)	0.281	0.310	0.337	0.364
Gas composition (% CH_4)	55	58	55	57
Volatile solids reduction (%)	27.8	31.7	34.1	40.6

TABLE 2: TWO PHASE DIGESTERS

	Stage 1 (ACID)	2 (METHANE)
pH	5.7 5.9	7 7.4
Retention	0.5 1 day	6.5 days
Methane	0.6 m^3/m^3 day	4.6 8.9 m^3/m^3 day
Acids (mgle)	4500	150

TABLE 3: COMPARISON OF DIGESTERS

	1	2
	High Rate	Two Stage
Methane production m^3/m^3	1	1.5
Volatile Solids Reduction	34	43
Digester Volume Ratio	1 (8 units)	1/3
Cost (10^6 \$)	13.5	4.8

3.2 COUNTRY REPORTS

3.2.1 Kenya

By Gichuki Muchiri and Lawrence Gumbe, University of Nairobi

SUMMARY

Floating dome, fixed dome, and plug flow digesters have been constructed. Tests have been conducted principally on the floating dome and fixed dome digesters. Measurements have been made of pH, digester temperature, and gas output. Various types of cooking stove have been tested. Problems have been encountered with a shortage of measuring instruments, and poor quality digester construction. Results so far obtained show the floating dome design to be preferable to the fixed dome.

I. OBJECTIVES

the "Biogas slurry systems" project centered at the Department of Agricultural Engineering of the University of Nairobi, Kabete Campus, was set up with the following objectives:

a) To analyse farm level energy needs for household and agricultural users;

b) To select biogas-slurry technologies that are likely to meet these energy needs;

c) to evaluate, modify design and test methane digesters under local conditions;

d) To carry out concurrent pilot schemes to determine farmer acceptance;

e) To maintain back-up research and development services which can provide design, operation and maintenance information to users and producers of biogas-slurry technology;

f) To produce a designer's manual for biogas digester design.

Three major types of biogas digester were selected for monitoring at Kabete the Indian (KVIC) floating dome type, Chinese dome type and the overground plug flow Javanese type.

II. TECHNICAL REPORT

Background

The 13 m^3 Indian design unit was constructed in 1978 with funds from the Industrial Survey and Promotion Centre of the Ministry of Commerce and Industry; it was attached to a family house with the purpose of monitoring the energy requirements of the family. Initially there were structural problems with the unit due to shoddy workmanship resulting in the collapse of the central portion during the first filling, and cracks in the digester wall. There were operational problems due to an inadequate supply of dung and shortage of water for mixing with the substrate. By late 1979 the above problems had been overcome and the unit was functioning satisfactorily.

The design of the 4 m^3 chinese type digester was completed in early 1982. The digester was sited near a house with the intention of monitoring gas consumption of the household. The construction was divided into three main phases:

a) excavation
b) material movement, and
c) building

Three casual labourers, a technician, a lab assistant and a mason were engaged for the work. The digester has a dome shaped gas holder with cylindrical sides, is flat bottomed and is underground. The foundation was made of 15 cm hardcore fill appropriately compacted. The cylindrical tank was built of salvaged hard building stones whilst the dome shaped gas collector was built of 1:1½:3 concrete reinforced with a single layer of 1 mm by 15 cm by 15 cm weld mesh.

Excavation of the hole was mainly done by the casual labourers and took 26 mandays. Movement of materials required 10 mandays. The hard core fill required 4 mandays whilst building the digester took 70 mandays, including:

a)	floor construction	-	9 mandays
b)	cylindrical tank construction	-	15 mandays
c)	dome construction	-	25 mandays

The gas was piped through a 7.5 cm steel pipe on which was installed a gas meter and a mamometer.

The digester was first filled with cowdung on 21.7.82 and gas production was first observed on 6.8.82.

(i) **Experimental methods**

The two digester units were monitored daily at 9 am and 3 pm for temperature, pH, pressure and volume of gas consumed.

The temperature for the Chinese unit was monitored by inserting a thermal probe in the inlet and outlet and averaging the two. For the Indian unit, the temperature was measured by inserting the thermal probe at two arbitrary points and taking the arithmetic mean of the two temperatures.

The pH was monitored by means of pH paper.
The gas pressure was monitored by U-tube manometers.
The volumetric gas consumption was monitored by the use of a gasmeter. Since only one gasmeter was available, it was periodically changed from one unit to the other. This obviously created discontinuity and is not desirable.

(ii) **Cooking trials**

Cooking trials were conducted in January and February 1983 in conjunction with the Department of Home Economics of the Kenyatta University College. The Indian design unit was used during this period. The aim of the trials was to compare the relative performance of various types of cooking energy sources, namely biogas, firewood, kerosene and charcoal. The cooking devices employed were the ordinary jiko for charcoal, the three stone for firewood, the wick-stove for the kerosene and a biogas burner. Different types of food were cooked using the same sized aluminium pots on each of the energy sources. Time taken and amount of fuel used to cook various types of food were recorded (table 1).

III **Results**

Temperature

An examination of temperatures for the Chinese design digester reveals that the internal temperature of the digester was fairly stable at about 23°C, generally higher than the ambient temperature by an average of about 6°C with a maximum of 10°C. The stability of temperature above ambient is very desirable as it is optimal for anaerobic digestion.

An examination of temperatures for the Indian design digester shows that the internal digester and ambient temperatures were more or less the same and stable at about 20°C.

The difference in temperature between the Chinese design and KVIC (Indian) design digester can be attributed to the Chinese design being entirely underground and therefore having better thermal insulation than the Indian design with its dome above ground.

pH

The pH of both digesters was very stable at around 7 (neutral) which is optimal for anaerobic digestion.

Pressure

The pressure in the Indian design digester was fairly stable at about 12.5 cm. of water; this is due to the floating dome which rises and falls as gas is either produced or consumed. The pressure for the Chinese design digester fluctuated rather widely from a maximum of 350 mm of H_2O to a minimum of 100 mm of H_2O. The fluctuation is due to the fixed dome which does not alter volume to maintain pressure as gas is produced or consumed.

Gas Consumption

Both digesters were designed for a 50-day retention period and were fed daily with 50 kg. of fresh dung mixed with 50 kg. of water. Gas production per kilogramme of cowdung for the Chinese design digester for the period 1.10.82 to 31.10.82 was determined to be 0.025 m^3 which corresponds to the figure established in 1981 for the Indian design digester. This dropped to 0.016 m^3/kg as opposed to 0.029 m^3/kg for the Indian digester.

Cooking trials

Tables 3 to 9 represent the various types of food cooked on the fuel sources. An examination of the tables reveals that biogas took the least time to be ready for use (cooking), kerosene was next whilst the other took considerably longer to be ready (about 28 minutes for charcoal and about 17 minutes for firewood). It has to be noted that the lighting of firewood and charcoal depend on factors like weather which are uncontrollable.

IV DISCUSSION

The performance of the Indian design digester was superior to that the Chinese design. The former produced up to 4 m^3 of gas per day, enough for about 3 hours of cooking with surplus gas to spare which may be sufficient for lighting. The latter at peak performance yielded 54 minutes of cooking per day before the gas was completely exhausted. However, the Indian design digester has airdome of 13 m^3 whilst the Chinese design is only 4 m^3. This factor would be contributory to the better performance of the former. There were also many problems like gas leakages, structural failure, and lack of instruments (gasmeters) which contributed to the poorer performance data of the Chinese design. Some of these problems have now been overcome and it is expected that more meaningful data will be collected.

Preliminary results of the cooking trial reveals that biogas is indeed a promising alternative energy source.

The data collected indicate the complicated inter-relationship between gas production, temperature, pressure and pH. There is still a need to collect and analyse more data before definitive design parameters can be established.

Table 1 : Cooking Tests

The first figure of each pair represents preparation time, which is the time taken to light and set up the stove, in minutes. The second figure is cooking time in minutes.

	ENERGY SOURCE			
	Firewood	Charcoal	Kerosene	Biogas
Food ingredients:				
(i) 1 glass of rice, 2 glasses of water	27,27	27,45	3,26	2,25
(ii) 20 leaves of sukuma Witz, 3/4 glass of water, 1 teaspoon of Kimbo	27,10	27,17	3,16	1,14
(iii) ½ Kg meat/onions 3 tomatoes, 2 carrots 1 teaspoon of Kimbo salt ½ teaspoon of curry powder 1½ mugs of water	17,30	28,38	4,40	2,37
(iv) 8 eggs 4 mugs of water	17,13	28,16	3,20	2,20
(v) 10 pieces of chopped carrot, 3 glasses of water 1 teaspoon of Kimbo and salt	18,20	28,20	3,20	2,20
(vi) 12 bananas 1 onion 1 teaspoon of Kimbo, curry powder and salt 4 glasses of water	17,33	27,35	3,31	3,38

(vii)	1 Kg Maize ½ Kg beans 2 onions 1 teaspoon of Kimbo, curry powder and salt 10 Mugs of Water	17,153	27,205	3,154	2,192

3.2.2 Mauritius

Dr J Baguant and Dr S Callikan, University of Mauritius.

Summary

The foreign exchange demand of energy imports for Mauritius is particularly acute because the country has almost no available fuelwood. Energy demand is expected to double by AD2000. Nevertheless the authors suggest that it should be possible to bring down the proportion of imported energy from 92% to 33%, by energy conservation, exploitation of agrowastes (bagasse) and hydropower, and popularising other renewable energy sources such as solar, wind and biogas. The authors propose that biogas could make a significant contribution, particularly in supplying energy for cooking. They discuss the pattern of energy use from existing supplies in Mauritius, especially for household cooking. In order to compare the feasibility of biogas for such purposes research has been carried out on the technical and economic viability of biogas digesters.

A range of experiments are reported on a batch and a semi-continuous digester. Work on the batch digester commenced with general tests which established that the digester performance was comparable with other reported results. More detailed experiments then followed to study some factors which might contribute to improved gas production characteristics, in particular the effects of temperature, slurry dilution, particle size, and the use of starter cultures. The addition of 2.5% w/w of starter culture had the effect of reducing the latency period for digestion from 35 days to six days, reducing retention time from 40 to 25 days for 50% extraction of gas, and increasing the daily gas production rate by a factor of about three. However, even with the use of a starter culture, gas production was observed to reduce after an initial peak period. It was postulated that this might be due to exhaustion of the microbial population. Tests were therefore conducted where a booster quantity of starter culture was added just before the gas production rate was expected to fall. The rate fell just as it had without the booster, leading to the conclusion that the rate fell because of exhaustion of the substrate, not of the bacteria. Tests on various dilutions of slurry indicated an optimum dilution of cowdung to water of 1:1. Tests using different sized particles as feedstock indicated that gas production was more rapid with fine particles than coarse.

Tests were conducted with variation of temperature, despite this being one of the most thoroughly documented aspects of biogas digestion, because the authors wished to observe the effect of temperature under the conditions in which they were operating. They also wished to observe the effect of temperature in the presence of starter culture. Raising the digester temperature from ambient (21°C) to 35°C had little effect on the duration of the latency period. However it increased gas output during peak production, and consequently increased the cummulative extraction of biogas. It also reduced the retention time for 50% extraction. Temperature increases to 40 and 35°C did not improve gas production. It was concluded that a digestion temperature of approximately 35°C coupled with the use of a starter culture could reduce the retention from 40 days to about 15 days. This would allow a smaller digester to be used with consequent benefit for the economic viability of the system, and was therefore the subject of a more detailed study which is reported later in the paper. Investigations into digestion in the thermophilic range at around 55°c are in progress, with high gas yields resulting. Tests for total and for available nitrogen, sodium and potassium have been conducted on the digested slurry and indicate that the fertiliser value of the slurry is enhanced during digestion.

Tests on a semi-continuous digester were undertaken to complement the tests on batch digestion, in order to give data for the definition of digester performance characteristics, digester design, and economic evaluation. Tests on variation of gas yields with retention time had been carried out, but tests were reported to be continuing with variable loading rate at ambient temperature and 35°C. Tests on various mixing modes, on partial recirculation, and on two-stage digesters were also intended to be undertaken.

Following the laboratory investigations tests will be conducted on a family sized (2 m^3) digester which has already been constructed to evaluate the practical and economic feasibily of the digesters. It is also planned to investigate the digestion of agrowastes other than cowdung, which has been used so far.

Gas utilisation tests are reported on a modified butane gas stove. Engine tests are proposed on a 5 hp single cylinder engine.

the report gives a brief economic analysis of the cost of biogas production, based on laboratory results. On the basis of this provisional information the cost of biogas from a 2 m^3 mild steel digester is comparable to that of kerosene and cheaper than LPG or electricity. The researchers identify the principal area for improvement as : (i) improved gas yield, (ii) less costly digester designs (iii) government initiatives to assist digester operation costs.

The full report is almost fifty pages long and is therefore not reproduced in this report. It is available on request from the CSC or from the authors, Dr J Baguant and Dr S Callikan at the School of Industrial Technology, University of Mauritius, Reduit, Mauritius.

3.2.3 SEYCHELLES

Mr V Dhanjeee, Research Unit, Ministry of Planning and External Affairs, Seychelles.

SUMMARY

In order to reduce the heavy foreign exchange burden of oil imports, the Seychelles Government has initiated the Seychelles Integrated Energy Project, with the objectives of developing (i) an alternative energy system to satisfy from non-fossil sources the electrical demands of Mahe, the principal island of the Seychelles archipelago, (ii) for the remaining islands, individual integrated energy systems including renewable sources, (iii) an energy management program. In 1979 the Seychelles Government created a Research and Development Unit within the Ministry of Planning and External Relations in order to implement its Integrated Energy Programme. The Programme has been divided into three phases. The current biogas project is part of the first phase, and aims to assess the biogas potential of the Seychelles, develop working digesters for the various types of available feedstock, and then to extend each of the designs to the field where cost/benefit analysis will be conducted. Both technical and social benefits will be considered. The technical merits to be considered are ability to supply energy, usefulness of digested slurry as fertiliser, and the ease of digester construction with local materials. The social merits under consideration will be waste treatment, public health, sanitation, and employment. The subsequent phases of the integrated energy programme are planned to involve a major extension programme if the first phase proves the feasibility of biogas systems in the Seychelles.

Because of the small animal population of the Seychelles, sources of feedstock other than animal dung are being examined. There are five digesters already constructed in the Seychelles, and a sixth under construction. Most of the existing installations are not in use because of managerial or technical problems. However, work is now underway to commission them.

At present the project work is taking place on a laboratory scale batch digester to obtain an indication of biogas availability per unit of feedstock at various retention times, in order to determine

the conditions for optimum gas production from the feedstocks which are available. The project work is reported to be behind schedule, due mainly to manpower shortages. It is hoped to bring the work back on to schedule within the next semester.

Several series of experiments have been carried out, as summarised below. They are reported in detail in the main paper.

Best age of starter - starter cultures of cow dung slurry of age 7, 14, 21, 28, 35 and 41 days were tested. A 28 day old starter gave the least latency period, of around 27 days. Results from tests with other feedstocks indicate considerable variation of the latency period with pig dung giving a shorter period, and chicken dung virtually none at all. The best rate of gas production was given by a 25 day old starter. The highest total gas production occurred with a 35 day old starter.

Chicken dung as a feedstock - the amount of biogas produced was greater than that for cowdung, although not as high as those reported by other researchers (this is possibly due to unfresh manure being used). The digestion process exhibited a period during which the gas production rate fell and then rose again with a fall followed by a rise in pH. It is postulated that this phenomenon is due to the pH or the carbon/nitrogen ratio of the slurry. Experiments were devised to test this, the pH being varied by the addition of vinegar or a buffer solution of pH=7, and the c/n ratio being varied by the addition of sugar or soot. Lowering the pH (making the solution acid) increased the duration of low biogas production, while keeping the pH above 7, i.e. alkaline, reduced the period. The addition of carbon had the effect of prolonging the period, which is in conflict with other researchers' reports that the low c/n ratio of chicken dung requires the addition of carbon to enhance the digestion process. This suggests that the commonly accepted optimal c/n ratio may not be appropriate in materials which have a high degree of easily biodegradeable chicken manure. A series of experiments on various dilutions of chicken manure is reported to be in progress. Preliminary results indicate that the period of low production is longer at high concentrations of slurry. Work by a previous researcher had suggested that the low production was due to the action of "Furazolidone", a protozoan antibiotic which is added to chicken feed. This hypothesis was discarded after tests on a set of slurry samples of equal dilutions - and therefore equal concentration of antibiotic - in which the variation of c/n ratio and pH greatly influenced the period of low gas production. It is suggested that this period is not due to the presence of "Furazolidone", but to the amount of organic acids released in the early stages of digestion. The pH rather than c/n is suggested to be the cause of the problem after studying the influence of changes in slurry dilution, which would not influence the c/n ratio but would affect the magnitude of pH change (the greater the dilution, the less a given amount of acid affects pH). An attempt to eliminate the period of low gas production was made by adding "Actizyme", an enzyme which is claimed to enhance biogas production. In practice the observed effect was to reduce the biogas production below that of the control experiment. It is postulated that either that the period of low pH changed the action of the enzyme, or that the addition of the enzyme altered the c/n ratio. It is concluded at the end of this series of experiments on chicken dung that : (i) a long retention time of 45 - 50 days may be necessary due to the period of low gas production; (ii) the daily feed input will have to be calculated with a view to maintaining the optimal pH; (iii) that the period of low gas production is influenced by pH, and therefore by dilution; (iv) that the methanogenic bacteria are resistant to the antibiotic "Furalzolidone".

Vegetation as a Feedstock - experiments are being conducted on elephant grass and sugar cane leaves. Samples of the leaves have been pretreated in various ways - cutting in strips, liquidising, and water soaking. Results were not yet complete when the report was presented.

Biogas production as a function of dilution ratio - experiments are under way on cow, pig and chicken manure at various dilutions. Results not yet complete.

Themophilic Biogas digestion - tests have been attempted on cow and chicken dung at 55°C but shortages of equipment and technical problems have so far prevented complete results being obtained. However, it is suggested that the high energy input needed to heat the slurry to 55°C would not be economic in a commercial system. Nevertheless it is intended to construct one pilot plant for data comparison.

Manufacture of New Pilot Plants - efforts are being made to develop cheap digesters using locally available materials. A design using 150 l tar drums was developed but had to be abandoned because of frequent leaks of gas from the drums. A design is now being developed using 207 l oil drums and plastic wine barrels.

200 l Indian Design Oil Drum digester - monitoring of gas production from this digester has indicated a lower gas production rate than expected. Several possible reasons are suggested: (i) Gas leakage from the gasholder, which is rather small, (ii) the slurry cannot be stirred, leading to settling of solids out of the solution, (iii) the gas meter reading was erratic when the gas pressure varied.

100 m^3 digester - a commercial farm, which was previously an experimental farm, has a 100 m^3 horizontal reinforced rubber 'sausage' type digester for a data collection exercise.

Slurry Examination - a standard soil test kit is being used to analyse digested and undigested slurries. Tests are continuing.

Gas Analysis - an Orsat gas analysis of the gas from the digestion of vegetable matter showed a low methane content, at 18-27%, and a high oxygen content, at 14 - 15%. It is concluded that these figures are erroneous due to airleaks during gas collection. Tests on the 200L Indian type digester show a methane content of 55%, Carbon dioxide 42%, and Oxygen 1%.

Promotion Activities - students from the National Youth Service have been involved in the project work. The research work has also been visited by individuals hoping to set up biogas systems.

Future Work Plan - includes monitoring the 100 m^3 biogas plant, storage and usage investigations for the gas, operation of a 9 m^3 KVIC plant, gas analysis, slurry analysis, constructing new pilot plants, investigating feedstocks such as fish waste and fruit and vegetable waste, and conducting further tests on thermophilic digestion.

The full text of the Seychelles country report is 75 pages long and may be obtained from the CSC or from the Research Division of the Ministry of Planning and External Relations, P O Box 656 Victoria, Seychelles.

3.2.4 TANZANIA

Mr S Mmakasa, Tanzania National Scientific Research Council

INTRODUCTION

The Tanzania national Scientific Research Council started research on renewable energy technologies in late 1979 when the Dodoma Rural Energy Project was launched.

Dodoma is a region in the central part of Tanzania. Dodoma region is semi-arid and forms an ideal site for testing renewable energy technologies, particularly biogas. In this region, the problem of rural energy supply is very acute and the threat of deforestation is considerable. At the same time however, there are high animal populations which provide abundant feedstock for biogas digesters.

The biogas technology project is one of the major activities of the Dodoma Rural Energy Project.

OBJECTIVES

The major objective of the Biogas Technology Project is to come up with solutions to the energy problems currently facing the rural communities in Tanzania by:-

- Adapting biogas technology as one alternative source of energy to supplement fuelwoood and charcoal, the use of which is causing serious deforestation.
- establishing standard conditions in biogas systems with respect to choice of plant design and operation for optimal economic use of the technology in Tanzania.
- assessing the impact of the technology on the rural communities in Dodoma.

RESEARCH METHODOLOGY

Biogas technology has already become well developed in other countries like China and India. However, direct transfer of this technology over the whole of Tanzania without finding out how it can best be adapted, could easily not be ideal for the recipients and thus alter the whole meaning of the technology transferred.

Thus the work which has already been conducted in a pilot project in Dodoma is not actually a repetition of what had been done in

RESOURCES

Project Staff

The project staff consists of give University graduates, two of whom are abroad pursuing further studies leading to Masters degrees. The project also has one technician, two data collectors, two biogas plant attendants, and a driver for the project vehicle.

Equipment and other facilities

The project is co-sponsored by the Commonwealth Science Council, the United Nations University and the Tanzanian National Scientific Research Council.

Equipment has been ordered to measure gas composition, pressure and flow, pH and temperature. Basic data will be collected, which will enable us to stop using the crude methods presently employed that could possibly give inaccurate data.

PROGRESS TO DATE

It should be pointed out from the outset that our activities on biogas have been conducted far from laboratories - in the villages, where it was not possible to subject our digesters to various variable conditions other than the natural ones within the project site. Thus in our experimental digesters, which are all of the Indian continuous type design, there has never been strict control over the temperature and PH of the slurry, though the latter had always been slightly alkaline (tested with litmus paper every week). The following were the experimental conditions that we were able to subject our digester to:

- The digester are stirred daily before feeding by simply rotating the gas holder.
- The substrate materials tested were a mixture of cowdung and goat droppings (about 1:1 mixture) and cowdung alone.

Summary of results

Within what we were able to do experimentally, the following is a brief summary of our results:

- There is an insignificant change in biogas production between the cool season (21°C) and the hot season (26°C) other countries, but an adaptation of biogas technology to the Tanzanian situation.

PROJECT PROGRAMME

The project programme consisted of three phases:

Phase one: 1979-80 to embark on surveying the energy consumption patterns and the estimation of biomass resources in the villages within the project area.

Phase two: 1981-82 testing the suitability of biogas technology in the villages which have acute energy problems but also high animal populations, and therefore abundant feedstocks for biogas digesters.

Essentially this phase also includes testing on the following:

- testing the various biogas plant designs and identifying which amongst them can best suit Tanzanian conditions
- Utilisation of biogas in cooking devices, gas lamps and internal combustion engines
- Suitability of the digester spent slurry outflow for the improvement of soil fertility.

Phase three: 1981-85: improvement and modification of the technology wherever necessary to suit the economic and social conditions of Tanzania.

Much of the work so far has been done on the Indian design plants. The Tanzanian way of keeping animals is such that the animals are left to graze in the bush and are brought to a fenced yard , normally uncemented, where they spend the night. The dung collected from such a yard is therefore full of high density materials such as sand. When mixed with water and put into the digester unchecked, these particles stratify slowly and block the inlet pipe in a period of less than five years. To overcome this a modification was made by raising the central inlet pipe of the mixing chamber by some 20 cm. Thus, when mixing the denser materials settle down while the lighter ones keep afloat. The latter is removed with a wire mesh while the former is hand removed when the digester is shut down for cleaning.

at Dodoma

- Not all animal wastes can be loaded directly into the biogas digesters. Goat droppings for example do not mix homogeneously with water. These bolus droppings keep afloat and after a day form a heavy scum on the slurry which blocks the release of biogas.

