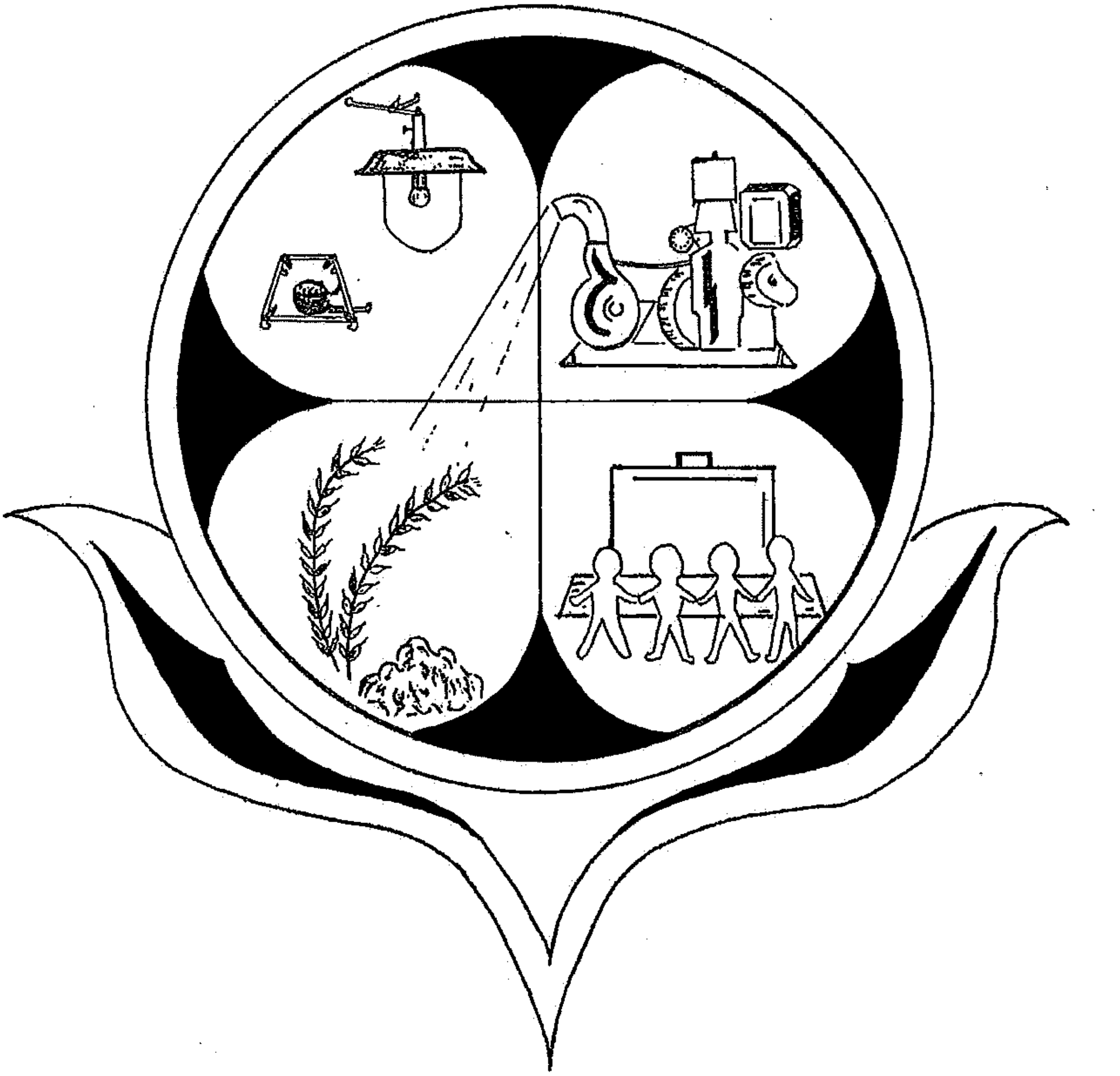
BIOGAS

Challenges And Experience From Nepal

Vol. II



United Mission To Nepal

BIOGAS

CHALLENGES AND EXPERIENCE FROM NEPAL
VOL. II

Authors:

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UNITED MISSION TO NEPAL

Cover design: by Mamie Lau-Wong

ABOUT THE AUTHORS

Andrew Bulmer, BA, General Arts from Durham University, U.K. After his