Interim Conclusions

Biogas technology is now gaining social acceptability in our villages and can be adapted without much deviation from the original Indian designs. Special treatment however needs to be given on certain feedstocks in order to avoid regular scum formation.

Outstanding technical problems

So far the project has encountered problems in making the fixed dome Chinese plant design gas tight despite the application of two layers of bituminous paint. Research into this design has been necessitated by the present high costs of constructing the floating metal gas holder for the Indian design.

Another problem is the lack of a workshop for fabricating burners and other biogas appliances.

OBJECTIVES AND PROGRAMME FOR REMAINDER OF PROJECT

Much of the remaining work is in the experimental determination of the best running conditions for the biogas digesters, and some aspects of the utilisation of biogas e.g. in running internal combustion engines. When the basic experimental apparatus has been acquired, the remaining part of the task will be conducted as follows:

Phase one: 1983-84

- Drawing up the relationship between gas production with pre-warmed dung/water mixture - thus determining the slurry temperature that leads to optimum production of biogas per kilogram of dung.
- Testing of a biogas powered water pump, including cost benefit analysis of this option compared to the conventional use of petrol or diesel powered pumps.

Phase two: 1984-85

1. Quality testing of the outflow slurry, including:

   (a) Laboratory test of existence of pathogen population at various retention times.

   (b) Soil fertility tests of the outflow slurry when wet and when dry, compared with:

      (i) raw manure

      (ii) artificial fertilizers

2. Testing the suitability of human excreta in biogas digesters as a measure to improve sanitation in rural communities. Emphasis to be put on 1(a) above. In view of problems foreseen with the high cost of gas holders - to strengthen activities in identifying simple methods of fabricating cheaper gas holders affordable by average peasants in rural areas.

Methodology

To involve Health personnel in a 1(a) and 2 above, and to involve agricultural extension personnel in 1(b).

Dissemination/Implementation Follow-Up at the End of the Project

Within the project area, dissemination is going on hand in hand with our research activities, i.e. researchers give technical advice to individuals who want to construct their own biogas plants. However after accomplishing all our objectives, a summary of our Project work and results will be circulated to the biogas extension service agencies in the country with advice on the prerequisites for efficient running of a biogas system. This will be followed by visits by our researchers (on request) to areas with serious problems in establishing biogas plant.

APPENDIX TO TANZANIA COUNTRY PAPER

HOMBOLO HEALTH CENTRE BIOGAS PLANT

Size of digestion tank:

- Internal diameter 2m
- Depth of the tank 2.4m
- Volume of the digestion tank .... $6.6m^3$
- Volume of gas holder .... $3.4m^3$
- Retention time .... 50 days

Materials used:

(1) Construction of the digestion tank: sand, cement and burnt bricks.

(2) Construction of the gas holder: galvanized steel plates gauge 18 (3mm thickness)

(3) Other fittings: Metal and plastic pipes of diameter 6mm and 19mm.

Other Information

- Ratio of dung to water 1:2
- p^H of water used 8.4
- Gas is used for cooking purposes in the hospital.

MSANGA VILLAGE BIOGAS PLANT

Size of digestion tank:

- Internal diameter 2.2m
- Depth of the tank 2.6m
- Volume of the digestion tank .... $9.72m^3$
- Volume of gas holder .... $5m^3$
- Retention time .... 60 days

MSANGA VILLAGE BIOGAS PLANT (contd.)

Size of digestion tank:

- Internal diameter 2.2m
- Depth of the tank 2.6m
- Volume of the digestion tank .... $9.72m^3$
- Volume of gas holder .... $5m^3$
- Retention time .... 60 days

Materials used:

(1) Construction of the digestion tank: sand, cement and burnt bricks.

(2) Construction of the gas holder: galvanized steel plates gauge 18 (3mm thickness)

(3) Other fittings:

- Metal and plastic pipes of diameter 12mm and 19mm.
- Reducers, unions, nipples, stop corks

Other Information

- Ratio of dung to water 1:2
- p^H of water used - undertermined
- Gas is used for cooking and lighting in a village restaurant.

3.2.5 UGANDA

Professor J O Ilukor, Department of Physics, Makerere University, Uganda

Objectives

(i) to develop and construct digesters best suited to Uganda considering the availability of raw materials, climatic conditions and cultural habits.

(ii) to develop efficient biogas appliances

(iii) to extend applications of biogas as a fuel to rural and urban areas bearing in mind the social and cultural life styles of various areas in the country, aiming to increase the fuels acceptability.

(iv) to develop testing and evaluation facilities which can be used for monitoring the performance of digesters which may be built in the country. The hazards and safety precautions necessary in utilising the gas are to be considered.

Methods and Programme

The methods used in the Biogas Project have involved construction and operation of small scale semi-batch and continuous culture units. The performance of each type under specific conditions of temperature, pH and pressure is monitored for at least six months. The gas produced has been analysed using Orsat gas analyzers and combusted in a variety of burners. the effluent has been used to fertilise maize tomatoes, and cabbages on a comparative basis.

Summary of Timing of Programme

- 1981	1981 - 82	1982 -83	1983 - 84
1. "Test Tube" type of experiments	1. Construction of digesters	1. Construction of digesters	1. Construction & evaluation of digesters
2. Small scale experiments	2. Workshop on Alternative Sources of	2. Construction of appliances	2. Testing & evaluation of appliances
3. Construction of different designs	3. Government attention and involvement	3. Gas Analysis	
		4. Popularisation	3. Evaluation of Fertiliser
4. Conductivity studies of Gas mixtures of	4. Construction of Appliances		4. Internal combustion Engine
CH_4, O_2; N_2; CO_2,	5. Fertiliser Trials		5. Extension

3. **Resources**

Institutions: The main efforts in R & D in Biogas are taking place in the Department of Physics.

(a) Students have taken up short period projects in addition to their regular laboratory experiments in order to enable them understand:

(i) Methods of biogas production

(ii) Calorific value of different gases contained in biogas.

(b) Small workshops in and around the city have been involved in constructing various parts of the Biogas systems. Similar support is received from the Department of Agricultural Engineering, Makerere University.

(c) Technical staff have been involved in minor construction, testing and record keeping of digester gas production, pH and temperature measurements, and fertiliser usage in the garden.

(d) The Department of Chemistry and Faculty of Technology at the University have been helpful in offering advice and loaning measuring and construction equipment.

(e) The Ministries of Power and Planning and Economic Development have been involved in communicating the concepts of Alternative sources of Energy to the Government, in order to incorporate them into the overall National Energy Plan.

Progress to date

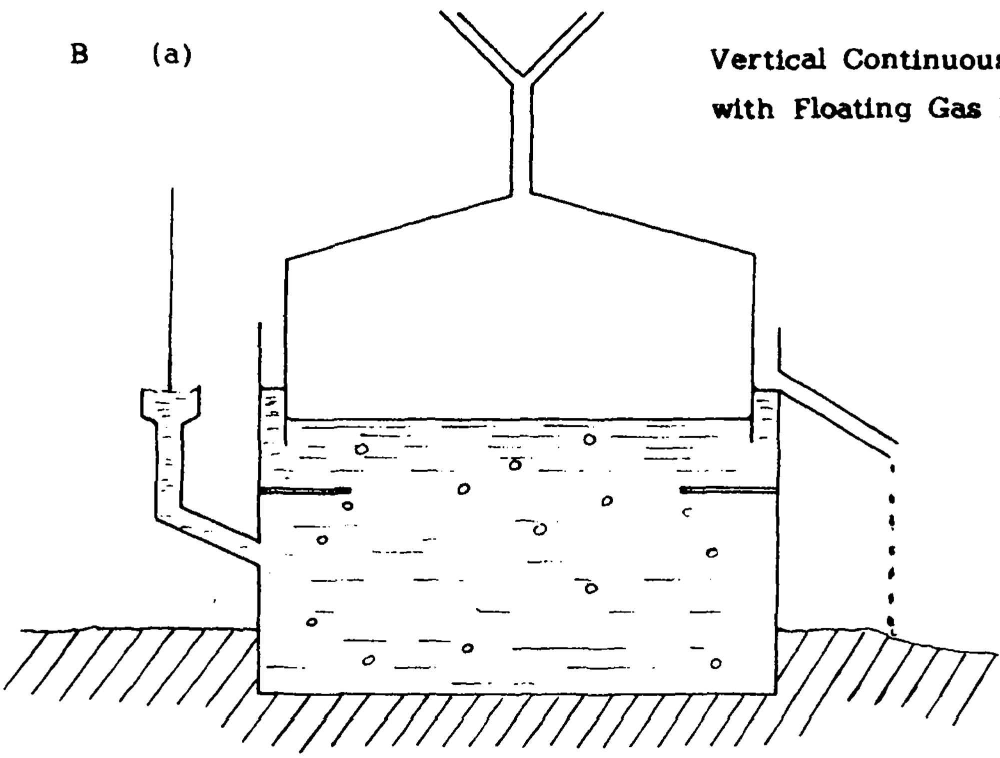
(i) **Experimental**

Experiments have been conducted on Biogas digesters ranging from the size of a Winchester Bottle (2½ litres), up to 650 Litres. The latest constructions, which are not yet in operation, are 1 m^3 and 5 m^3 vertical digesters with floating gas holders, and are made out of mild steel.

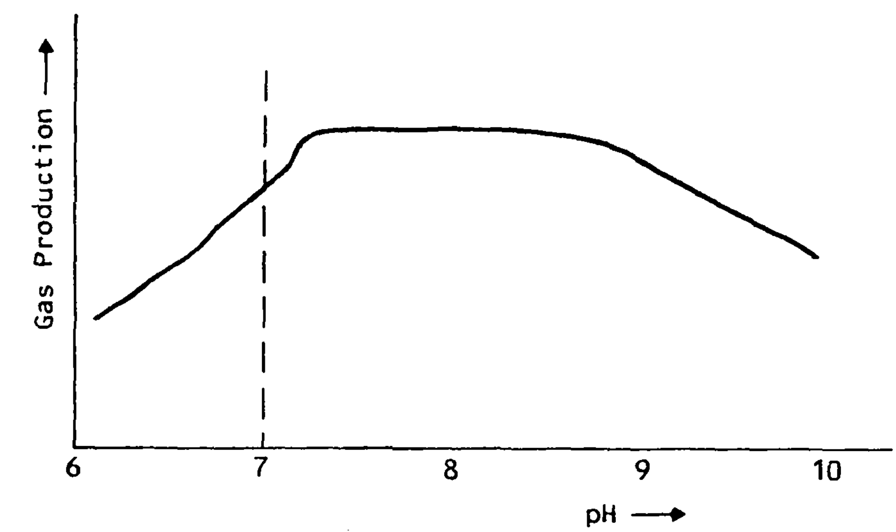
A mixture of cowdung and water, in a ratio of 1:1 put in a Winchester bottle and digestion is allowed to take place at a temperature of 22-30°C in each case. The volume of gas collected in each case is measured and particular attention paid when methane production is maximum.

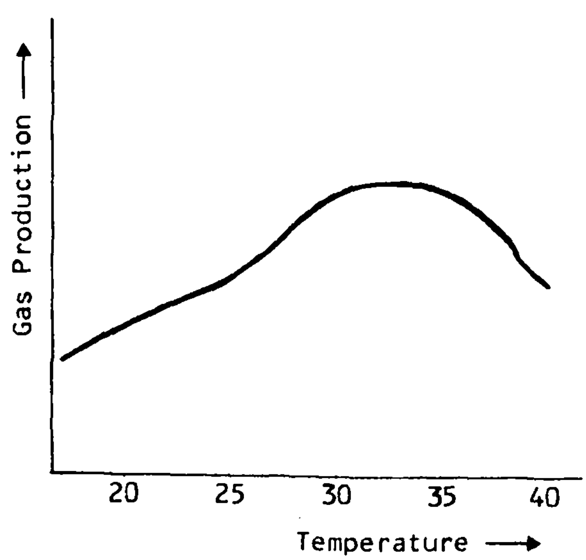
For maximum gas production, the ratio 1:1 should be varied slightly with increase of temperature to accommodate more water and to allow for evaporation.

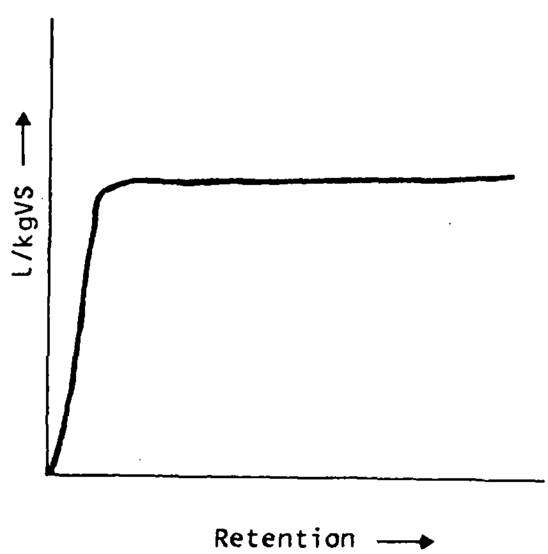
B (a) **Vertical Continuous digester with Floating Gas Holder**



Several Vertical digesters with floating gas holders as shown in the sketch have been constructed out of mild steel oil drums. Some have been insulated with a layer of clay and canvas or straw and grass. All the gas holders have a floating dome. The slurry is stirred at least once a day through the vertical inlet column. The main raw material has been cowdung. The temperatures in all except one digester have been controlled at room temperatures 22-30^{o}C within a variation of one or two degrees. To obtain temperatures in the range 30-35^{o}C experiments were done in the open during the hot season (Nov-Feb). The pH for each digester is monitored daily and the experiments were done for a range of pH up to 9.5. The gas production is virtually constant for a pH of 7.2-8.5, and declines outside this range, especially below 6.5







(b) **Horizonal Digester (semi-continuous)**

Three mild steel oil drums are welded together to give a total volume of 650 litres. This lies North-South but inclined at angle of 15^{o} to the north where the fresh cowdung inlet is. The effluent comes out from an opening at the southern end. The operation is semi-continuous in the sense that when gas production is low or the gas pressure is low, batch conditions prevail.

The digester pressure is monitored with a water manometer and the gas is collected over water in a separate gas holder.

All the measurements carried out for the Vertical Digester are carried out in this case also.

One distant study in this experiment that of estimating gas production as a function of pressure, other parameters being nearly constant.

The nights may get as cold as $16^{o}C$, a drop of $7^{o}C$ from the daily mean, in one season. In this case the gas production reduces to 30% of the daily average.

(ii) **Summary of results**

1. The results have shown the effect of temperature, concentration of substrate, pH and frequency of loading on overall gas production per kg VS.

2. Operating of optimal conditions as indicated by 1 above, the quality of composition of biogas is good in the sense that it has been possible to suppress the production of H_2S and to substantially reduce CO_2 while sustaining a percentage of Oxygen desirable for combustion:

CO_2	2%
CO	3%
O_2	13%
CH_4	80%
N_2 & H_2O	2%

3. **Appliances:**

Several burners above have been constructed and tested. A commercial kerosine pressure lamp and propane gas cooker have been modified to burn biogas. What is left is to make quantitative measurements of efficiencies of these devices.

(iii) **Interim conclusions**

The results of the project are positive and are encouraging for construction and extension to much larger plants.

(iv) **Outstanding technical problems**

Construction materials and tools have only presented temporary problems as they are now getting more readily available in Uganda.

5. **Objectives and Programme for Remainder of Project**

The generation of gas from various substrate materials and compositions must continue while the gas produced is used for the development of efficient stoves, lamps and other appliances. The effluent materials must also be analysed quantitatively and the best methods of storage be investigated. The timing therefore indicates areas of concentration of efforts rather than being the only focus.

September 1983 - March 1984

Digesters : (i) Complete the $1m^3$ and $5\ m^3$ plants and operate. Improve on the horizontal digester and design a second model.

(ii) Extension to various Research Stations in the country where there are adequate resources for installation and proper maintenance.

Appliances

(i) Evaluation of stoves, lamps, etc.

(ii) Construction of other appliances e.g. heaters

(iii) Internal combustion Engine application

Gas Analysis

(i) Analyse the gases at different times of production for different plants.

(ii) Relate the gas composition to the appropriate appliance.

(iii) Investigate best storage system for various appliances.

Fertiliser

(i) Quantitative analysis of the effluent materials at different stages of gas production.

(ii) Continuation of field trials

Further work after March 1984 will very much depend on which areas above need to be rounded up or extended.

Dissemination/implementation of the end of phase

It is proposed to initiate a project which in principle is a study of the interaction between designer, researcher, and end-user all living in the same community.

3.2.6 ZAMBIA

Mr G V Chimwala, National Council for Scientific Research, Zambia.

I. INTRODUCTION

The main objectives of the Biogas project for Zambia are to develop and promote biogas technologies for use in the rural and peri-urban areas of Zambia, through investigations into user needs, feedstock for biogas digesters, cost-effectiveness of the system, and utilisation of the biogas and slurry from the digesters.

Although biogas generation is already a well known technology in some countries such as India and China, the first phase of the Zambian project was to design biogas digesters and monitor their performance in order to gain the practical techniques associated with the construction and management of biogas technology under the local conditions. Once these techniques have been gained it was envisaged that the second phase of the project would be to promote the construction and popularisation of biogas digesters in the appropriate areas of Zambia which have the necessary animal manure or agricultural wastes.

Several benefits could be gained from the adaptation of biogas technology in Zambia, besides the obvious direct application of the biogas as a source of energy and manure from the digester effluent. One important indirect benefit that will be gained is the reduction in the use of fuelwood and charcoal as major sources for domestic energy requirements. Both charcoal and fuelwood are obtained by cutting large tracts of forest areas, so partial substitution of these two energy resources by biogas energy will go a long way to prevent our land, much needed for agriculture, from turning into a desert.

II. WORK PROGRAMME

The project was started by the National Council for Scientific Research (NCSR) of Zambia in 1980. It was planned in two phases. The first one was a "study period" while during the second phase the technology would be introduced and popularised in selected areas where feed materials are available.

First Phase

(a) **Objectives**

The main objective of the first phase activities was to gain practical skills and knowledge on the design, construction and management of biogas systems under local conditions. The plans included construction of two biogas digesters, one based on cowdung and the other on pig manure. These two digester feed materials were selected not only because of their availability in rural areas but because of their social acceptability for handling by human labour. The digester based on cowdung was constructed in 1981 at the NCSR Chalimbana Farm. The construction of the second digester based on pig manure has recently been completed at the Rural Development Corporation's Nkumba Farm.

(b) **Resources and Progress**

The progress of the project has so far been rather too slow, for a number of reasons, the most prominent being frequent changes of technical personnel in charge of the project. These changes are made either because the staff directly involved in the project go for further studies, or leave to go and work for other organisations. The supervision of the project has so far changed hands about three times.

The project has however, received favourable financial and material assistance from the British Overseas Development Administration through the Commonwealth Science Council, enabling the NCSR to design and construct the two digesters and to acquire equipment for monitoring the performance and efficiency of the two biogas digesters already constructed. Equipment acquired so far includes an Orsat Gas Analyser capable of determining composition of hydrogen (H_2) and carbon-dioxide

(i) **Chalimbana Biogas Plant:**

The Chalimbana Farm plant is of the KVIC design. The pit was constructed using concrete hollow blocks. The digester is one metre underground and one metre above ground, i.e. 2m deep, and its diameter is 2.1m. A mild steel tank of 2m diameter and 2m height serves as the gas holder. The biogas plant supplies gas to three farm labourers' houses where it is used for cooking and lighting purposes. The plant is fed a mixture of cowdung and water in a 1:1 ratio on a batch fill and draw basis. The retention period of the feed has ranged from fourteen to thirty days. An optimum retention period has yet to be determined.

Initially, a plastic hose served as the gas line from the plant to one user who employed a simple stove with a bamboo gas inlet and mixing chamber. A perforated coffee tin was connected to this bamboo tube to serve as a burner. This stove served for a short period until the bamboo got burnt away. Better and more durable stoves have now been designed and fabricated. Later the hose pipe which served as the gas line developed leaks and it was decided to replace the entire gas-transmission system with more reliable and durable, although rather expensive materials. Galvanised iron pipes were installed as gas lines to three farm workers' houses.

The digester contents are unmixed and external heating is not employed. Because the effluent slurry from the biogas plant could not be immediately used on a crop field or otherwise disposed of, a way of drying it was devised by constructing three drying troughs on the effluent outlet side of the biogas plant.

The Chalimbana biogas plant has two main technical problems. The gas holder has no system to enable it maintain a balanced position when it is filled with gas, which results in the gas holder getting easily tilted from side to side. In tilting the gas holder can lose some gas. The second technical problem is caused by the digester inlet being one metre above ground level, creating the extra manual labour of having to lift feed loads from the ground into the inlet chamber.

Because the Chalimbana farm biogas plant is not close to the water and cowdung supplies it is difficult to continuously feed the plant. A comprehensive and close monitoring of the performance of the digester and the quality of the gas from it has yet to be carried out. This work will be initiated soon now that equipment is available.

(ii) **Nkumba Piggery Biogas Plant**

The Nkumba Piggery biogas plant is also of Gobar design but uses pig manure as feed. Unlike the Chalimbana Plant the digester was constructed with burnt bricks and a steel central guide was installed prevent the gas holder tilting. The outlet level of the plant is such that digester slurry will flow out freely as the new feed is introduced in the digester. The gas holder is of $6m^3$ capacity and made of steel but of a slightly different design from that installed at Chalimbana. It is designed to be fed on a continuously. The gas holder has scum breakers and a central guide. The Nkumba plant will supply gas for cooking and lighting to three farm workers' houses. Galvanised ½ inch mild steel pipes have been installed as the gas transmission lines. The construction was recently completed but at the time of reporting the plant had not been commissioned.

(iii) **Interim Conclusions:**

Although no evaluation has been conducted on the performance and efficiency of the two pilot digesters, the Chalimbana Farm digester is satisfactorily producing gas. However, it is recognised that quantitative and qualitative evaluation of the digester plants will make it possible to operate them at the optimum conditions, so more detailed monitoring work will have to be started. The project has demonstrated that biogas plants in the Zambian climate can produce gas throughout the year without any external heating of the digester. It has also been demonstrated that biogas can easily be utilised for cooking and lighting purposes with stoves and lamps that are fairly cheap.

(iv) **Objectives and Programme for the Second Phase**

It has already been pointed out the NCSR project on Biogas has proceeded at rather a slow pace. Monitoring of the performance and efficiency of the biogas plants has not yet been accomplished. When the monitoring component of the project is completed, the NCSR intends to disseminate information on the construction and management of the biogas plants in the appropriate areas. Information dissemination will inevitably involve various Government and Quasi-Governmental organisations with extension services such as the Department of Agriculture, the Village Industry Service, the Co-operative Department and the Zambia Council for Social Development. The monitoring work is most likely to be completed by the end of 1984. However, the popularisation programme of biogas technologies in Zambia will run concurrently with the monitoring work and it is planned to initiate the second phase towards the end of this year. If this will not be possible then the original aim to complete the project in three years, 1981-1984, as manifested by the period of financial support by the ODA, will not be achieved. For this reason Zambia would favour an extension of the period in which to execute the project to end of 1985 at the earliest.

The popularisation of biogas technologies will involve the following:

(a) Conducting surveys in peri-urban and rural areas of Zambia to locate suitable villages/communities in which biogas plants could be constructed. The most important factor determining the suitability of any locality will be the availability of animal manure or agricultural wastes that could be used as feed for the plants.

(b) To identify cheaper materials for constructing biogas plants, gas transmission lines, gas burners and lamps.

(c) In some cases family size biogas plants will be easier to manage compared to the medium sized ones the national Council for Scientific Research has constructed at Chalimbana and Nkumba Farms. For this reason the NCSR will also embark on a programme to design and construct individual family size biogas plants since the Department of Agriculture has plans to concentrate on popularising small family size plants.

3.2.7 ZIMBABWE

Mr G Marawanyika, Department of Energy, Ministry of Industry and Energy Development, Zimbabwe.

1. **Objectives**

The main objective is to embark on a programme of promoting the development and use of biogas technology in Zimbabwe. 80% of Zimbabwe's population live in rural areas and depend almost exclusively on fuelwood as their primary source of energy. The use of biogas for cooking and lighting will form part of a fuelwood conservation programme and will also provide a viable alternative to fuelwood which is already in short supply in most districts of Zimbabwe.

2. **Methods and Programme**

(a) We propose to build at least two biogas plants in each of the 55 districts for demonstration purposes. The plants would be of the fixed and floating dome (i.e. Chinese and Indian) continuous types. Batch types will be used only as trials for individuals using used oil drums as digesters and inner tubes as gasholders.

(b) The work programme would be divided into the following sections, with the time schedule for building each digester illustrated on the bar chart:

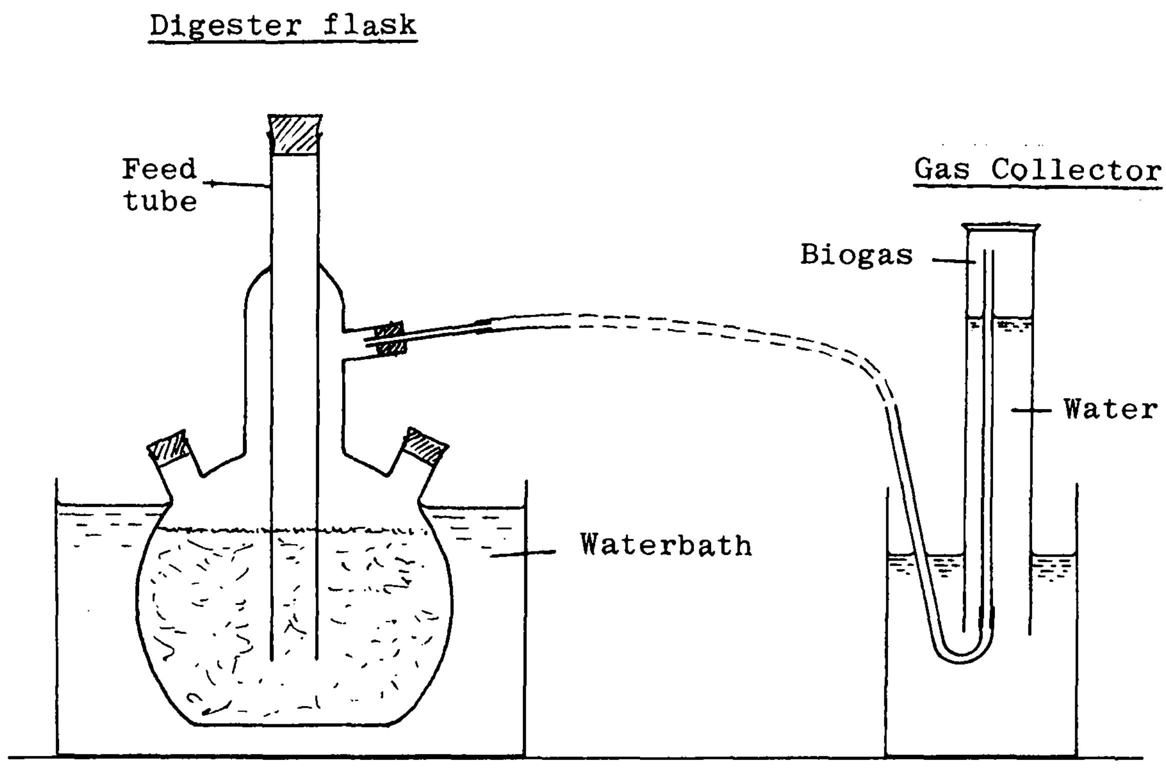
	WORK	TIME IN MONTHS
		0 1 2 3 4 5 6
(i)	Site location and Pit Digging	
(ii)	Building Digester	
(iii)	Plumbing and Start-Up	
(iv)	Development of Appliances	

With more experienced builders we could reduce the period of building each plant to about 2 months. Three plants are usually built at the same time so this would take about 2 years to complete the whole project.

3. **Resources**

Most of the work will be carried out by members of the Department of Energy Development. They will be assisted by the Appropriate Technology Group of Silveira House. Local companies would be asked from time to time to help when these two groups feel they need some help from them. The University of Zimbabwe has made available the use of one of its laboratories for biogas experiments.

4. **Progress to date**



- Apparatus was set up as in the above diagram. The vessels were specifically made to our specification. The aim was to test gas yield rates from various wastes available in the country.
- The digesters were fed daily with the feed rates gradually increased.
- Stirring was achieved by swirling the vessels a few times a day by hand.

- Temperature maintained at 37°C + 0,1°C in a thermostatic water bath

- pH was measured by indicator strips. No automatic control and at some instance the ph had to be controlled (see results)

- The substrates tried so far are; coffee waste (industrial); Pigeon droppings; chicken droppings; "Masese" (beer dregs) from brewing of opaque beer.

Substrates planned for future tests are : pig waster; cow dung; dairy waste and other agricultural wastes.

- Retention period was between 200 - 400 day when the digester was started. Feeding rate was 5 - 10g into 2l per day. Retention period then dropped to 67 days as the daily feed was increased to 30g. Minimum retention period for coffee waste was 25 days.

The measurements carried out were as out were as follows:-

- Gas volume - every day on graduated cylinder,
- Total Solids (TS) Monday, Wednesday and Friday
- pH Monday, Wednesday and Friday.
- Volatile Solids (V.S) Monday, Wednesday and Friday
- Fixed Solids (F.S) Monday, Wednesday and Friday

No equipment is available to measure the volatile Fatty Acids and the gas composition.

(ii) **Summary of Results**

The results obtained in the laboratory experiments are given in the table below.

Comparison of Gas Yield for Feed Rates of about 10g V.S. per day

Substrate	**Gas Yield Rate (M^3/Kg VS/day)**
Coffee waste	0,10
Pigeon waste	0,30
Chicken waste	0,35
Coffee waste + 20% chicken waste	0,62

The results obtained from unheated digesters in the country have not yet been tabulated.

(iii) **Interim Conclusion**

The most important conclusion we made was that the gas yield increased when we mixed coffee waste and chicken waste. A lot of people in Zimbabwe keep chickens and cultivate small gardens.

Thus by mixing chicken manure and rotting vegetable matter they would boost the production of gas from their plants. So far 14 digesters have been built in 9 districts. The use of these digesters is helping to promote the development of biogas technology in Zimbabwe which is our main objective.

(iv) **Technical Problems**

The most outstanding technical problem is the lack of measuring equipments and gas lamps. We have approached several firms asking them to fabricate the lamps but up to now not one has done it. The other major problem is lack of transport to go to rural areas.

5. **Objectives and programme for Remainder of Project**

The main objective remain the same. The timing might be a bit longer due to lack of transport but we hope to stick to it by training many more builders.

After building the demonstration plants we shall take groups of people to show how the biogas plant works. We hope to start with districts which have an acute shortage of fuelwood. This programme would run in conjunction with the afforestation programme.

We also hope to encourage people to use the biogas plants for sanitation purposes by encouraging them to connect their pit latrines to the plant. In this way we hope to spread the use of biogas technology to the rural people.

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TECHNICAL APPENDIX

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Anaerobic Digester Designs in the Third World

(From: Proceedings of 1st International Symposium on Anaerobic Digestion, Cardiff, Britain)

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INTRODUCTION

It is a daunting prospect to even attempt to review the state of the art of digester design in the Third World: the literature is so voluminous, and the conditions so different, that any generalisation is likely to be hopelessly inadequate or over-simplified. On the other hand, to focus on one location or one application would itself lead to distortion. In this paper, then, I shall first attempt to summarise the principal strands of current practice and current objectives and then I shall discuss a few particular problems and some of the possibilities facing biogas.

Up to the present time the main interest in the Third World in biogas has come from the countries of Asia and the Pacific region. Interest in Africa and Latin America has made little real impact, although experience goes back some decades (in East Africa, for example, work on biogas has proceeded since the 1950s (Mann,[33] Boshoff[7]). Despite the interest shown in various quarters, however, a realistic appraisal (see, for example, the excellent review of Asian practice by Subramanian,[59] FAO Soils Bulletins 36[16] and 41[17] and ESCAP[14,15]) must conclude that only in two or three countries has biogas made any impact, and that nowhere, with the possible exception of parts of China, does biogas make a significant contribution to either energy production or the recycling of organic matter.

SOME EXPERIENCES WITH BIOGAS IN THE THIRD WORLD

As noted earlier, Subramanian[59] gives an excellent and comprehensive review of developments in Asia. For that continent, I can only paraphrase

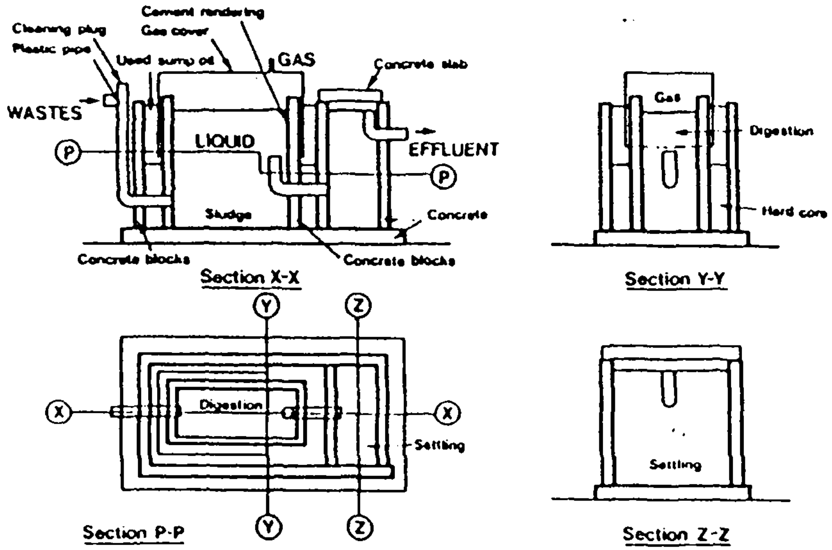


FIG. 1. Farm-type digester. Chan design.

some of his conclusions and add to them evidence from the recent ESCAP meeting and more recent publications on biogas in China (FAO,[17] Van Buren[8]). For convenience the summaries are made on a country-by-country basis.

Bangladesh

Until recently there has been little or no activity with biogas. Islam[26] reports that there are eight plants operating (seven Indian designs and one Chinese) but that neither the Indian nor the Chinese design is sufficiently cheap to make much impact at a family level; some research and development work into Chinese plants is proceeding (Islam[27]).

Fiji

There are about a dozen digesters reported to be operating, mainly on pig wastes. The majority are square 'plug flow' designs (Chan,[9] Richard[52]) (Fig. 1), with a retention time of around 4 days. This is so low that if the plants do function (i.e. without complete wash-out) there must be significant dead regions in the digesters and their technical and socio-economic functioning cannot be accounted a success (Solly and Yarrow[56]).

India

Most of the publicity for biogas has arisen because of the programme in

India. Detailed accounts of Indian practice can be found in Subramanian,[59] ESCAP,[15] FAO,[16] Sathainathan[53] and the seminal paper by Prasad *et al.*[46] The majority of India's biogas or gobar (cow dung) plants are built on the well-tried KVIC design (Fig. 2(a) and (b)); plants from 2 to 140 m^3 are available; the smaller domestic units are unheated and unstirred and operate with retention times around 55 days. Despite the long history of work on biogas in India there is little information on the efficiency of these units, but it is clear that under typical conditions the plants produce around 0·25 vol gas/vol digester (excluding the gas holder) per day. Srinavasan[58] gives some details of an alternative horizontal design (Fig. 2(c)) but again with few operating details. The programme to install some 500 000 plants (with a 20% grant for the capital cost) has met with variable success. The following reasons have been reported (Yadava,[61] Subramanian,[59] Reddy[50]):

(1) Organisational and management problems—for example, inadequate technical help and follow up, lack of co-ordination between bodies involved, problems in running community-scale plants.

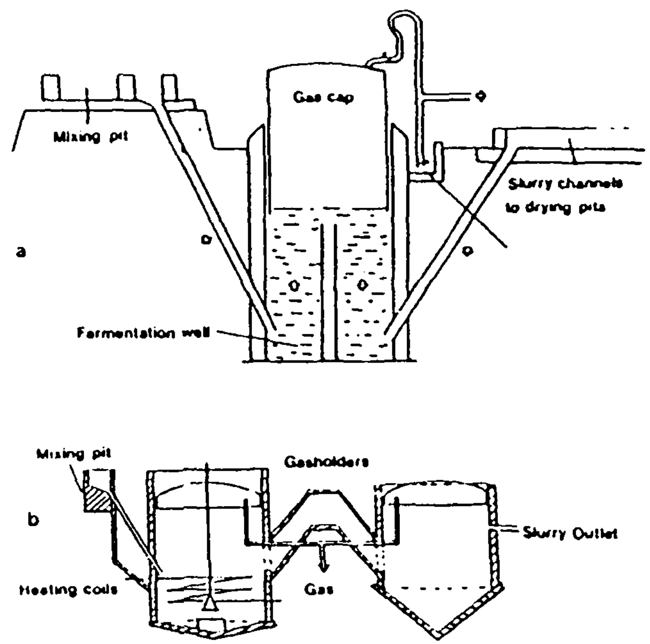


FIG. 2. Indian designs (schematic), (a) 4 m^3 biogas plant, (b) two-stage digester.

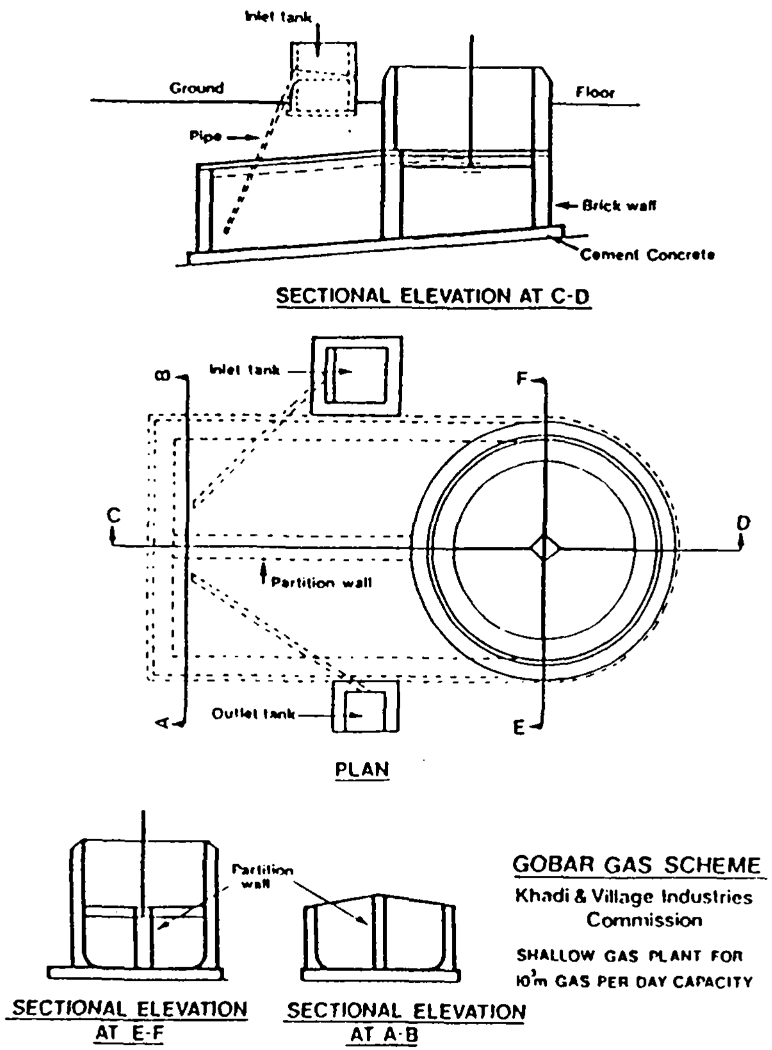


FIG. 2c. Horizontal design (India).

(2) Technical problems—for example, operational problems from pipe blockage to 'stuck' digesters, problems in slurry handling, corrosion of metal gas-holders, etc.
(3) Economic problems—for example, use in non-productive situations, dubious financial viability, demonstrated non-viability for the poorest sections of the community, etc.

It is certain that, in India, as in other countries, biogas has been 'oversold' in terms of its productive capacity, its simplicity, its economic benefits and its pollution control benefits (Ratasuk,[48] Taiganides[60]).

It is also significant that very few plants working on inputs other than cow dung have been reported (one exception being a sugar-waste plant at Kampur). There are few integrated waste systems despite the overwhelming

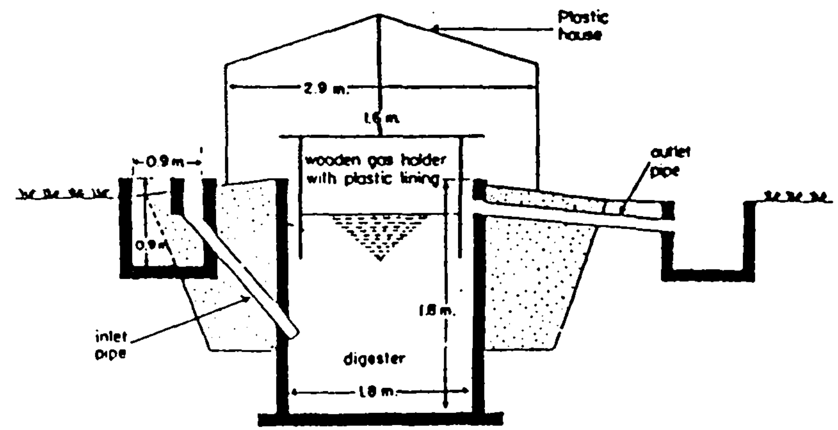


FIG. 3. Digester (Korea).

evidence that small (i.e. $<10\,m^3$) plants are too expensive and inappropriate.

The experience with community-scale plants—except in one or two highly organised or authoritarian communities—has been disappointing. However, it is reported that more community plants are planned under the sixth five year plan (Agarwal[1]).

There is also a lack of variety of designs available, in contrast with China (Van Buren[8]). Subramanian[59] notes that early attempts at cost reduction have been unsuccessful, although it has been long recognised that a major element in the capital costs is the metal gas-holder. Vidyarthy and Misra's figures[62] show that the gas-holder represents about 27% of the cost of a $3\,m^3$ plant and some 44% of the cost of a $140\,m^3$ plant.

Korea (Fig. 3)

It is reported that about 29 000 small plants have been installed in Korea (Yoshida[64]). However, because of the low winter temperature, the plants were effective only for six to seven months of the year and the attempt at a mass programme must be recognised to have been a failure.

Nevertheless, trials and development are continuing and it appears that biogas technology may still have a future.

Nepal

Since about 1975 some 200–300 plants have been constructed. Finlay[19] and Pang[41] have reported on the Nepali programme and point to the (by now familiar) problems that the plants (mainly based on the KVIC design) are too expensive, that their financial viability is at best marginal and that there are enormous managerial problems involved in mounting a major programme in a poor country.

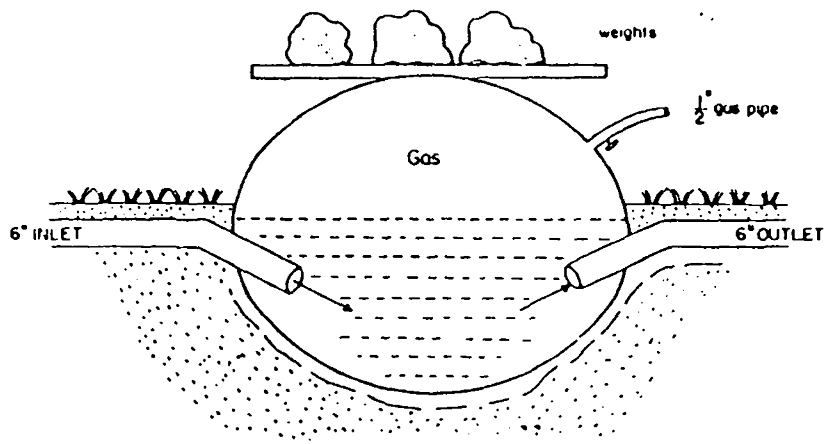


FIG. 4. Bag digester.

Taiwan

Two features of Taiwanese practice are of some interest: first, the introduction of a neoprene 'bag' digester (Fig. 4) which may have some relevance to other countries (Chung *et al.*[10]), secondly, the use of integral systems with the slurry used for *Chlorella* and fish cultivation.

Philippines

In the Philippines the use of agricultural residues has been identified as of special significance and there is considerable emphasis on integrated recycling systems (PCARR[43]).

One installation of special interest is the Maya farm plant (Subramanian,[39] Obias[39]) which is the largest biogas unit established in Asia, handling the effluent from 7500 pigs. Gas is used for cooking and powering engines; the slurry is settled, the liquor is used as fertiliser and

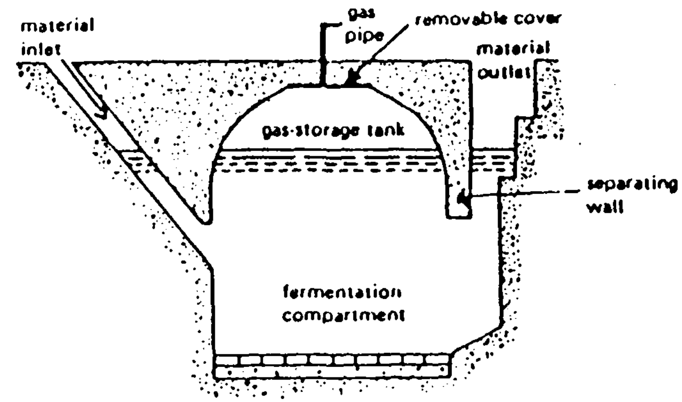


Diagram of a circular biogas pit.

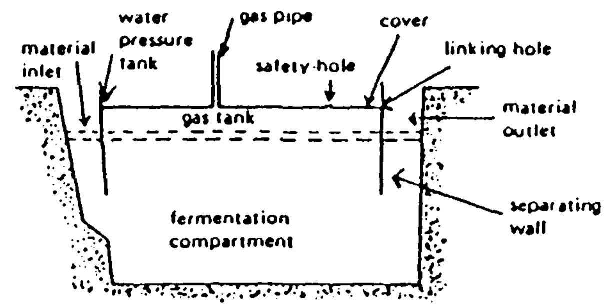
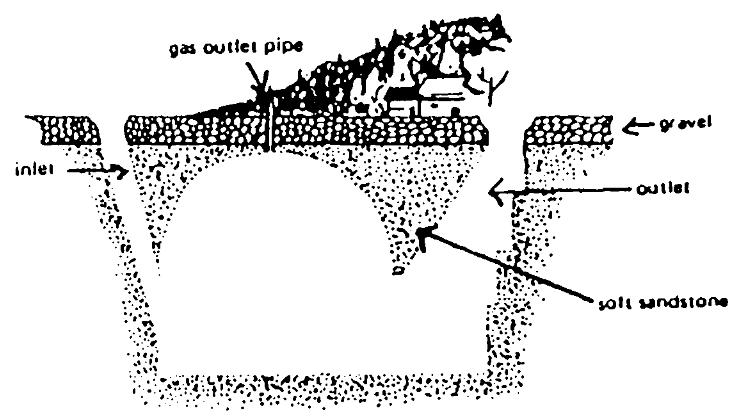
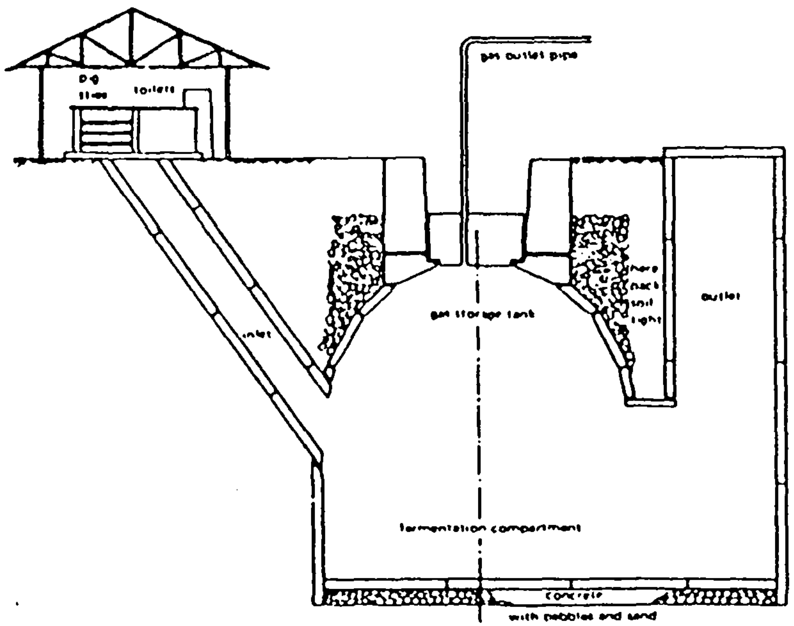


Diagram of a rectangular biogas pit.



Biogas pit carved out of soft sandstone.

FIG. 5. Chinese designs (1) [Van Buren,[8]]



Design of a circular pit made from stone slabs.

FIG. 5.—*contd.*

algal feed; the solids are used as a soil conditioner. Technically, the plant is interesting in that it consists of 48 × 3 m^3 *batch* digesters—as opposed to most developing country experience where the continuous digester holds sway. Interestingly, there is little evidence to suggest that the volumetric efficiency of batch and continuous plants, as currently operated in the LDCs, is different.

Thailand

The same pattern repeats itself: Ratasuk[48] notes that the investment for a typical biogas plant is so high as to put it out of the reach of all but the well-to-do farmers and this has been confirmed by a recent survey.[49] The importance of cultural beliefs and traditions comes out here as in India, as there can be strong inhibitions against using human excreta to produce gas.

China (Figs 5–7)

One of the most stimulating features of biogas development has been the gradual dissemination of information on developments in China (McGarry

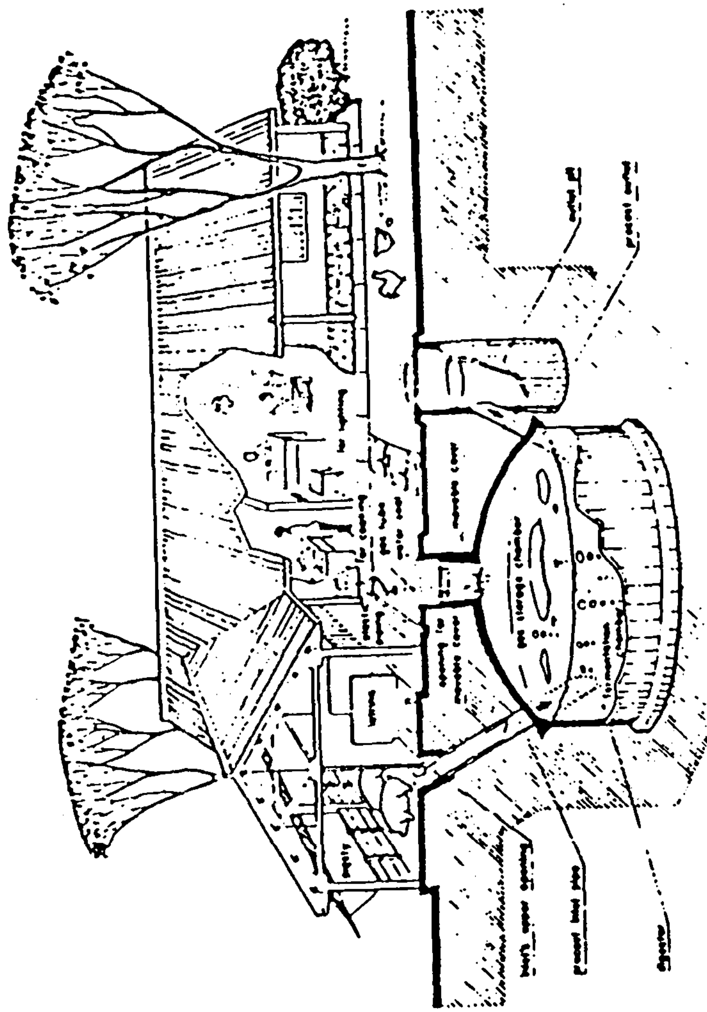


FIG. 6. Chinese designs (2) (a) The placement of a typical three-in-one biogas unit in a Chinese household.

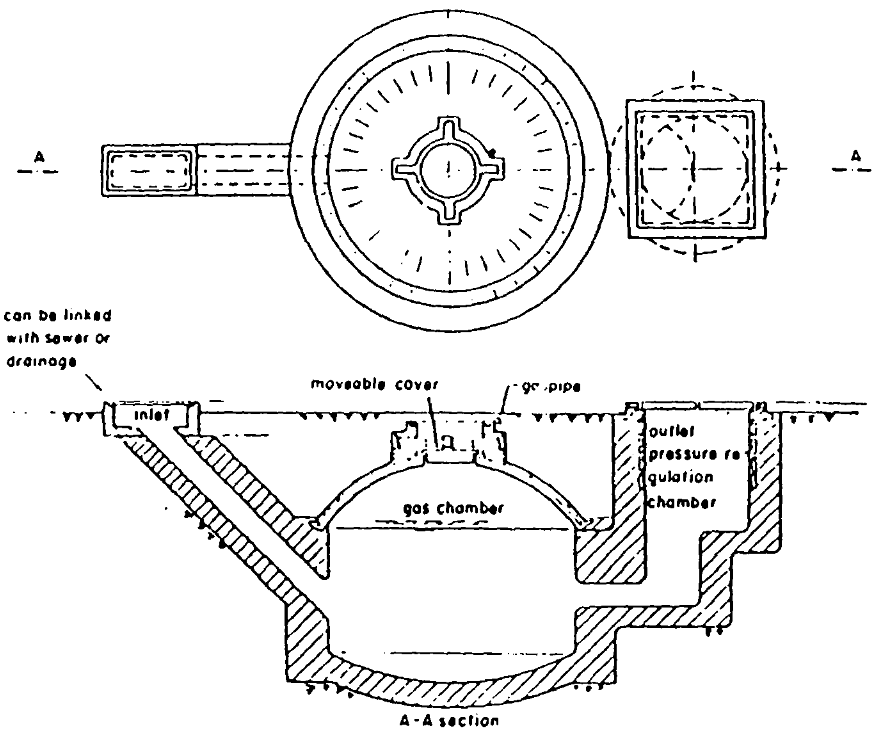
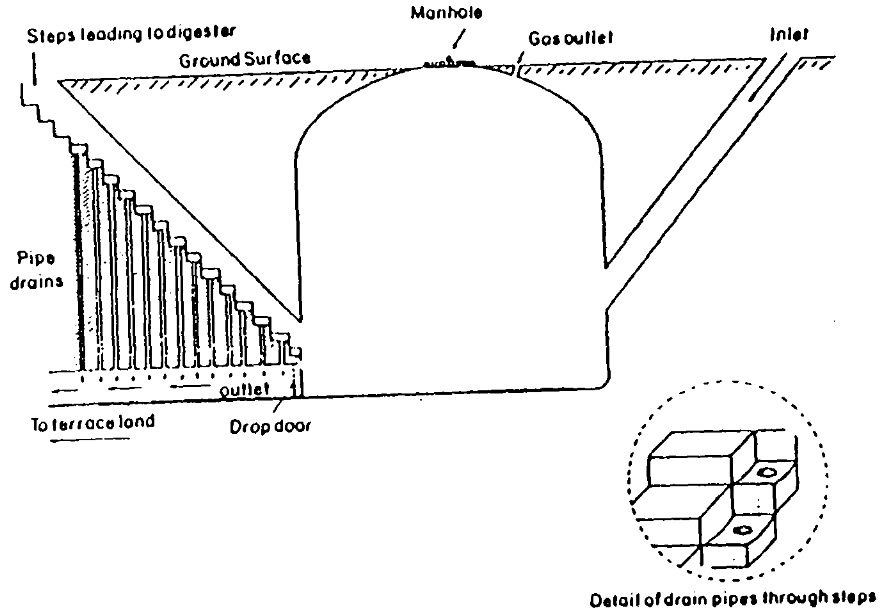


FIG. 6—*contd.* (b) Design for an excavated biogas unit with a masonry built tank (Sichuan).[17]

and Stainforth,[35] FAO,[17] Van Buren[8]). Three aspects are particularly significant.

First, the Chinese designs have eliminated the use of a floating metal gas-holder and incorporated local materials (sand, bricks, cements). The reductions in capital cost are significant and workers in a number of countries are developing or testing similar designs.

Secondly, the design manual edited by Van Buren[8] illustrates the wide range of designs possible, and the book is a fascinating example of the creative possibilities of committed but poor people. The third aspect relates to the objectives of the process: examination of the economics of biogas production shows that it is necessary in some way to allow for the recycling or conservative nature of the technology. Small plants are rarely, if ever, viable in terms of their gas production alone. On the other hand, accounting for the fertiliser and nutrient value of the slurry is no simple task



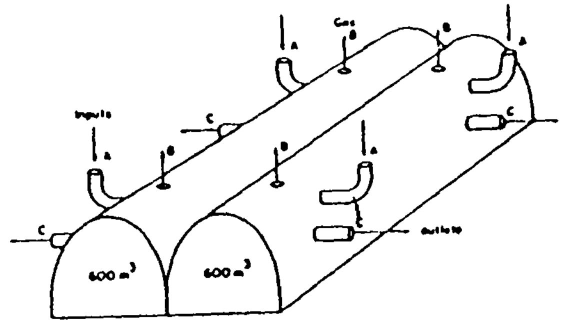


FIG. 7. Chinese designs (3) Above: A 268 m³ biogas plant under construction at the Weicheng People's Commune, Sichuan Province. Below: Design of inter-connected large-scale biogas digesters of 600 m³ each at Pin Niu People's Commune, Jiangsu Province.

(Barnett,[5] Disney,[12] Taiganides[60]). It may be that the long tradition of recycling organic matter is a key element in the Chinese success. It is very difficult to translate the economics of biogas in China into more familiar terms for example, there is a lack of concern about continuous gas production throughout the year. (It is necessary to shut down these plants at approximately 9–12 month intervals).

55

Other Countries

As noted earlier, despite some pioneering work in East Africa, biogas technology cannot be said to have taken a foothold there. In Kenya, for example, despite the commercial activities of the Tunnel Co. and although there are around 50 plants, only a handful are operating (King[30]). The majority are in disuse because of the lack of technical back up for economic reasons. (Although Hutchinson claims that the technology is economically viable.[25])

Cultural and sociological, as well as economic, reasons are undoubtedly important in this situation, since a good proportion of the rural population lives in scattered hamlets.

Hanlon[24] reports a simple and effective cost-reduction design in Tanzania: the sheet metal gas-holder is replaced by a 'cluster' of oil drums. The cost reduction achieved is of a comparable order to that involved in the Chinese design.

Another innovation from Botswana (Anon[2]) is the 'micro' design using an oil drum as the digester itself. Here at least is a digester which can approach zero cost but, given the problems of scale, its contribution will always be marginal.

DISCUSSION

It may appear that the account above is too negative. Nonetheless, there seems little reason to be over optimistic, still less to fall into the trap of encouraging the myth that biogas is *the* solution to the energy problems of the Third World. That myth has been fostered too long, and too uncritically, by too many people both in and outside the Third World, and as a result many people have been cruelly deceived. A pattern does emerge from the successes and failures of biogas technology in the Third World, and we will discuss some of the elements of that pattern below. First, however, it may be useful to review some of the objectives of biogas technology in the less developed countries (LDC).

OBJECTIVES OF ANAEROBIC DIGESTION

It is symptomatic that in the LDC's the process of anaerobic digestion is almost universally identified with its gaseous output—'biogas'—rather than viewed as a technology with a contribution to make towards meeting a

number of objectives. It is more useful to consider how the attributes of technologies with 'biogas' as their core match up to the many objectives of the LDC's. A second point should also be made at the outset: in practice biogas is only one option amongst many, and it is important that the competing options are also identified and evaluated.

The attributes of biogas include:

(1) Provision of gaseous fuel for direct or subsequent use.
(2) Provision of a slurry with value as a land- or water-based source of nutrients and fertilisers.
(3) As a waste treatment system, for human, some agricultural and some industrial wastes.
(4) A *relatively* simple technology, and one that can incorporate a relatively high input of local resources.

It is not so easy to enumerate the corresponding requirements of the developing world, although it is clear that all of the elements above—energy supply, nutrient supply or organic recycling, waste treatment and development based on local resources and skills—will, with different weights, be components.

The contrast between the relatively rich and the poor is reflected in the patterns of consumption and demand, and perhaps nowhere is this more clear than in the case of energy supplies. Table 1 (from Earl[13]) gives an indication of the problem: the majority of the world's population depend on their own labour, animal power and, for heat and power, on wood and its derivatives, agricultural residues and animal manures (see Table 2). In many parts of the world these traditional sources of energy are under pressure as firewood supplies become more difficult to find and, thus more demanding in labour time; the problem is compounded by a developing ecological crisis and by increasing pressure on agricultural land (Arnold[3]).

A number of factors are thus crucially relevant to the appropriateness or otherwise of biogas technologies. The majority of the wood, residues and dried dung that is used as an energy source is used for domestic purposes (Tables 2 and 3, Reddy[50]) and most is used *very* inefficiently (with efficiencies of 10–15%, Reddy,[50] Floor,[21] Morgan and Icereman[36]) on stoves, often made of a few stones. We may consider it bad practice to burn wood inefficiently but the peasant must pay for our outrage in cash, if he is to replace the stoves by a gas burning stove. The majority of these traditional fuels are not marketed—the cost incurred is more likely to be in gathering time than rupees.

Revelle[51] makes the point that energy is needed in agriculture for: (1)

TABLE 1

Per capita GNP and energy consumption for some selected countries (modified from Earl[13])

Country	GNP per capita (US $)	Consumption per capita fuelwood (m³)	Energy consumption per capita CE† Forest only	Energy consumption per capita CE† Total	Proportion of total energy supplied by fuelwood (%)
Malawi	80	0·77	335	376	89·1
Nepal	80	0·57	248	259	95·8
Tanzania	100	2·30	999	1 042	96·0
India	110	0·19	33	274	30·3
Sri Lanka	110	0·31	135	291	46·4
Guinea	120	0·50	217	314	69·1
Nigeria	120	1·00	435	480	90·6
Madagascar	130	0·52	240	304	78·9
Uganda	130	1·07	478	531	90·2
Kenya	150	0·69	299	447	66·9
Rhodesia	280	0·63	274	838	32·7
Algeria	300	0·02	9	479	1·9
Ivory Coast	310	1·01	438	618	70·9
Zambia	400	0·90	391	900	43·4
Brazil	420	1·60	695	1 176	58·1
Cuba	530	0·20	87	1 140	7·6
Chile	320	0·31	135	1 345	10·4
S. Africa	760	0·04	17	2 763	0·6
Venezuela	980	0·63	274	2 427	11·3
Greece	1 090	0·25	109	1 259	8·7
Italy	1 760	0·14	61	2 492	2·4
Libya	1 770	0·20	87	569	15·3
USSR	1 790	0·36	157	4 356	3·6
UK	2 270	0·01	4	5 143	0·1
Finland	2 390	1·63	709	4 859	14·6
Belgium	2 720	0·20	9	5 438	0·2
W. Germany	2 930	0·03	13	4 836	0·3
France	3 100	0·12	52	3 570	1·5
Canada	3 700	0·20	87	8 881	1·0
Sweden	4 040	0·41	178	5 946	3·0
USA	4 760	0·10	43	10 817	0·4

† For making comparisons between fuels and power on a commercial scale and for measuring the extent of reserves and resources in this book the unit chosen for convenience is the tonne of coal equivalent (CE), which is equal to 6·9 million kcal or 8000 kWh.

TABLE 2(a)

Estimated per capita use of energy in rural areas of seven developing countries

(10³ kcal/day)

	India (1)	China, Hunan (2)	Tanzania (2)	Northern Nigeria (2)	Northern Mexico (2)	Bolivia (2)	Bangladesh (6)
Human labour	0·67	0·64	0·64	0·61	0·75	0·71	0·67
Animal work	1·00	0·92	—	0·13	1·30	1·83	1·00
Fuel wood	2·86	13·69 (Fuel wood, crop residues and dung)	15·07	10·27	9·70	22·83	0·93
Crop residues	1·16						1·65
Dung	0·67						0·57
Total non-commercial	6·36	15·25	15·71	11·01	11·75	25·37	4·82
Coal, oil, gas and electricity	0·53	2·05	—	0·02	19·81	—	0·27
Chemical fertilisers	0·22	0·34	—	0·05	5·33	—	0·10
Total commercial	0·75	2·39	—	0·07	25·14	—	0·37
Total all sources	7·11	17·64	15·71	11·08	36·89	25·37	5·19

TABLE 2(b)

Characteristics of energy use in rural areas of seven developing countries

	India	China, Hunan	Tanzania	Northern Nigeria	Northern Mexico	Bolivia	Bangladesh
				(10^3 kcal/day/head)			
Total use	7·11	17·64	15·71	11·08	36·89	25·37	5·18
Domestic uses	4·85	13·92	15·30	10·51	11·85	23·09	3·58
Non-domestic uses	2·26	3·72	0·41	0·57	25·04	2·28	1·60
Domestic/non-domestic uses	2·1	3·7	37·3	18·4	0·47	10·1	2·2
Non-commercial/commercial	8·5	6·3	No com.	157·3	0·47	No com.	13·0
Annual use (kg coal equivalent)	346	858	765	539	1 795	1 235	252
Cereal yields (kg/ha)	800	1 750	700	900	2 750	900	1 100

TABLE 3

Estimated cash flows

Design	Size (Cows)	Capital cost, K (Sh)	Repayment (= 0·3 K) (Sh p.a.)	Gas m³/day	Gas Sh p.a.	Slurry value (Sh p.a.) Low	Slurry value Med	Slurry value High	Net cash flow (Sh p.a.) Low	Net cash flow Med	Net cash flow High
Hutchinson	5	1 650	495	1	365	0	300	600	−130	170	470
	20	3 850	1 155	4	1 460	0	1 200	2 400	305	1 505	2 705
Stone or	2	500	150	0·4	146	0	120	240	−4	116	236
A.A.T.P.	5	750	225	1	365	0	300	600	140	440	740
	20	1 500	500	4	1 460	0	1 200	2 400	960	2 160	3 360

Labour costs assumed = 0

irrigation and water supply, (2) to provide fertiliser and nutrients, (3) for seedbed preparation and (4) for transportation (see also Makhijani and Poole[32]). Consider point (2), for example: with every ton of rice in Asia or Africa almost two tons of straw is grown with about the same energy content as the rice. Analyses of energy inputs in agriculture (for example, Pimental,[44] Leach[31]) show that in mechanised agriculture the crop residues contain several times as much energy as that needed for modern agriculture. Of course, traditional patterns vary enormously and it is impossible to prescribe for every country. In India, for example, 'the quantity of these wastes . . . is much less than in other countries because a large proportion is used for animal feed or as fuel or not collected at all' (Vidyarthy and Misra[62]). In other words, the world of the rural poor is enormously intricate and subtle: calculations to show that X million kJ of energy *could* be obtained only have a meaning if all the consequences of introducing new practices or new technologies are taken into account.

Moreover, the fact of poverty must always hang over any discussion: the appearance of the cleverest technological fix in the world on a market where demand is zero will make not the slightest impression on the condition of the poor except, conceivably, to worsen it. At the same time it is imperative to seek out technologies which will assist and be a motor for productive activities if ever the cycle of underdevelopment is to be broken. Perhaps, in recognising the crucial role of technology for development, we have come to expect too much of technology, to perceive problems as technological, when the real problems are structural, political and economic? It remains to be seen whether the two objectives—of easing the commercial energy problem by using local renewable resources and the provision of energy to the rural poor—can be solved simultaneously.

The second attribute of anaerobic digestion is its role as a conservative or recycling technology. Given the needs for fertiliser and nutrients, and for ecological stability, it hardly needs pointing out that this attribute is mirrored in the developing world. Once again, however, the problem is far from simple to resolve: if crop residues or animal dung play a key role as energy sources at present and thereby have an effective social cost due to the nutrients withdrawn from the soil, a proposal to realise their value as both energy and nutrient must realistically ensure continued domestic energy supply to the poor. To make realistic proposals implies an intimate knowledge of current practice and involves some very difficult problems of economic evaluation (for example, Prasad *et al.*[46] Disney,[12] Barnett[5]).

Few of the technical options which may be complementary to—or substitute with—biogas (for example, fermentation to alcohols (as liquid fuels), treatment of wood and crop residues to produce char, pyrolitic oils or fuel gas) provide both energy and organic recycling: this means that, in direct comparisons with biogas technology, both the attributes are relevant.

The need for public health and pollution control technologies is clearly of outstanding importance (for example, Feachem *et al.*[18]). In many parts of the Third World, both rural and urban, facilities are poor or non-existent; the Chinese experience shows the possible role of biogas in such situations. It seems that this application has not received much attention in other countries, perhaps for cultural reasons or perhaps for economic reasons. Certainly, digesters based on human excreta alone will not make a major contribution to energy supplies.

The final attribute is to attempt to design or adapt technologies such that they make a significant contribution to the development of local skills, technologies, industries and productivity. Reddy[50] makes the point very clearly that it is necessary to break with the patterns of the past, of imported technologies and imported solutions. 'Appropriate' technology will be one whose attributes—simplicity, materials and cost of construction—and its operation, material and human inputs, products and their end uses will best fit the local conditions. There is no reason to suppose that the best solution in one country or locality will necessarily be the best in another. In particular it is vital not to underestimate the relevance of traditional practice—and therefore developed skills.

SOME ISSUES FOR ANAEROBIC DIGESTION TECHNOLOGY IN THE THIRD WORLD

In general, most proven designs are too expensive for the rural poor: this much is agreed by workers from many countries (for example, Reddy,[50] Pang,[41] ESCAP[15]). Taiganides[60] remarks that present capital costs are around \$200-\$300 per animal unit (1 AU = 500 kg animal), with operating costs of around \$50-150; the gas produced has a value at market prices of ~\$20/AU per animal. Pang's analysis leads to a similar conclusion: in financial terms (and using a discount rate of 6%) based on direct costs and benefits the process is barely economic in Nepal. If indirect benefits are included it can be argued that the process is viable. Similar results come through from case studies in India and Thailand: given the fairly strong economies of scale in capital costs, the process looks more attractive at larger scales.

There are various possibilities of avoiding this impasse:

(1) Building community plants.
(2) Reducing construction and operating costs.
(3) Improving the efficiency of the plants.

Option (1) has been discussed (for example, Prasad *et al.*[46]) and large digesters exist in many countries. So far, however, there are few successful community scale plants, and there are clearly many managerial and social problems which are difficult to resolve outside authoritarian societies. Parikh & Parikh[42] (1979) discuss one scheme which would involve the purchase and sale of inputs and outputs, but it remains to be seen whether this could function in practice. The majority of plants in China are domestic (4–10 m^3) rather than community, scale (Van Buren[8]).

Option (2)—the reduction in construction and operating costs—has become an explicit objective of research and development. As noted above (and see Ratasuk[48]) the most obvious area for cost reduction is, with traditional (i.e. Indian) designs, in the gas-holder itself, since this may account for up to 50% of the total costs. Ratasuk argues that, in fact, there is little point in attempting to reduce the digester volume until this has been achieved. However, this seems rather extreme if one compares the volumetric efficiency of a high-rate digester. The Taiwanese neoprene bag digester may be a solution in some situations. The innovation from China of constructing plants in locally available materials and eliminating the gas-holders altogether (so that the gas pressure is now no longer constant) appears to be a great stimulus and, already, modified designs are reported in Nepal, India (the 'Janata' digester, using ferro cement) (Fig. 8), Thailand and other parts of the world. It should be noted that Chinese practice is *not* to count the labour time involved in the digester construction; translation to economies on the periphery of capitalism may not be so straightforward.

Option (3)—to seek to improve the plant efficiency—ought surely to be an objective of research and development programmes. However, remarkably little effort has been carried out into investigating the operating characteristics and constraints of existing digesters (Pyle,[47] Ratasuk[48]) and apparently still less into alternative operating conditions or designs. For example, there has been very little work on thermophilic operation (Subramanian[59]) although the literature is full of vague statements to the effect that thermophilic operation is non-economic; the possibilities of reducing digester volume by operating under conditions of high solids loading or 'packed bed' conditions (Wong-Chong,[61] Augenstein *et al.*[4]) have similarly barely been explored. Similarly, the effect of input material

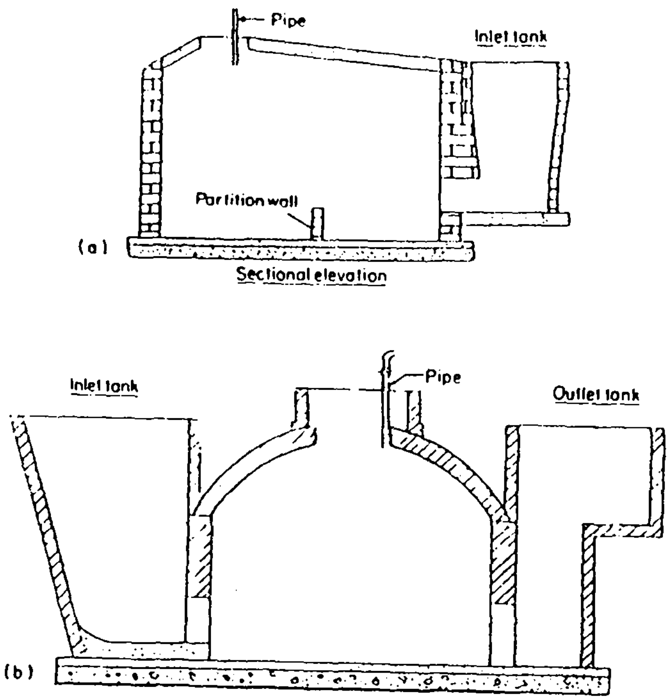


FIG. 8. 'Janata' designs (India).[55] Janata biogas plant (a) near post office, Ajitmal; gas production 150 ft³. (b) Bakewar; capacity 100 ft³.

on gas yield has apparently not been appreciated, since a large proportion of plants function on cow dung alone. The consequences of the reaction kinetics and their constraints (for example, the fact that the rate limiting step is probably in the hydrolysis stage rather than the methanogenic phase (Hadjitofi[23])) have not been explored. It is, of course, important to recognise that the problems of research and development in poor countries are especially difficult and the choice of research and development policy all the more crucial.

The problems involved in the economics of the process and the crucial importance of capital costs, slurry valuation and labour costs are illustrated in the following example, based on Kenyan conditions.

POTENTIAL FOR BIOGAS PLANTS: A KENYAN EXAMPLE

In his excellent review of rural energy needs Muchiri[38] estimated that the 1·48 million holdings in Kenya could produce (by the year 2000) 7·390

$\times 10^{13}$ kcals of energy from animal and crop residues. Assuming that the gas were used at an efficiency of 40%, and replaced firewood, this would leave $5{\cdot}84 \times 10^{13}$ kcal (about 1·5 times firewood consumption) for mechanisation, etc. The fertiliser contribution would also be very significant, providing some 270 kg of nutrients per year per holding. It is also of interest to estimate the size and cost of the units necessary. If individual biogas plants were installed (i.e. one per holding on average) the average capacity would be roughly 4 m^3 of gas per day; the capital cost of such a plant (see later section) is between Sh 1500 and Sh 3850. The total investment in plants would thus be between Sh 2200 millions and Sh 5700 millions (£1 = Sh 14·7).

Muthee's (1978) study[37] of biogas raises the severe limitations on its application inherent in the distribution patterns of land holdings, livestock and household incomes which are current in Kenya. Muthee concentrates on cattle manures as the main raw material although, as Muchiri's work shows,[38] the potential from vegetable matter is considerably greater. Muthee shows that only 64% of farmholdings have cattle; in some areas the numbers of cattle kept, for whatever reason, is judged to be too small for viable operation; finally, some 40% of all landowners have annual incomes of less than Sh 2000 (and this excludes the landless poor). In coming to these judgements Muthee based his assessment on the assumption that a minimum of five cattle is necessary and that the minimum cost of a biogas unit is Sh 3000.

In fact, as the calculations above show, if the possibility of using vegetable and animal wastes is accepted the restriction on unit size can be relaxed. In practice a unit of only 1–2 m^3 capacity would be feasible *technically* (providing $\frac{1}{4}$–$\frac{1}{2}$ m^3 biogas per day). These arguments are *not* meant to suggest that community scale plants should not be considered seriously.

The plants currently marketed in Kenya by the Hutchinson Tunnel Co., Fort Ternan, are constructed of corrugated metal. However, there are many other possible designs; one low-cost design would be a stone- or brick-built design based on the Chinese technology. Another design has been described by the AATP centre in Arusha, Tanzania (Hanlon[24]). The cost of a 3 m^3 Indian KVIC design was reduced to £133 (KSh 1955) by using opened-out oil drums as the main source of steel. An even simpler design was achieved by fastening seven oil drums in an hexagonal pattern to serve as the floating gas-holder. The cost of such a unit was quoted as £45 (KSh 660), and has the additional benefit that no welding is required so that local manufacture is possible.

The financial viability of three designs is briefly compared with a view to defining the possible feasibility of biogas in rural Kenya.

(a) Capital Costs

Two digester sizes have been chosen for this discussion: a five-cow unit producing around 1 m^3 of gas per day and a 20-cow unit producing 4 m^3/day. The capital costs of Hutchinson units, including piping and some accessories, would be Sh 1650 and Sh 3850, respectively. The units produce around 0·25 vol/vol/day. The digester volumes would be around 4 m^3 and 16 m^3.

The stone plants (Chinese design) have been assumed to be of the same volume as the Hutchinson units and to produce the same amount of gas, so the only variable is the capital cost. Based on a stone price of 2 Sh/ft run for quarried 9 in × 9 in stone, the stone costs would be Sh 450 and Sh 1000, respectively; the cost of pipes and fittings at the two scales would be Sh 750 and Sh 1500, respectively. Further, a two-cow (or equivalent) unit has been considered, with gas production of 0·4 m^3/day; this would have a capital cost of Sh 500. (These figures are all tentative).

The quoted cost of the simple AATP design is very close to that estimated for the Chinese plant. The subsequent discussion will therefore not attempt to differentiate between them.

(b) Raw Materials

Although the units are treated in terms of the number of head of cattle this does not preclude the use of other inputs (for example, crop residues). For the purposes of calculation the material costs are taken to be zero. However, in most cases the organic input will have a positive opportunity cost and this clearly affects the value of input materials and the slurry produced. Similarly, the assumption that water is free is often a poor one.

(c) Gas

A value of 1 Sh/m^3 has been taken.

(d) Slurry

There are a number of ways of estimating the slurry value. (Barnett[5]). One can estimate a value based on the nitrogen content and the current price of nitrogenous fertiliser, but this probably underestimates the fertiliser value of the slurry. Alternatively, one can attempt to estimate the slurry value from field trials. In any event the slurry value taken should clearly be its value *relative* to the feed.

The current price of nitrogen is around US$ 50/kg, or 3·5 KSh/kg. It is assumed (Pyle[47]) that each animal produces around 4 kg of dry matter as dung per day; the slurry is reported to contain around 2 % of the dry weight as nitrogen; thus, per animal, the slurry will contain 0·08 kg/day.

On this basis the slurry value would be 0·08 × 3·5 = 0·25 Sh/day per animal, or 90 Sh/year/animal. However, it should be re-emphasised that this nitrogen was also in the input material, so that, although it can be argued that the fertiliser value of the dung is superior to that of the raw material, the above estimate is certainly optimistic. On the other hand, this valuation does not allow for the humus value, etc.

Hutchinson[25] asserts that the annual slurry for one animal has a value of Sh 120. This an *over-optimistic* valuation.

In the following calculations three slurry values relative to the input material are taken: a low value of zero and a medium value of 60 Sh and the high value of Sh 120 animal/year.

(e) Labour

A labour cost of zero is assumed; if 1 h per day were needed an approximate valuation of the opportunity cost would be Sh 600 per annum.

(f) Maintenance

Maintenance costs have not been included although they will be significant for a metal plant.

(g) Financing

In the first set of calculations it is assumed that the plant owner repays the fixed capital cost of the plant in fixed instalments over 5 years. Further, a 10 % interest charge is assumed so that, in the first 5 years of the project, there is an annual repayment of approximately 0·3 K where K is the capital cost of the plant.

CALCULATIONS AND DISCUSSION

The results of the calculations for a typical year in the first five years of the project are summarised in Table 3.

These results show that if the slurry value is zero the Hutchinson five-cow unit is *not* financially attractive. The 20-cow unit is viable but not particularly attractive. However, if the high slurry valuation is included both units are financially viable and quite attractive.

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The results for the stone plant show the undoubted advantages to be obtained by cost reduction. The very small unit is not viable if the slurry value is zero, but is attractive for higher slurry values. The stone plant is a better proposition than the Hutchinson plant and one could make an argument for the five-cow unit even on the basis of zero slurry value. At higher capacities the units look extremely attractive.

If the opportunity cost of labour is not taken to be zero the results are seriously modified. Neither design is viable when the slurry value is zero and 20-cow plants are only attractive propositions at higher slurry values.

TABLE 4
Net present value of project (KSh) (£1 ≡ KSh14·7)

	Low value slurry		Medium value slurry		High value slurry	
Size	Hutchinson	Stone	Hutchinson	Stone/ A.A.T.P.	Hutchinson	Stone/ A.A.T.P.
2	—	960	—	1 960	—	3 360
5	2 000	3 265	5 000	5 900	8 000	9 265
20	12 210	13 100	22 750	25 100	36 210	37 100

The results of an alternative method of calculation are given in Table 4. Here the Net Present Value (NPV) of the various projects has been calculated; for ease of calculation it was assumed that all the capital is paid in the first year of the project, that there are no interest repayments, that the project life is infinite and that the discount rate is 10%.

All the options considered have positive net present values and may therefore be judged worthy of consideration for investment. As expected, the stone-built plant is always superior to the Hutchinson design and the results are extremely sensitive to the valuation placed on the slurry. Even if labour costs are included, the larger scale plants provide a very attractive financial picture. The results show that (provided financing and credit arrangements are made), individual plants may have a role to play.

These calculations suggest that biogas could make a serious contribution to energy supplies in Kenya and, by diverting pressure off firewood and by recycling nutrients to the soil, would have other positive benefits. It also suggests that the case against individual plants is not overwhelmingly proven; no consideration has been given to the role of the technology in excreta disposal and public health control, which, again, is a significant argument in favour of this process.

Choice of Retention Time and Digester Volume

Clearly, there are strong arguments—perhaps insufficiently appreciated until now—to reduce digester costs. One way of achieving this may be to improve the efficiency of the technology (e.g. with a 'high-rate' digester), or by attempting to operate digesters under different conditions (e.g. under high solids loadings[61]) or under thermophilic conditions (see, for example, Augenstein *et al.*[4]). Few of these options have received serious considerations as options for Third World operation, although as Subramanian notes,[59] thermophilic digesters have been used and successfully in the treatment of industrial wastes in Japan. There is another, and related, issue which it is instructive to consider: the question of the best choice—for *given* technology—of the residence time (or, alternatively, digester volume). Practice tends to vary: in India retention times of 50 days and upwards are common (e.g. Padmanabham[40]). Subramanian quotes residence times of 20–40 days in Korea;[59] in Nepal, residence times at 50–70 days are recommended (Finlay[19]). Richard[52] recommends an implausibly low residence time of 1–4 days for the Chan-type digesters used in some parts of the Pacific region. Neoprene bag digesters are run at residence times in the range of 6–16 days (Chung *et al.*[10]). Given the variety of dilution rates, the range of loading rates corresponding to these conditions ranges from around 0·1 to 7·0 kg/m^3 day. There are obvious constraints on the residence time: a lower limit, corresponding to 'wash-out' conditions, will usually be around 5–10 days; if the transmission of pathogens is an important consideration (e.g. in disposal of human faeces) higher residence times will probably be called for. However, neither of these considerations appear as a serious arbiter of choice in the literature referred to; indeed it is often difficult to establish the rationale behind the choice of residence time, or even to appreciate from the literature that the digester performance depends on retention time.

It may be instructive, therefore, to consider briefly the economic 'optimum' retention time. Consider a biogas digester of volume V m^3 handling continuously F kg/day input organic matter, and producing—at a given temperature—G m^3/day gas and S kg/day slurry. The unit opportunity costs in rupees (not necessarily Indian!) of input, gas and slurry are P_F, P_G and P_S respectivelyand the capital cost of the digester is K. We wish to consider the best choice of V, i.e. K for given F, remembering that as we change V so G and S will alter. If the annual discount rate is r then the capital cost can be written as an equivalent annual payment

$$K_a = Kf$$

where

$$f = \frac{r(1+r)^n}{(1+r)^n - 1}$$

and n is the project lifetime. For our purpose it is more convenient to work in terms of daily production and costs, i.e. $K_d = Kf/365$. Now assuming that labour costs do not vary with volume (in the region of interest) the optimal operating condition will occur when the cost of a marginal investment in volume (which can be translated into residence time or loading rate) exactly balances the marginal value of the increase in gas and slurry produced as a result.

That is, at the margin

$$\frac{\partial K_d}{\partial V} = P_G \frac{\partial G}{\partial V} + P_S \frac{\partial S}{\partial V} \quad \cdot\cdot \quad (1)$$

There is no data on the variation of S or P_S with volume (residence time), but it seems unlikely that there will be any significant change. We can thus conclude that, for optimal operation:

$$\frac{\partial G}{\partial V} = \frac{1}{P_G} \frac{\partial K_d}{\partial V} \quad (2)$$

In order to use eqn (2) we need an operating curve of G versus V or τ (for given feed rate). Unfortunately there is very little reliable data available. Figure 9 has been constructed from some data from India.[47,54] Equation (2) shows that the optimum operating condition (i.e. residence time) is when the gradient of the G–V curve $= (1/P_G)(\partial V_d/\partial V)$. An immediate and explicit

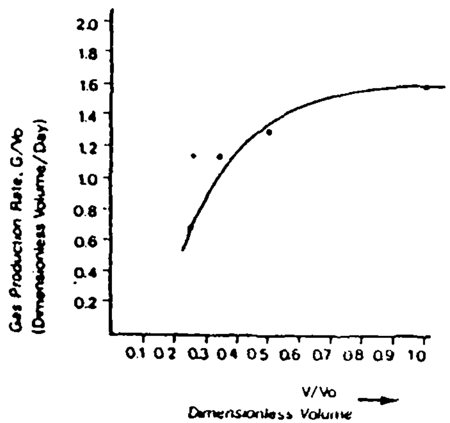

FIG. 9. Gas production at constant feed rate.

(and obvious) consequence is that the optimum operating condition should depend on the local opportunity costs of gas, of the plant itself and of capital (since this appears through the discount rate r). Considering conditions in India, for example, we have approximately P_G at 0·66 Rs/m³, $\partial K_d/\partial V$ at 350 Rs/m³.[40] Thus, Table 5 has been constructed giving values of $(\partial G/\partial V)$ optimum as a function of discount rate, assuming a project life of 10 years. The final column, of optimum retention times, τ_{opt}, has been

TABLE 5
Optimum retention times (Indian conditions)

Discount rate r	f	$\frac{\partial G}{\partial V}$ $\frac{m^3/day}{m^3}$	τ_{opt} (from Fig. 9) days Retention times
0·1	0·163	0·24	~50
0·2	0·239	0·35	~45
0·3	0·323	0·47	~38

estimated locating the optimal gradients $\partial G/\partial V$ on the (very approximate) Fig. 9.

The approximate nature of the data used in these calculations must be stressed. Nonetheless it is clear that the choice of retention time is a crucial variable in determining the viability of biogas plants and under the conditions taken is a remarkably sensitive variable; we note that as the opportunity cost of gas and the capital cost of the plant increases so does the optimal retention time; the resulting answer is sensitive to discount rate and we note the considerable difference between a rate of 10% which is commonly used in calculations and rates of 30–35% which may be better indicators of the real cost of capital in the rural area of the poor countries.[22] Given the wide range of operating conditions quoted above it seems likely that some plants at least are operating well away from the optimum conditions.

One of the problems of the above analysis is that it is true only for one operating temperature. If however temperatures vary widely during the year (as in Korea or Nepal) and there is no temperature control, the G–V curve will shift, so that the optimal operating conditions will depend on the time of year. Finally, it must be emphasised that the above analysis holds only for a given technology.

Engineering and Management

Perhaps one of the most under-estimated elements in the programmes for the diffusion of small-scale biogas plants is the crucial need for careful and foolproof engineering. The basic principles of digester design are fairly well defined[47,48] yet many plants fail or operate badly because of poor engineering.[30] Critical problems to be faced in plant construction, include sealing of the digester, misaligned gas-holder guides, misplaced feed pipes, poor control over feed quality and consistency, missing water traps in the gas pipelines, maintenance etc. There is an excellent account of likely problems and an exemplary guide to good practice from the D.C.S. group in Nepal.[19,20] In the context of the Third World such aspects are by no means trivial and the technical and managerial problems involved are enormous for a programme such as that promised in India—to establish half a million plants between 1978 and 1983.[1]

From an operational point of view it appears that major problems are related to temperature control; operation during low temperature conditions, and operation with feedstocks other than animal manures. The potential for gas production is certainly far higher with other inputs and especially vegetable matter. Despite the reports of Chinese plants operating with mixed feeds, the operational problems are by no means solved. It may well be that batch plants will provide a means to solve this problem. In any event, if rational policy choices are to be made it is imperative to have a solid base of information, technical and socio-economic, on the operation of various plants; surprisingly, perhaps, there is very little such data, and what there is (for example, Finlay[19]) is difficult to interpret.

DISCUSSION AND CONCLUSIONS

Despite the increasing interest in low cost designs there are many problems to be solved before biogas technology can genuinely be hailed as a component of a solution to poverty in the Third World. Whilst the cheapest small plant to supply a family's domestic needs costs in the order of £100 and the returns on that investment remain low, it must remain at best a marginal proposition to the really poor.

There are strong arguments in favour of developing community scale plants (that is, to produce 150 m^3 gas/day and upwards). The very strong economies of scale lead to significant cost reductions (capital costs reducing from Rs 1166/m^3 at a 2 m^3 capacity to Rs 414/m^3 for a plant of 140 m^3 under current Indian conditions). The increase in scale can also make

possible technical innovations and refinements (e.g. running under high-rate conditions, temperature controls, external heating etc.). It is also clear that popularisation programmes which concentrate only on the energy-providing role of anaerobic digesters seriously under-value the technology and probably misjudge many potential consumer's attitudes (e.g. Agarwal[1]).

In attempting to survey and evaluate the state of the art and current developments I have been very struck by the apparently limited scope of research and development. Outside the work on cost reductions there is strikingly little activity into alternative designs and alternative configurations. It may be a consequence of the fact, as Agarwal[1] remarks, that 'biogas researchers' continue to be treated as second class citizens in energy research. There is little doubt that anaerobic digestion has a very important role to play in future in the Third World; the extent of that role however needs sharper definition, and it seems to me a matter of the first priority to attempt to evaluate the possible contribution of anaerobic digestion against the alternative options within the framework of the objectives and inspirations of the poor countries. If Taiganides[60] is correct in stating that 'Digestion is more of a conservation scheme than an economic investment . . . (it) does not have to make money, since it is making resources out of wastes', the role of anaerobic digestion in the Third World should not be overstressed.

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Paper 2: Developments and Trends in Biogas Technology, by Dr. L. Pyle

There already exists a range of biogas designs which can handle a variety of input substrates and operate more or less reliably and more or less efficiently. (Details can be found, for example, in Basnett et al, Pyle (paper 1)). However, there is a need to develop new designs and to refine the detailed designs of existing models to meet the following objectives in particular:

1. To improve technical efficiency (i.e. the yield and rate of production of gas);

2. To improve reliability;

3. To enable operation with a range of inputs (e.g. crop residues, effluents, human excreta, etc. etc.), and to minimise the use of expensive or scarce materials;

4. To reduce the costs of operation.

In practice, there will be no single 'best' design; in a particular location this will result from a trade-off between competing objectives and intelligent adaptation to accommodate local constraints. On the other hand, there is a lot to be learned from work across the world to improve digester designs to meet the listed objectives. Few radically new, tested designs have been developed since my survey (paper 1) a few years ago, but a number are very close to adoption. The need now is to collect and assess reliable and comparable data on the technical (and economic) operation of the range of designs.

Figure 1 illustrates schematically the range of digester types. Some examples of conventional single stage units are outlined and described briefly in paper 1. For example the familiar Indian KVIC and Chinese fixed dome designs fall into this category. Examples of plug flow digesters include the early Fry design, the large scale interconnected Chinese design (fig. 7, paper 1); the Taiwanese bag digester (figure 2); a similar and well-tested design has also been developed by Jewell and co-workers. Many local variants on these designs are known or being tested: there will always be a need to accommodate designs to local conditions, materials availability and price.

Surprisingly little serious attention has been paid to batch or semi-batch operation, despite the relative simplicity of such designs. One possible advantage is their ability to handle essentially solid or "dry" substrates (i.e. up to 40 to 50% solids concentrations): although little experimental data is available we do know that such designs can be operated. Apart from opening up a wider range of feed materials, operation at high concentrations should imply lower digester volumes (and therefore costs), and, of course, reduced water requirements.

It is now widely accepted that one of the intrinsic limitations in all these designs is the limited 'natural' hold-up of active micro-organisms in the digester. In any through-flow system a mixture of living and dead bacteria will be lost with the slurry. In practice the rate of gas production per unit volume of digester is directly proportional to the concentration or hold up of bacteria in the digester. Considerable attention has thus been devoted recently to increasing this concentration level. The recycle digester (3) in figure 1 is one example: this invariably gives rise to problems in the separator/concentrator and does not look a very attractive proposition for on-farm or small community applications.

The anaerobic filter ((4), fig. 1) is a well-proven and old alternative, which has mainly been used in larger scale urban sewage disposal systems. The packing or support is an inert solid such as stone or coal. One limitation of this design is that it cannot handle inputs with high solids contents (because of blocking). It also must be cleaned and regenerated from time to time. Recent developments have however shown that simple filters may be suitable in developing countries, especially for liquid wastes - designs incorporating local materials are easily engineered and operation is relatively straightforward.

The fluidised bed digester takes the anaerobic filter a stage further. Here the support particles are suspended in the upflowing liquid and are thus free to move. This has a number of consequences. Blockage should be less of a problem; the digester contents are more-or-less mixed; it is possible to operate such a unit continuously since particles can be withdrawn and added without interrupting operation. Some of the advantages of such units are discussed by Mistry et al (1983).

Both these designs depend on the ability of the micro-organisms to stick to surfaces and to each other and thus to form films. This ability - or flocculation - is used in the upwards flow sludge blanket (U.A.S.B.) digester ((4) in figure 1; figure 3), which is suitable for soluble waste streams. Here a 'blanket' of active biomass forms in the digester and the substrate flows through it. Another design which depends on the flocculation/settling ability of the active biomass is shown in figure 4. This is an extension of the plug flow digester, and is presently being tested.

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Sometimes it may be appropriate to hold the bacteria in position - for example, by trapping them inside a porous envelope: Mistry et al (1983) describe one such design where the biomass is immobilised in spheres of alginate gel. It is interesting to note that the process of immobilisation itself apparently accelerates the rate of gas production. Again, this design is more likely to be useful for soluble rather than insoluble substrates.

In all this set of designs, the retention time in the digester of liquid and solid biomass is different, and this is an important key to their improved performance.

Another key feature of anaerobic digestion relates to the microbiology. Although the overall process is complex and involves different types of bacteria (see paper 3) we can divide the process into two or three main stages (figure 5). When the starting material (i.e. the polymer) is insoluble (e.g. straw), it is likely that the rate-limiting stage is the rate of hydrolysis to simple sugars and intermediates (i.e. stage 1). When the starting materials are easily hydrolysed (e.g. soluble wastes, piggery wastes etc.) the limiting process is that of methanogenesis (stage 3). In any event (see paper 3) the implication is the same, since the optimum conditions for stages 1 and 2 do not necessarily coincide with those for the methanogenesis to flourish (stage 3): thus, why not separate out stages 1 and 2 and 3 from each other? This is illustrated by 5 in figure 1. The first example there outlines a configuration for a relatively soluble substance, in which the conditions in digester 1 are optimal for acid production (low pH); digester 2 operates at a higher pH and is the vessel where the acids are converted to methane and carbon dioxide. The second example refers to an insoluble substrate: this is converted to acids (again at low pH) in the first, concentrated, digester; the acids are recycled through the second digester where most of the methane production takes place.

Tables 1, 2 and 3 summarise some recent comparative information on, (a) continuous and plug flow digesters and, (b), two stage processes. These are also discussed in paper 3.

Conclusions

This review supplements paper 1, and indicates some recent developments at a process level, rather than at the level of detailed design, in anaerobic digestion. The designs described above are being developed in response to a variety of stimuli and also reflect the growing understanding of the basic process. They illustrate the wide range of alternatives available, and the need for careful definition of the problem and the objectives of biogas operation.

Although I have said little here about detailed design and the need to adapt basic designs to local needs and constraints, that does not imply that such processes are unimportant - quite the contrary. However, it is useful and instructive to separate out the principles of the basic design and the detailed and practical issues in developing any basic design into a working digester system.

TABLE 1: COMPARISON OF COMPLETELY MIXED DIGESTER WITH PLUG FLOW DIGESTER

	Completely mixed		Plug flow	
HRT (d)	15	30	15	30
Gas production rate ($m^3 m^{-3} d^{-1}$)	2.13	1.13	2.32	1.26
Specific gas production ($m^3 kg$ VS added $^{-1}$)	0.281	0.310	0.337	0.364
Gas composition (% CH_4)	55	58	55	57
Volatile solids reduction (%)	27.8	31.7	34.1	40.6

TABLE 2: TWO PHASE DIGESTERS

	Stage 1 (ACID)		2 (METHANE)	
pH	5.7	5.9	7	7.4
Retention	0.5	1 day	6.5 days	
Methane m^3/m^3 day	0.6 m^3/m^3 day		4.6	8.9
Acids (mgle)	4500		150	

TABLE 3: COMPARISON OF DIGESTERS

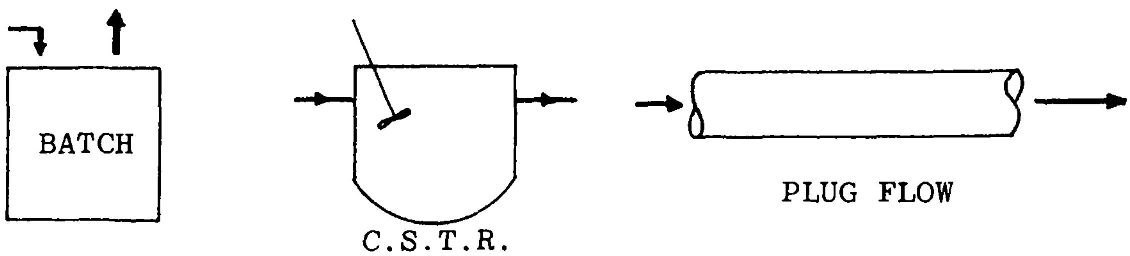
	1 High Rate	2 Two Stage
Methane production m^3/m^3	1	1.5
Volatile Solids Reduction	34	43
Digester Volume Ratio	1 (8 units)	1/3
Cost (10^6 \$)	13.5	4.8

DIGESTER TYPES

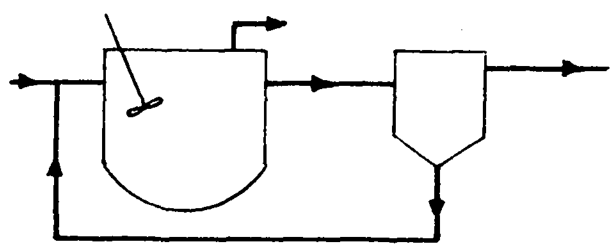
FIGURE 1

1 BATCH, SEMI-CONTINUOUS, CONTINUOUS

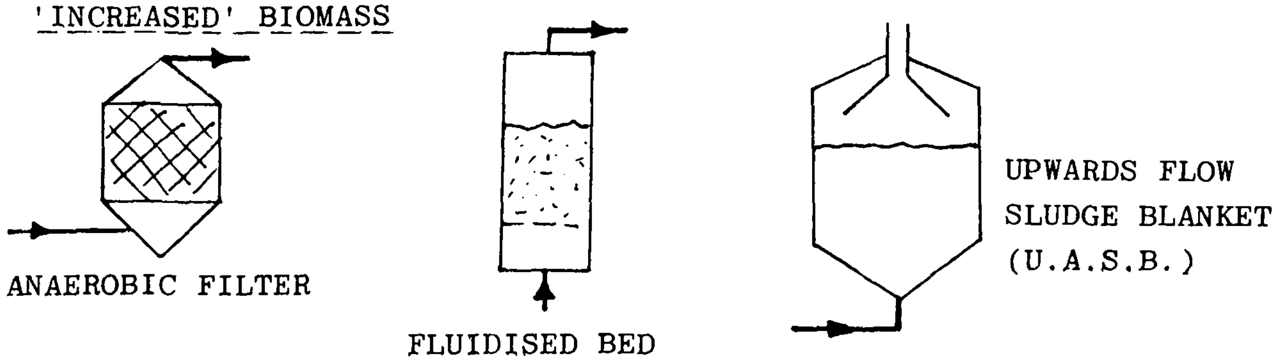
2 CONVENTIONAL SINGLE STAGE



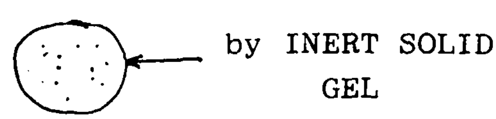
3 RECYCLE



4 'INCREASED' BIOMASS



+ IMMOBILISED
REACTORS



5 MULTISTAGE

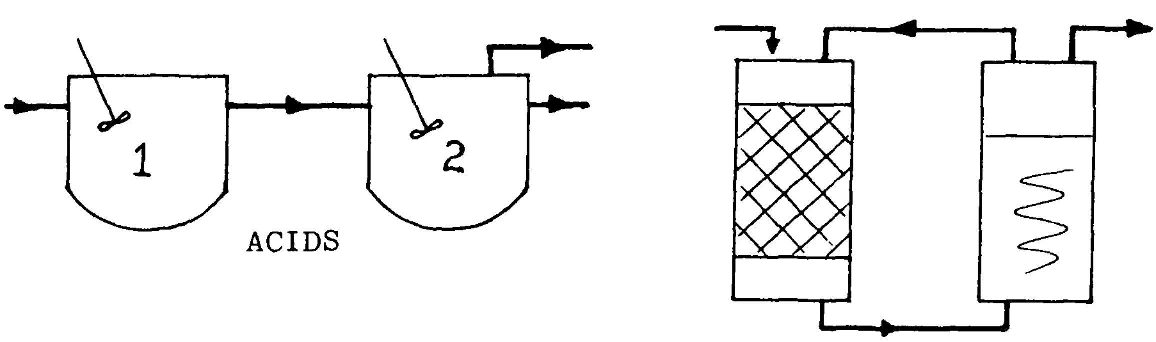


FIGURE 2 : BAG DIGESTER (TAIWANESE DESIGN)

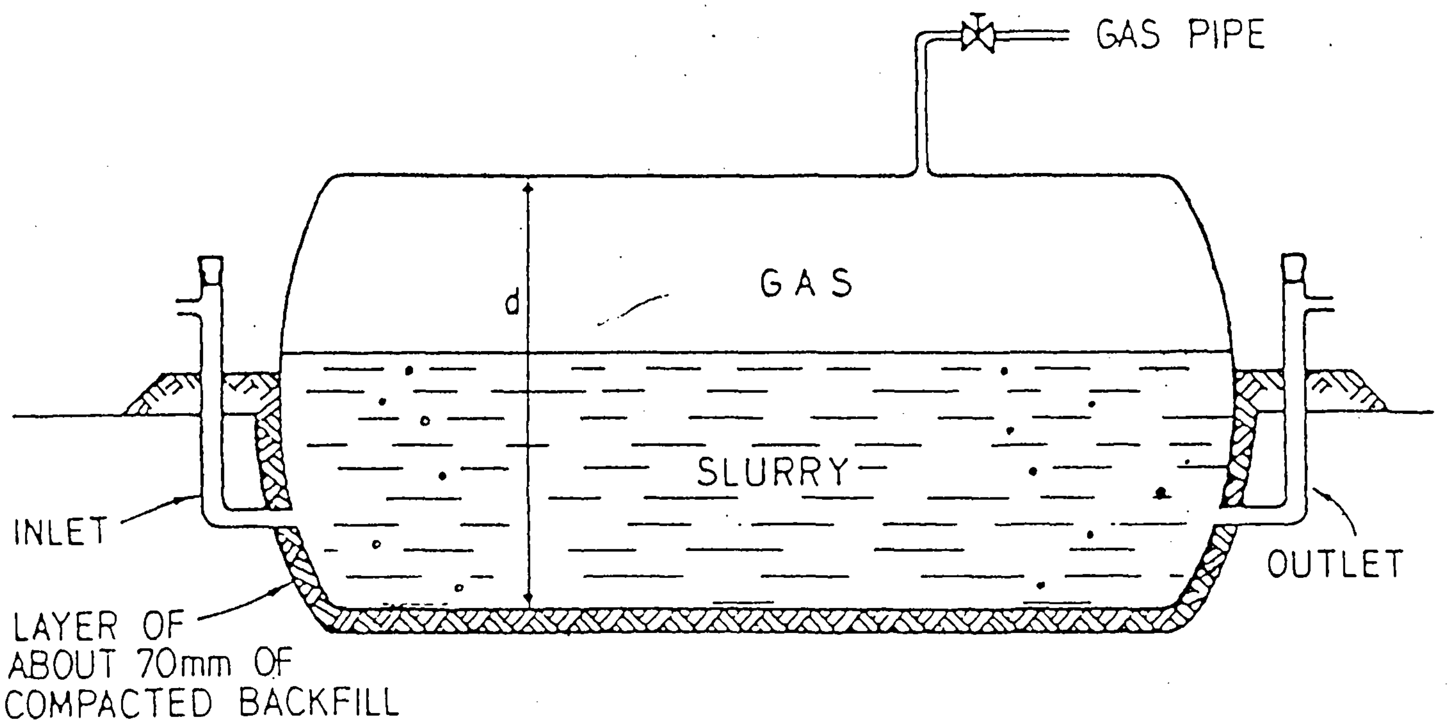
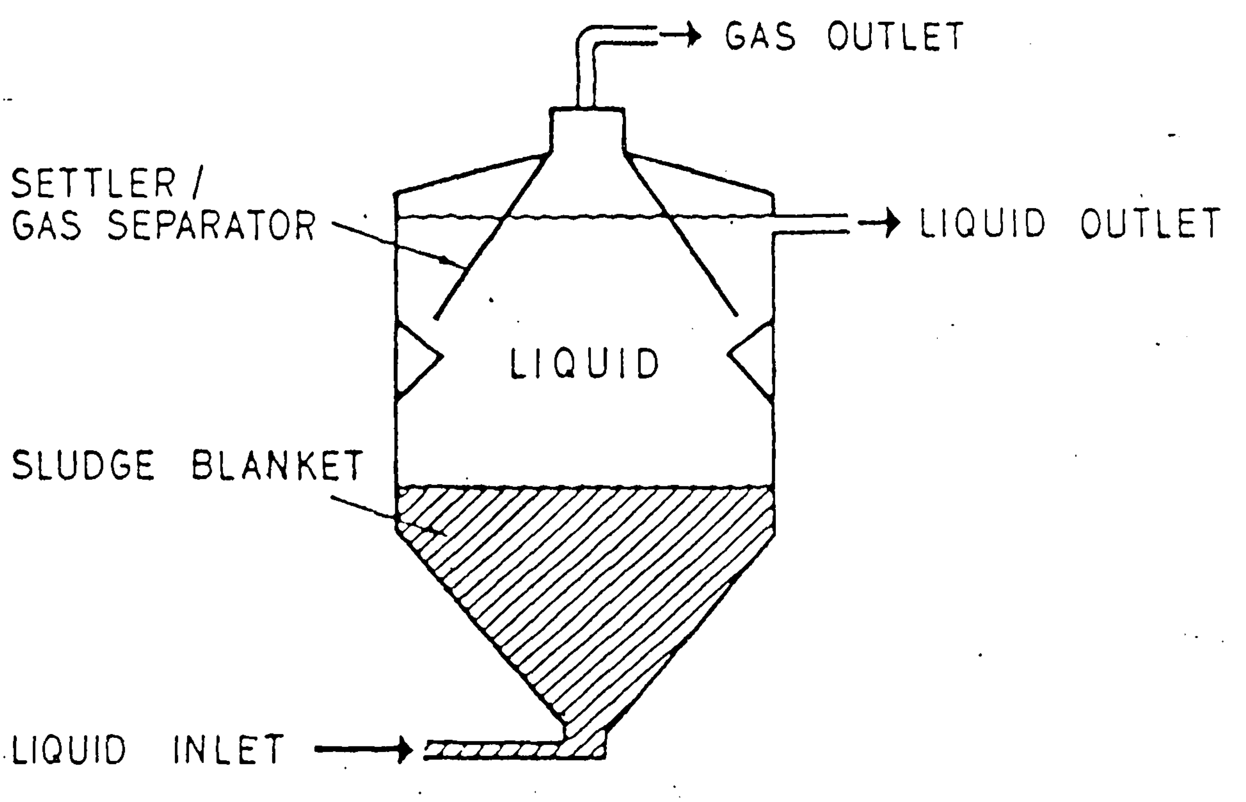


FIGURE 3 : UPFLOW ANAEROBIC SLUDGE BLANKET DIGESTER



Typical Operating Details (at 30°C):

C.O.D. inlet	L.R. Kg/m³day	H.R.T. hours	C.O.D. Reduction
500 - 10000	4-10	5-48	90-97%

Paper 3: Anaerobic Digester Principles and Design Alternatives, by Dr L Pyle

The first two papers have referred, in passing, to some of the basic features of anaerobic digesters. In this paper I shall develop a few of these themes in more detail, in order to provide the necessary background for subsequent discussion on the objectives of biogas R, D & D, and on the evaluation of anaerobic digestion systems. I make no apology for considering some fundamental aspects of the processes here: it is essential in order to develop theoretical limits against which to measure the practical performance of particular units and to understand how better designs or operating strategies might be developed.

The anaerobic process (i.e. where free oxygen is not available) involves a series of oxidation and reduction reactions. The substrate constituents are simultaneously broken down into smaller molecules (ultimately, to methane and carbon dioxide) and into more complex molecules and polymers to make up the micro-organisms. The processes necessarily involve closely coupled oxidation/reduction or redox reactions which can be represented:

$$\text{Oxidation} \quad : \quad \text{Donor} \longrightarrow \text{Donor}^{+} + e \qquad (1)$$

$$\text{Reduction} \quad : \quad \text{Acceptor} + e \longrightarrow \text{Acceptor}^{-} \qquad (2)$$

where the electrons (e^-) produced in (1) are conserved in the system by being used in (2). In practice the processes are often linked with hydrogen or proton transfer e.g. the oxidation of ethanol to acetaldehyde:

$$CH_3CH_2OH \longrightarrow CH_3CH = 0 + 2H^+ + 2e^-$$

Different organic materials exist in different states of oxidation and reduction; for example, methane (CH_4) represents the most reduced and carbon dioxide the most oxidised states of carbon. These two ideas can be coupled together to provide a very important indication of the possibilities in anaerobic digestion. Consider a simple carbohydrate (formula CH_2O): in the process of digestion elections must be conserved and we can see that if the two final end products are methane and carbon dioxide since

$$CH_2O + 4e^- \longrightarrow CH_4$$

$$\text{and} \quad CH_2O - 4e^- \longrightarrow CO_2$$

then <u>necessarily</u> the ratio of methane and carbon dioxide in the product must be 1:1 in order to conserve the electron balance. The ratio will depend on the substrate composition, and is plotted versus the mean oxidation state of the substrate in figure 1. Alternatively, the relationship can be expressed in the form of a stoichiometric relationship:

$$8C_xH_yD_zN_t + 2\ (4x-y-2z+3t)H_2O \longrightarrow$$

$$(4x+y-2z-3t)CH_4 - (4x-y+2z+3t)CO_2 + 8t\ NH_3$$

for the general substrate $C_xH_yO_zN_t$

In other words the CH_4 : CO_2 ratio is determined by the substrate (s): for a pure single substrate no amount of process changes or research can alter that ratio. For a mixture of substances (which is more usual) altering the process conditions may alter the relative degradability or rate of digestion of different constituents, so leading to different gas compositions.

In strict fermentations there are no external election acceptors so that, for example, glucose acts as both donor and acceptor in the production of ethanol. In anaerobic respiration, however, some organisms can use other moeities as acceptors e.g. nitrate (N_2), sulphate (H_2S) and CO_2 (CH_4). The overall process of digestion yields energy and the yield depends on the donor - acceptor couples. This is shown in figure 2, where the free energy released is plotted for various substrates (donors) and acceptors. For any substrate (e.g. glucose) to free energy change is very much greater when oxygen is the acceptor than in anaerobic fermentations using the acceptors listed above. Also, as a rule of thumb, about 60% of this free energy change is 'captured' by the micro-organism and used for further cell growth, which explains why in aerobic processes the cell yields (and growth rates generally) are higher than in anaerobic processes. Low cell yields are an advantage from a disposal and treatment point of view; low rates of growth are a disadvantage (since they imply large retention times) especially when the desired product is growth-associated.

The process of breakdown to methane and carbon dioxide (or catabolism) is clearly very complex and in detail will depend on the substrate. However the main routes of catabolism are common and can also be identified with different groups of bacteria (figure 3).

One or two points of great significance for process design can be emphasised, when the polymeric starting material is insoluble or recalcitrant, the hydrolysis rate is what limits the overall rate of the process. In that case we must ask: when do these conditions apply (e.g. what substrates?); what can be done to accelerate the process - pretreatment?; operation under different/optimised conditions (e.g. in a two stage process)? Moreover, whilst the different groups of bacteria have their own preferred operating conditions, in general the methanogens are the slowest growing and probably the most fastidious and sensitive. A further factor is the key role played by hydrogen; as well as being an important intermediate, the range of end-products is partly controlled by the dissolved hydrogen concentration (which is, however, usually too small to measure on-line). As this concentration rises, so does the proportion of volatile fatty acids produced, which leads to an increase in pH and decrease in activity (or even death) of the methanogens.

Another key element in the whole process is the buffering role played by the carbon dioxide in the presence of fatty acids, ammonia etc. There is a close and equilibrium relationship between carbon dioxide in its various forms viz:

$$CO_2(g) \rightleftharpoons CO_2(1) \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^-$$

Figure (4) shows the relation between gaseous CO_2 and operating conditions in establishing the pH. If the operating conditions change slightly - for example, if the substrate composition changes - it is important to know if the pH changes a little or substantially. This can be measured by a buffer index, β defined by

$$\beta = \frac{dc}{d(pH)}$$

the higher the β the smaller the pH change for a unit concentration change (c), and thus the better the buffering capacity. Fortunately, as figure 5 shows, the buffering capacity is high in the region of normal operation; so that under normal conditions, anaerobic digestion is a relatively 'robust' technology.

The pH has a number of consequences. It profoundly influences the behaviour and activity of the micro-organisms. Figure 6 shows the effect of pH on some pure cultures of methanogens. Note how their activity decreases sharply and is generally confined to the region above pH = 5.5. The activity pattern of the other groups of bacteria involved is different: changes in pH lead to a change in product spectrum; rates of production usually decline sharply below around pH = 5. Thus we can understand how the different groups of micro-organisms operate better at different conditions (the motivation behind multi-stage operation). In a single mixed culture fermentation the overall optimal pH is usually around 6.8 - 7.5. Because of the close interaction between gaseous CO_2, dissolved CO_2, and pH (and temperature and pressure) changes in pH (and T & P) can also lead to changes in liquid and gas composition. These effects are summarised below:

Increased	:	pH	Temp	Pressure
Alters dissolved CO_2	:	$\uparrow$	$\downarrow$	$\uparrow$

The effects of temperature go beyond alterations in dissolved carbon dioxide, of course. Micro-organisms show a marked sensitivity to temperature and, once again, the sensitivity is very dependent on the particular strain of micro-organism. In a mixed culture, the effect of temperature will be complex; if a particular strain of micro-organism remains rate-limiting then the overall consequences of changes in temperature will depend on this micro-organism. However, with changing temperature, the rate limiting process may well change, so that the process is difficult to predict. In general micro-organisms can be grouped by their range of preferred temperatures. This is illustrated in figure 7. This shows how critically sensitive to temperature are some particular micro-organisms and also that different micro-organisms can tolerate different ranges of temperature. Many methanogens (and most A.D. processes) operate best between around 25-40^{o}C, with an optimum activity and level (see figure 7) around 35-38^{o}C. However, others operate in a higher temperature range (the thermophiles). It is usually thought that the thermophile processes will be the whole be faster by virtue of the accelerating effect of temperature on chemical and enzymatic processes. Once again, reality is more complex than such simple ideas but there may be advantages to be gained from thermophile operation: this is shown in figures 8 and 9 (taken from a pilot scale study). However, the key question is whether the net energy production rate at higher temperatures is improved over mesophilic conditions. The answer to this question will obviously be different between different climatic zones and will depend on the method of heating.

The performance of any biochemical process also depends on the nutrient supply: the micro-organisms need ample supplies of major elements such as carbon, nitrogen, hydrogen etc. both for product formation and for cell formation/growth. Other elements are also needed to facilitate these processes. In most rural applications the mixed substrates will themselves contain the necessary nutrients; with some effluents it may be necessary to add additional nutrients to the substrate. In the anaerobic digestion literature these requirements are often lumped together in the C:N ratio, which occasionally appears to take on an almost magical significance. Two points should be made: first, the relative requirements for carbon and nitrogen depend on the operating conditions and, in particular, on the proportions of substrate diverted to new cells and product. This is illustrated in figure 10, showing how the quantity of N consumed for all growth changes with retention time. Secondly, the important factor is the available C/N not the total, since some of these primary elements may be 'locked' away in intractable substrate. In other words, the C:N ratio is a useful, tentative guide to the requirements, but no more than that.

So far, I have outlined the effects of some key parameters on likely process performance. Before discussing some further implications for design and operation a few additional remarks on the rate of fermentation may be in order. Simple quantitative models of the process kinetics are not available to cover the whole range of possibilities. For insoluble or readily accessible substrates, it seems likely that the growth of the limiting methanogens follows the classic monod equation:

$$r_x = \frac{\mu_m \; sx}{k_s + S}$$

where x is the biomass (organism) concentration, s the concentration of the limiting nutrient and r_x is the rate of growth per unit volume. It is possible to lump together the major components into one effective concentration term, s. Sometimes, this equation simplifies to

$$r_x = \frac{\mu_m}{K_s} sx \quad \underline{\text{or}} \quad r_x = \mu_m x$$

It is usually assumed that the gas production rate is directly proportional to r_s. The implication of these rate equations is that increased reaction rates will follow from increased biomass concentration, x, and if $K_s \geqslant s$, from increased substrate concentrations. If $K_s < s$, increasing substrate concentration will have no effect. The influence of pH, temperature and pressure on r_x has been briefly mentioned above.

Some design considerations

On the basis of the observations above a few general principles for process design can be outlined. The significance of some key parameters (pH, T, P, C:N ratio) has already been mentioned; here we focus mainly on the question of the process configuration and operating strategy.

The key elements in any core system design or specification will be:

1. Mode of operation (batch, semi-batch, continuous)

2. Mixing mode (poor, perfect mixing, plug flow, immobilised biomass)

3. Configuration (single stage, multi-stage, recycle etc.)

4. Operating conditions:

e.g. Loading rate (kg/m^3 day)
Temperature
Pressure etc.

5. Detailed design considerations:

e.g floating or fixed dome
materials of construction
method of mixing
internal arrangement
etc. etc.

Typical operating conditions for a single stirred digester are summarised in figure 11, but it must be emphasised that the efficiency and characteristics can change significantly with some of these parameters. For example, figure 12 shows the variation in gas yield per kg. total solids added as a function of retention time and substrate concentration. The lower limit on retention time is normally imposed by the low growth rate of the methanogens or a change of rate controlling step to hydrolysis. Mixing has a significant influence: whilst most intermittently-stirred fermenters produce around 0.5 digester volumes of gas per day, a really well-stirred, continuously fed digester may achieve up to around 4 volumes/day. however, this latter figure does appear to be the upper limit of what is possible with well-stirred digesters: any further improvements has to be sought by significant process changes. It is noteworthy that operation at long retention times is not necessarily the best strategy; paper 1 outlines some simple features of optimisation policy relevant to this question. Figure 13 also illustrates some other features of digester performance.

We know comparatively little about the relative merits from an efficiency point of view of stirred versus plug flow digesters (see paper 2). However, Table 1 in paper 2 shows that plug flow digesters may be at least as efficient as conventional fermenters as well as having other advantages.

The rationale for multi-stage processing and recycling (see paper 2) follows from the microbiological and kinetic information discussed above. Improved performance will result from increased bacterial concentrations ('x' in the rate equation above), which can be achieved in a variety of ways, as discussed in the previous paper. Multi-stage operation may also be helpful from a kinetic point of view, especially when it becomes advantageous to separate out the acid-forming and methane-forming stages of the process (see Tables 2 and 3, paper 2).

Finally, Table 1 summarises some of the key features of the design alternatives described in these papers.

Detailed design

It is much more difficult to generalise about the influence of detailed design points and operating efficiencies or process economics. From an efficiency point of view the main determinant is likely to be the basic process design: detailed design will significantly affect how close one can approach the ideal characteristics in practice. Detailed design will also, of course, have significant effects on operability, reliability and costs and we look forward to learning from this workshop what the most promising lines of development and adaptation are within the region.

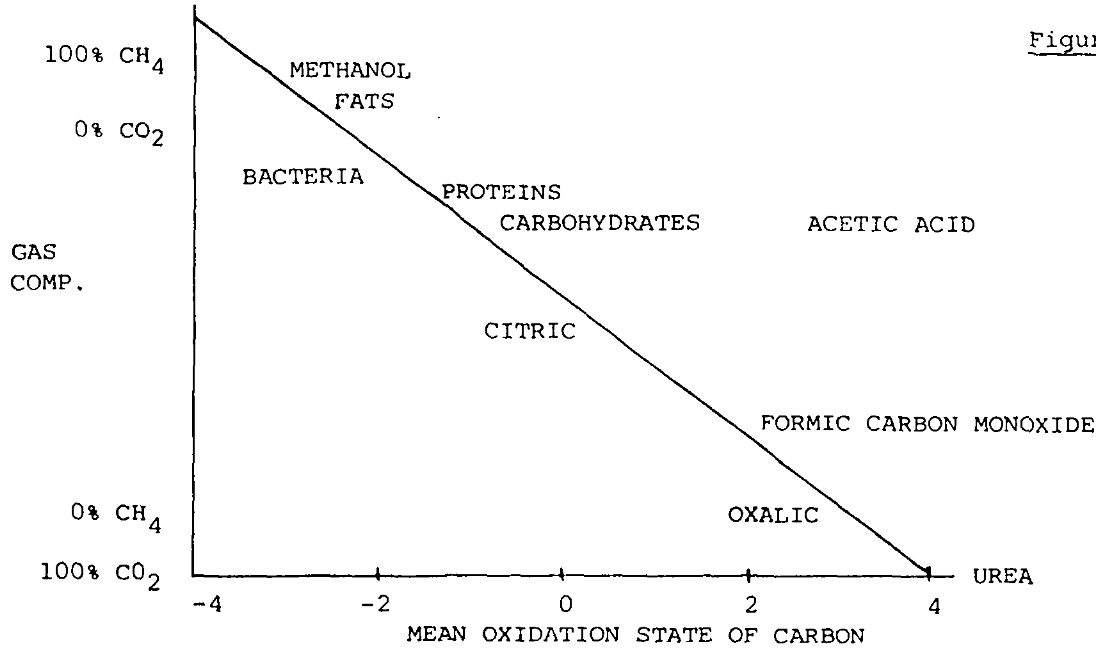


Figure 1

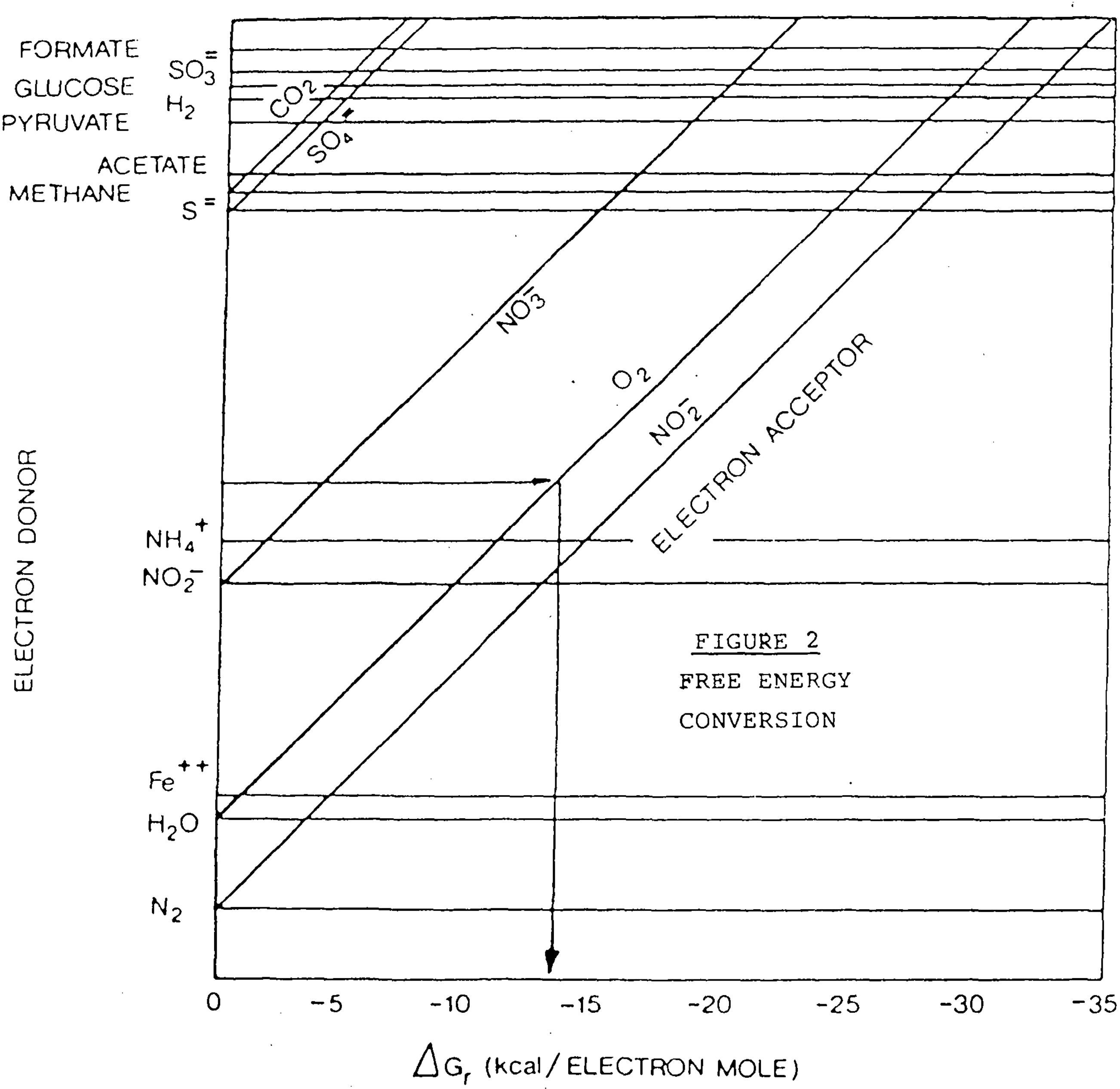


FIGURE 2

FREE ENERGY CONVERSION

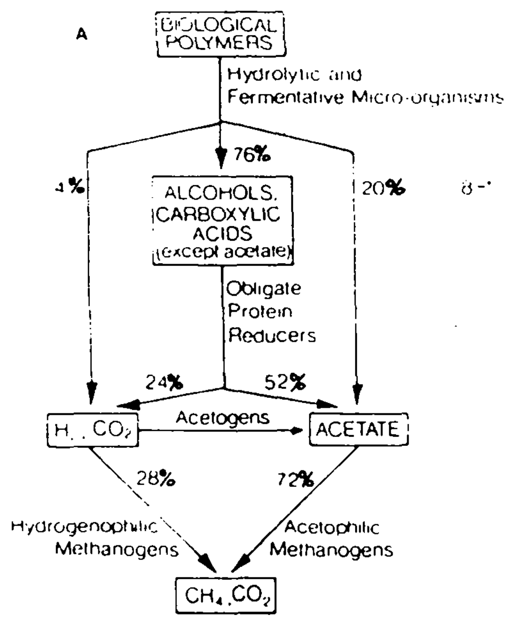


FIGURE 3 b

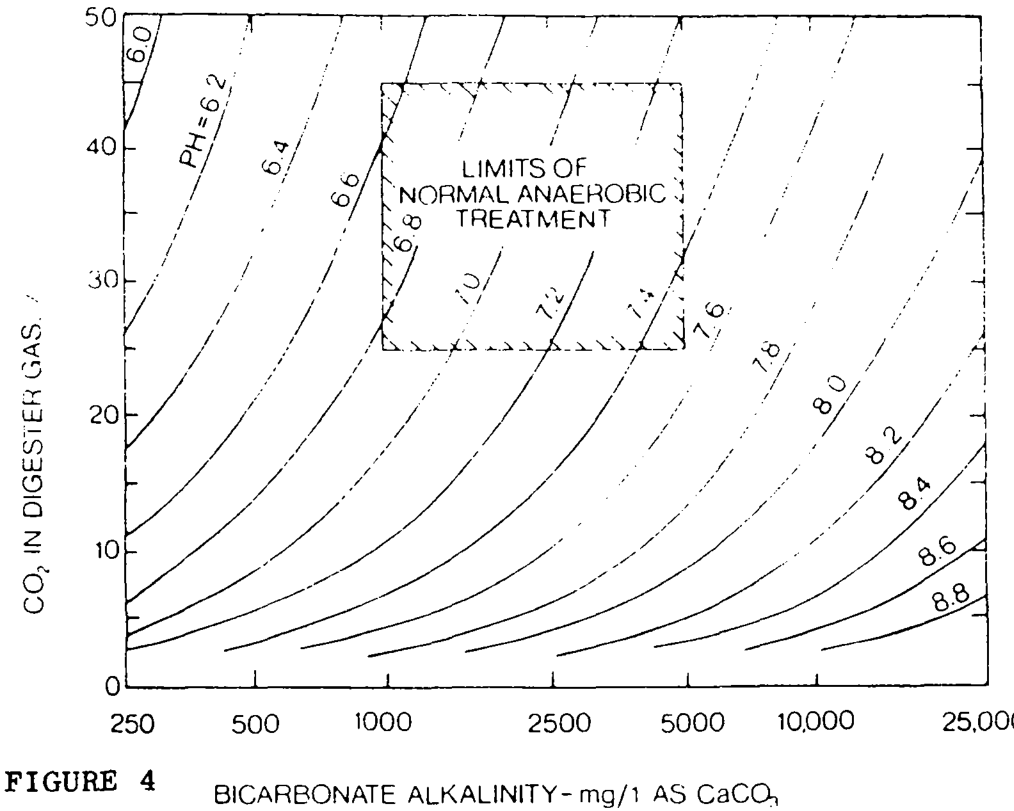


FIGURE 4

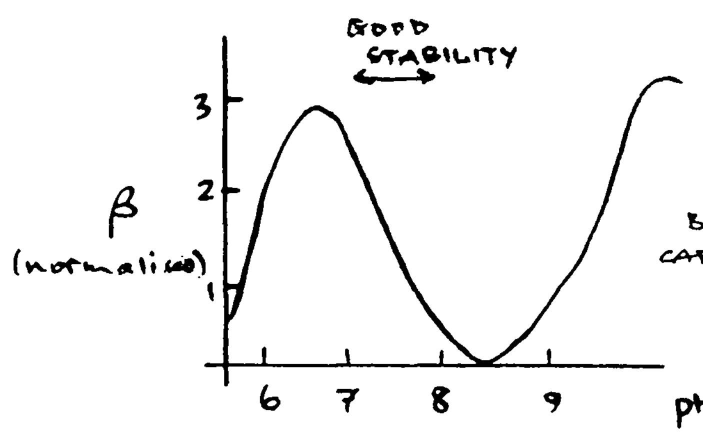
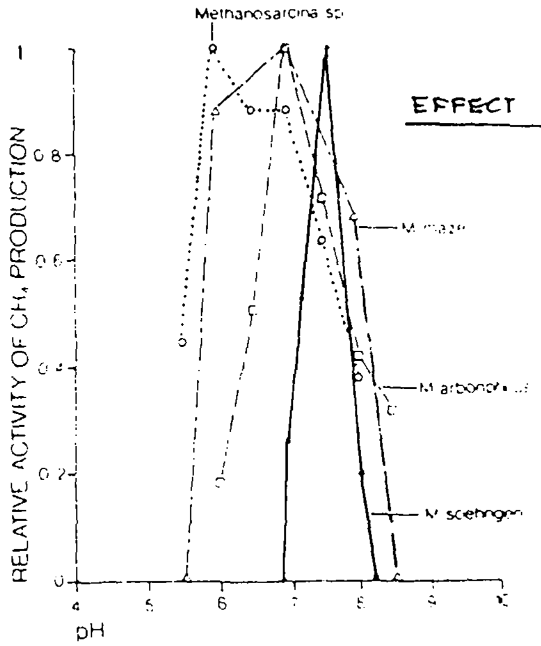


FIGURE 5

BUFFER CAPACITY

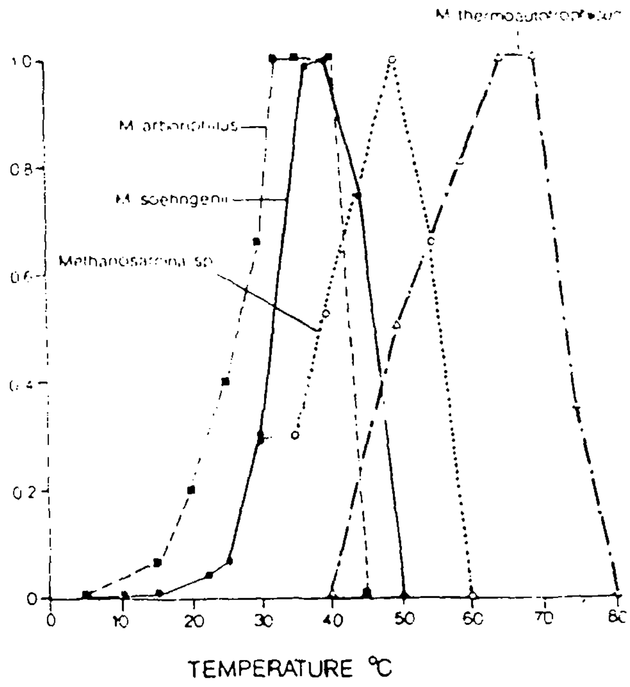
EFFECT OF pH

FIGURE 6



Proton activity relationship for methanogenesis

FIGURE 7



The effect of temperature on Methanogens.

TEMPERATURE

FIGURE 8

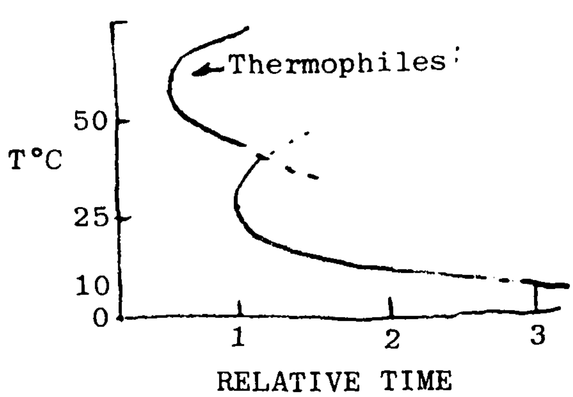


Figure 9

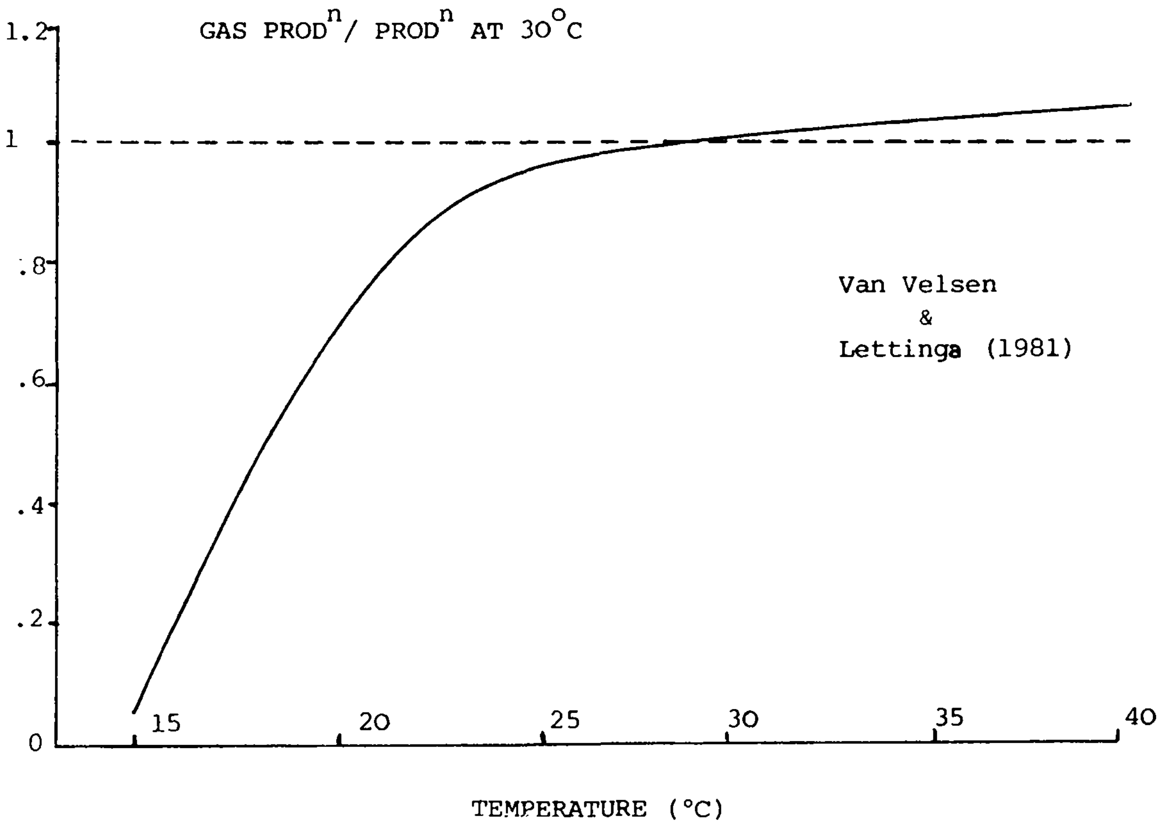


Figure 10

C/N REQUIREMENTS

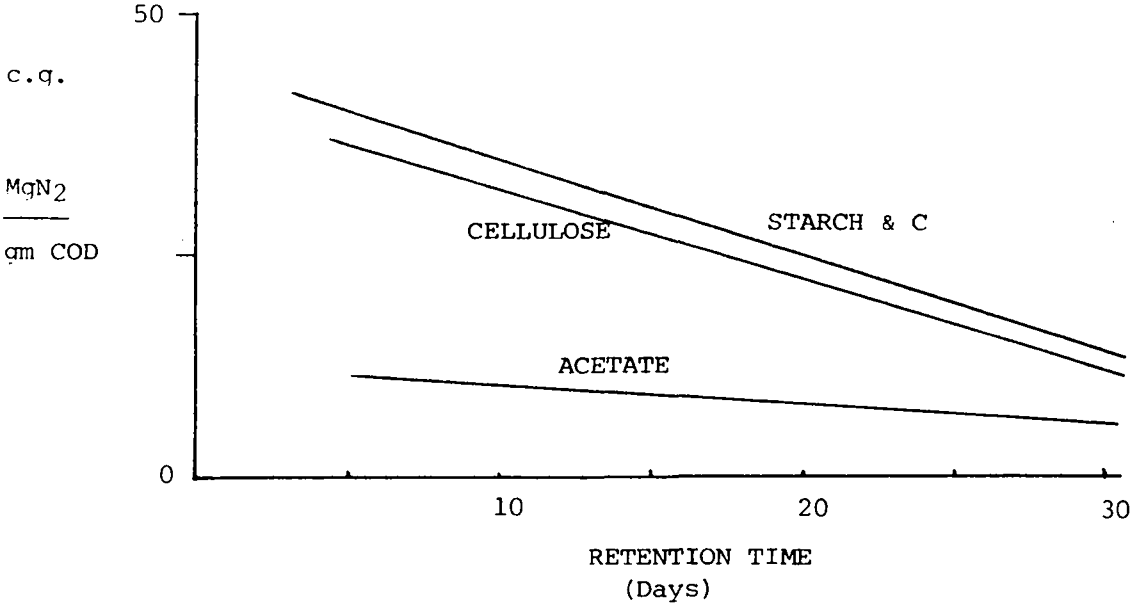


Figure 11

TYPICAL STIRRED DIGESTER

CONCENTRATION	30 - 100 (TS) kg/m^3
RESIDENCE TIMES	10 - 25 DAYS
LOADING RATE	2 - 6 kg TS/m^3 day
PRODUCTION	0.5 - 1 m^3 gas/m^3 day
EFFICIENCY	0.3 - 0.5 VS DESTROYED
"	$0.2m^3$ gas/kg VS ADDED

Figure 12

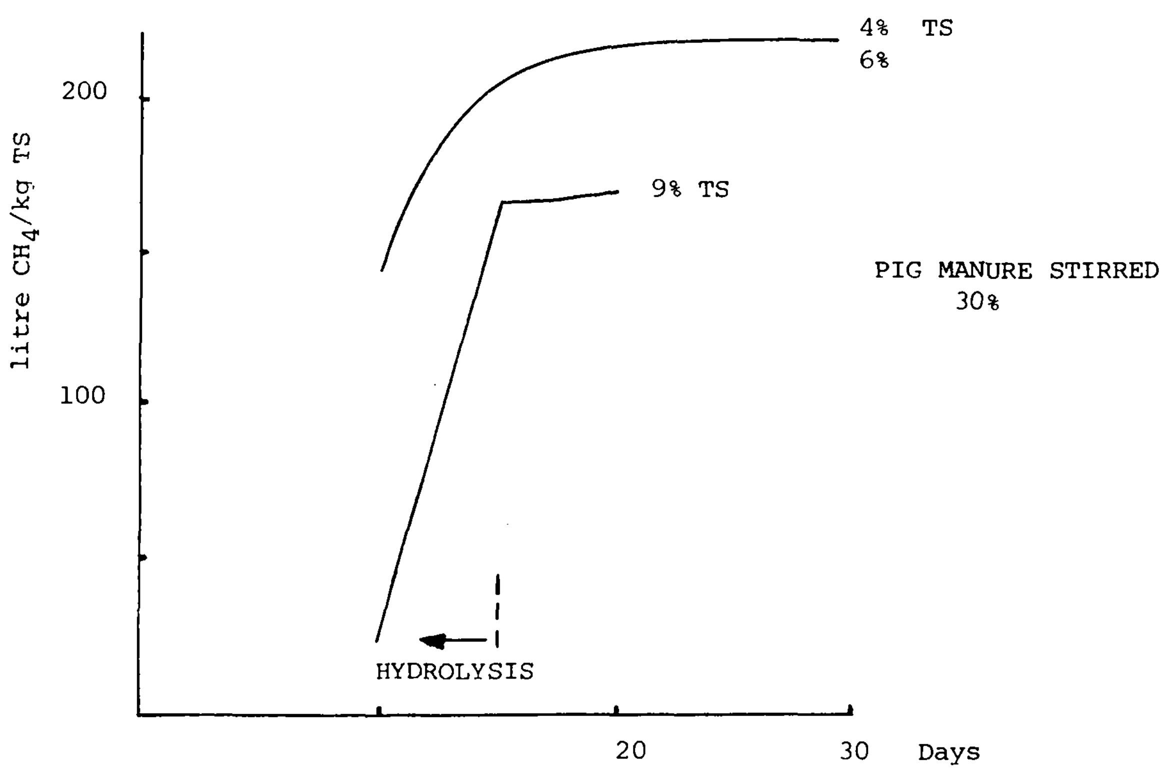
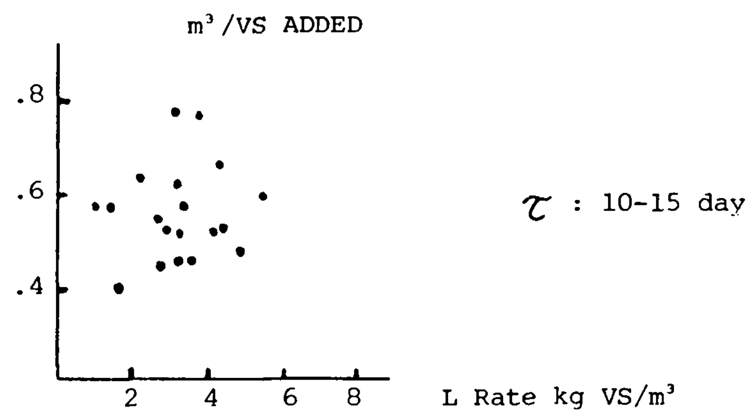
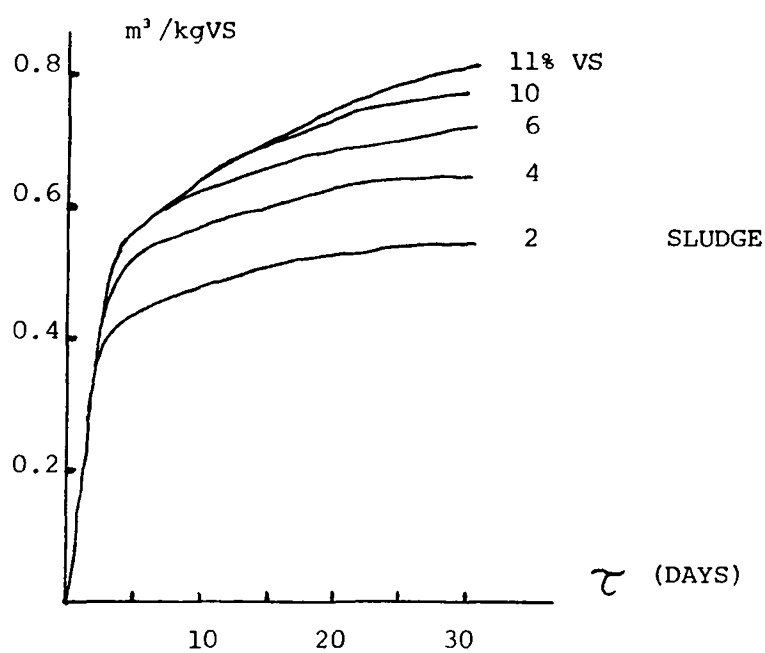


Figure 13



m³/VS ADDED
.8
.6
.4
2
4
6
8
L Rate kg VS/m³
τ : 10-15 day



m³/kgVS
0.8
0.6
0.4
0.2
11% VS
10
6
4
2
SLUDGE
τ (DAYS)
10
20
30

TABLE 1: SUMMARY OF DIGESTER DESIGNS

Option	Stage of Development	Advantages	Disadvantages	Installed Capital Cost $/m^3$	Applications
1. Batch (low solids)	Advanced - a number of operating units in DC	1. Simple construction 2. Easy operation, with low skill requirement	1. Varying gas production with time 2. Gas storage required		1. Manures mixed with bedding 2. Animal manures 3. Aquatic plants
2. Batch (high residues solids) - "dry fermentation"	Pilot plant studies, some operating units in DC	1. Simple construction 2. Easy operation, with low skill requirement 3. Reduced water requirements 4. Digest ag. residues with no pretreatment 5. Relatively high gas yields	1. Varying gas production with time 2. Gas storage required		1. Agricultural 2. Aquatic plants 3. Animal manures

SUMMARY OF DIGESTER DESIGNS (cont'd)

Option	Stage of Development	Advantages	Disadvantages	Installed Capital Cost $\$/m^3$	Applications
3. Fixed dome (Chinese)	Advanced - considerable data on operation and economics Many units throughout the world	1. Simple construction - with readily available materials - low cost 2. Relatively high pressure gas supply 3. Easy to insulate by constructing below ground	1. High structural strength required in construction 2. High quality workmanship to make gas tight 3. Low concentration feeds, hence low gas yields 4. Varying liquid levels 5. Scum control difficult	7 (simple) 13 (cast concrete)	1. Animal manures 2. Nightsoil 3. Mixtures of above with ag. residues 4. Aquatic plants
4. Floating cover cover (Indian)	Advanced - considerable data available on operation and economics. Many units throughout the world	1. Gas supply constant and at stable pressure 2. Gas yields higher than with fixed dome 3. Easy to control scum formation 4. Low structural strength of fixed dome 5. Amenable to passive solar heating	1. Higher total cost/m^3 due to floating cover 2. High heat losses due to cover 3. Short working life of gas holder	60-100	1. Animal manures 2. Nightsoil 3. Some fraction of ag. residues 4. Aquatic plants

SUMMARY OF DIGESTER DESIGNS (cont'd)

Option	Stage of Development	Advantages	Disadvantages	Installed Capital Cost $\$/m^3$	Applications
5. Bag (Taiwan)	Relatively advanced - considerable experience in Taiwan, other units in China, Latin American, Fiji, Korea	1. Low cost 2. Simple transport and installation 3. Amenable to simple passive solar heating	1. Thin membrane vulnerable to puncture 2. Low gas delivery pressure	8-30	1. Animal manures 2. Nightsoil 3. Aquatic plants 4. Some fraction of ag. residues
6. Plug flow	Laboratory and pilot studies - a few units in DC	1. High solids loading possible with high efficiencies 2. High gas yields 3. Relatively simple construction 4. Relatively easy to control scum layer 5. Amenable to passive solar heating	1. Low gas delivery pressure 2. Relatively high land requirement of fixed and floating dome	50-80	1. Animal manures 2. Nightsoil 3. Acquatic plants 4. High fraction of ag. residues

SUMMARY OF DIGESTER DESIGNS (cont'd)

Option	Stage of Development	Advantages	Disadvantages	Installed Capital Cost $\$/m^3$	Applications
7. Filter	Laboratory and pilot plant studies relatively few scale units, and none in DC	1. Low 0 possible: small reactor volumes 2. High loading rates: high gas yields 3. Temperature operation has minimal effect on yields 4. Simple construction with readily available materials 5. High process stability	1. Feed must be low in TS 2. Gas storage required		1. Soluble (2% TS) wastes ranging from low (COD 480 mg/L) to high strength (70,000 mg/L)
8. ABR	Laboratory studies	1. Low 0 possible: small reactor volumes 2. High loading rates: high gas yields 3. Simple construction (e.g. modified septic tank) 4. High hydraulic stability 5. Capable of treating partially insoluble wastes	1. Gas storage required		Predominantly soluble wastes ranging from low (480 mg/L COD) to medium strength (2000 mg/L COD)

Paper 4: Objectives, Testing and Evaluation of Biogas Systems, by Dr L Pyle

The main purpose of the meeting is to arrive at an agreed framework and method for testing and evaluating biogas systems. The main requirements of any methodology must be to ensure:

1. That results are meaningful;

2. That results are reliable and the errors and inaccuracies are quantifiable,

3. That results from different tests and from different locations are comparable with each other and with reference data in the literature.

Before outlining some of the ways in which these requirements may be met, it is necessary to consider the objectives of any programme.

Objectives of biogas research and developments

Testing and evaluation may cover technical and/or economic and related issues. These should be clarified and distinguished.

They may cover parts of the system (e.g. the digester itself) or the whole technical system. Here a number of questions should be asked

1. Is the work necessary and why? What is being studied that is not available?

2. If the whole system is being studied:

   (a) What are the objectives of the system and how does this affect the testing programme?

   (b) Have/can individual system components (e.g. digester, heating system, burner, engine) been tested independently. If not, why not?

3. Finally, what are the main objectives of the study, what particular features are of importance to the testing programme, what are the independent variables or parameters in the study and which are the dependent variables you would like to monitor?

Give the objectives, independent and dependent variables, then one should ask how can these parameters be measured (if at all) and at what cost, how is the testing programme to be run and, finally, how are the results to be assessed, evaluated and reported?

1. Technical measurements

The detailed methods of measurement will be discussed at the meeting. The following outlines the main independent and dependent variables.

Key Independent Variables

Apart from the design configuration and details, the following variables affect digester performance and should, where possible, be measured. They should not be changed <u>during</u> the course of a test:

1. <u>Feed:</u>

(a) <u>Substrate:</u> Composition

Quantity and frequency of feeding
Dry matter (%)

Size (if vegetable matter included)

<u>plus:</u> (if practicable)

volatile solids

B.O.D. and C.O.D.

elemental composition (C,H,N)

(b) <u>Water:</u> Quantity

Temperature (at inlet)

2. <u>Operating Conditions:</u>

Temperature

Retention time

Loading rate (i.e. kg solid/m^3 day)

Mixing (method, frequency)

pH (if controlled independently)

<u>Dependent (measured) variables</u>

The following variables are needed to evaluate digester performance:

Gas production rate

Gas composition (when practicable)

Solids content of slurry

plus (when practicable):

pH

volatile solids

B.O.D.

C.O.D.

Elemental composition of slurry

Engine conditions (where practicable):

Gas feed rate	)
Diesel (liquid fuel) feed rate	) Hold steady under test conditions
Air rate	)
Load	)

Rating

Length of test

Operating temperature

Cooling rate

Monitoring Procedure

The test procedure and results are only meaningful if the digester conditions are clearly defined and, for continuous digesters, if conditions are held constant during the period of the test, and for a period to the test. Any variations in key parameters (temperature, gas rate, pH, etc.) during the test must be recorded. For convenience the time scale adopted is the retention time of the digester (= V/Flow rate of slurry).

No test should commence within ½ retention time of significant changes in flow rate, loading rate, substrate material (composition, temperature). Preferably, retention time should be left constant between tests but this will often be impractical.

A test should preferably be carried out over several retention times; again this will normally be impractical. It is suggested that each test be carried out over a minimum of ½ x retention time with daily (or more frequent) monitoring of key parameters and variables.

2. Technical Evaluation

The earlier papers and the appendix to this paper summarise a range of technical features associated with biogas system performance.

The objects of a testing programme should include:

1. a comparison of the actual performance against established or theoretical reference levels. This will usually include calculation of gas yields per unit volume, per kg feed, under defined conditions;

2. a comparison of the performance of the system with different key variables (retention times etc.) - preferably varied at a time or at least in a planned experimental matrix or with design modifications at constant values of the independent parameters.

It is recommended that, as a matter of routine, certain checks be made, especially on the material and energy balances.

Some typical results will be used as the basis for an evaluation exercise during the workshop.

3. Economic Evaluation

The need to improve the economics of biogas plants is a key objective of R & D programmes. The economies of scale associated with biogas plants and the relatively large investments called for have often, in the absence of clearly articulated credit and community-based actions, led to the more or less successful implementation of biogas plants by the richer farmers, with the poor untouched or even impoverished due to the secondary effects of the technology. The higher capital cost in relation to rural incomes is a more significant part of this problem.

Some of the major economic issues that need to be faced include the following:

1. Who pays? What price? What credit?

2. Given the economies of scale, what are the relative benefits of individual versus community scale plants?

3. Valuing and paying for inputs, slurry gas - how are these priced? Is the analysis carried out in financial, economic or social terms?

4. There is a great need for reliable data and realistic assessment, including all costs, financial and social, of proposed developments, including a proper appraisal of the local needs and people's ability to pay.

5. The requirement for clearly articulated research programmes aimed to reduce capital and operating costs - by conserving scarce resources, is absolutely fundamental. As the two studies summarised below show the key element in the biogas system cost is invariably the capital cost of the digester. Moreover, the value of the gas <u>alone</u> is often not enough to make the process viable.

These points and some methodological issues are illustrated by two Indian studies.

K S Parikh (1976) concluded that family-sized biogas plants have "a gross return of 14-18 per cent purely in financial terms ... (and) from a social benefit/cost point of view, the plants are even more attractive". Bhatia (1977) concludes "the present estimates of benefits and costs do not indicate that investment in biogas units is economic from the viewpoint of society".

Both these studies are based on the Khadi and Village Industries Commission (KVIC) 2m^3 of gas per day plant; as the following table shows, Parikh shows substantial benefits, and Bhatia substantial losses from the plant. This is more difficult to explain than the bare figures suggest, for Bhatia has used shadow prices and Parikh market prices. In most cases, the shadow prices of inputs and outputs decrease the market values of costs, and in the case of the slurry increase the value of benefits. However, the biogas benefits must have been reduced by the use of shadow price. With capital costs, only the holder (by Rs 187) and the pipelines and appliances (by Rs 51) increase as a consequence of 'economic costing', and overall these shadow prices give an investment cost of Rs 2830 in present value terms compared to a market price investment cost of Rs 4738 (including compost pit construction of Rs 1380 and land at Rs 1026). In the notes to the table, the assumptions are explained, and attention is drawn to the principal points of difference.

The table shows only one reference result from Bhatia. In fact, Bhatia provides a comprehensive sensitivity study. His selection of the five parameters for alternative valuation (gas end-use, value of manure, plant investment cost, calorific value of alternative fuels and plant size) reflects the main uncertainties. Bhatia also provides convincing arguments for not assuming any additional fertilizer value for digested slurry. In his use of shadow prices he has put premiums on steel and cement (20%) on foreign exchange (30%) for fertilisers and kerosene, and has used a zero shadow wage rate for unskilled labour.

Table : Alternative Evaluations of the KVIC 2 Cubic Metre Biogas Plant

	Parikh	Bhatia
A. Investment (est. Rs)	2332	2830
B. Annual Operating Costs	50	59
C. Present value of Lifetime Operating Costs	426	496
D. N. content 1 kg digested dung / N. content 1 kg composted dung	1.92	1
E. Effective Cooking Heat (Kcal.) per cubic foot biogas	82	81/70
F. Use of Gas (Cubic feet daily):		
Cooking for 5	59.5	50
Lighting	4.5 (1 lamp x 1 hr) 1	20 (2 lamps x 2 hrs daily)
G. Imputed Value of Biogas per effective Kilocalorie ($X10^3$) in cooking (Rs)	0.16	0.09
H. Value of N. (Rs per kg.)	4.5	3.24
I. Gross Annual Benefits	348/414	290
J. Net Present Value (Rs)	205/767	-860
K. Benefit - Cost Ratios	1.09/1.33	0.69

N.B.(i) The two values given by Parikh in rows I, J and K depend upon whether dung was previously burnt (348, 205, 1.09) or composted (414, 767, 1.33).

(ii) Following Bhatia we have used a cumulative discount factor of 8.51349 (= 20 year life at 10% discount rate). Parikh compares the annual return from a biogas plant with two alternatives, and does not look at lifetime returns to investment in a plant.

(iii) For explanatory notes on differences between Parikh and Bhatia see next page.

Notes

The Table illustrates how different assumptions can affect the economic evaluation of biogas plants. Out of 7 major parameters (A, B/C, D, E, F, G and H) in only 1 (E) is the same value assumed, and in only 1 (F) does Bhatia make a more favourable assumption than Parikh. The bases for calculation are as follows:

A. The value of investment costs includes pipeline and appliances. Bhatia's shadow prices have reduced the cost of unskilled labour to zero and put a 20% premium on steel and cement (approximately 40% of costs).

B. Rs 50 is the agreed cost of painting. Rs 9 is half the cost of the hose pipe which is replaced every two years according to Bhatia. Bhatia assigns a zero shadow price to labour and water for plant operation. Parikh does not mention these costs.

C. Discount factor of 8.51349 (x B).

D. Parikh assumes 1 kg of dry dung gives 0.50 kg of fertilizer with 1.5% Nitrogen when composted and 0.72 kg of fertilizer with 2.0% Nitrogen when digested. This yields an additional 52.6 kgs of N annually from 3.55 tons of (dry) dung fed into the plant. Bhatia assumes there is no Nitrogen in his reference analysis but does give illustrations of b-c ratios where the fertilizer value of slurry has been estimated to increase by 2.3 times compared to compost; i.e. N from compost per 1 kg dry dung = 5 x 1% and from slurry = .73 x 1.6%.

E. Both are based on 135 kcals per cubic foot of biogas and 60% burner efficiency.

F. Bhatia's estimate is higher because he assumes a 70 cubic foot (2 cubic metre) output, whereas Parikh assumes the plant only produced 64 cubic feet. This difference reflects a confusion in technical knowledge, but also shows how important the other differences are.

G. Parikh uses the market price of dung cakes and Bhatia the shadow price of soft coke to calculate biogas value.

H. Bhatia's nitrogen value is based upon a cif price of urea (50% N) of $135 per tonne with a 30% foreign exchange premium and a Rs 300 per tonne transport cost. Parikh's nitrogen value is assumed, without any explanation, to be Rs 4.5 per kg.

Why use the opportunity cost of soft coke to value the gas? The use of kerosene, for example, as the replacement in cooking would (on his figures) have made the next present value positive in all but four cases, under the assumption that kerosene was the most likely contender to replace biomass. Opponents of biogas could argue convincingly that in fact firewood, crop residues, and perhaps dung would continue for the foreseeable future to be the source of cooking fuel for most villagers. The market biomass replacement costs of biogas has a lower value than kerosene and, as Moulik et al (1978) demonstrate, at very low costs of firewood investment in biogas incurs major losses.

Parikh suggested that where dung was burnt, the prospects of biogas were best. He compares biogas with wood, petrol and diesel, as the cheapest alternatives and also argues that other fuel possibilities, such as electricity, kerosene and coal, are too expensive. Like Bhatia he assumes a zero shadow wage, and looks at the variability in effective heat according to the volume of biogas, methane content and end use efficiency. He argues that slurry gives more nitrogen, and consequently more food than composting. This is based on the all-India average figure of 36% of the dung available being used as fuel. The dung available for manure will increase when a biogas plant is used because the 36% previously burnt will now be available for manure. He also draws attention, as did Bhatia, to the non-nitrogen benefits in using slurry for soil improvement, and to the social and economic benefits of improved health through use of smokeless fuels.

In the Table above he used only purchased dung cakes, instead of wood and dung cakes, as the traditional fuel replaced by gas. Secondly, he assumed that the quality of fertilizer in the slurry was better than than from composted manure. The consequence of the first assumption was that households that now burnt dung could save Rs 298 per year by investing in a biogas unit, whereas households that composted dung would receive a benefit of Rs 364 per annum. The second change was to give the digested slurry an assumed nitrogen value of 2 per cent of the dry weight of slurry compared with 1.5 per cent in dung, and to assume a larger quantity of fertilizer (0.72 to 0.5 kgs) as slurry from 1 kg of dry dung. As a consequence the economics of biogas units improve considerably.

In summary, the major differences between Parikh and Bhatia are due to their choice of fuels with which to measure the replacement of biogas in cooking, and the valuation of the fertilizer content in digester slurry and composted manure. There are three general uncertainties that affect the potential of small-scale biogas plants. First, how does investment in biogas compare with alternative village level investments, especially those which generate cash, how are biogas investment decisions related to variations in the price of other fuels, including of subsidies on electricity, kerosene, diesel and bottled gas? In most countries these fuels are subsidised, and this clearly affects the financial viability of biogas. In social cost-benefit analysis these subsidies are ignored, but in financial analysis the lower price of other fuels makes biogas a less attractive option. Finally, how do the economics appear when non-dung organic materials, (e.g. crop residues) are used? Dung may not be the lowest cost source of organic material, but there is obviously a trade-off between the prices of various feedstocks and their ability to produce biogas.

Paper 4: Appendix: Some Features of Biogas Production, by Dr L Pyle

1. The range of organic matter which can be used for methane generation is outlined in Table 1.

TABLE 1: ORGANIC MATTER WITH POTENTIAL FOR METHANE GENERATION

Crop Wastes	Sugar cane trash, weeds, corn and related crop stubble, straw, spoiled fodder
Wastes of Animal Origin	Cattle-shed wastes (dung, urine, litter), poultry litter, sheep and goat droppings, slaughter house wastes (blood, meat), fishery wastes, leather, wool wastes
Wastes of Human Origin	Faeces, urine, refuse
By-products and Wastes from Agriculture-Based Industries	Oil cakes, bagasse, rice bran, tobacco wastes and seeds, wastes from fruit and vegetable processing, press-mud from sugar factories, tea waste, cotton dust from textile industries
Forest Litter	Twigs, bark, branches, leaves
Wastes from Aquatic Growth	Marine algae, seaweeds, water hyacinths

Source: NAS (1977)

1. The most common source of substrate is animal manures. Details of average quantities and compositions are quoted in 'Biogas Technology in the Third World' (B.T.T.W.) p.23 and additional details are given in Tables 2 and 3.

TABLE 2: MANURE PRODUCTION AND COMPOSITION[a]

	Daily Production				Composition		
	Per 1,000-lb live animal		Per 500-kg live animal		Volatile solids[b]	Nitrogen	Phosphorus
Animal	Volume (ft^3)	Wet Weight (lb)	Volume (m^3)	Wet Weight (kg)	Percent of Wet Weight		
Dairy cattle	1.33	76.9	0.038	38.5	7.98	0.38	0.10
Beef cattle	1.33	83.3	0.038	41.7	9.33	0.70	0.20
Swine	1.00	56.7	0.028	28.4	7.02	0.83	0.47
Sheep	0.70	40.0	0.020	20.0	21.5	1.00	0.30
Poultry	1.00	52.5	0.028	31.3	16.8	1.20	1.20
Horses	0.90	56.0	0.025	28.0	14.3	0.86	0.13

[a] Adapted from Fogg (1971).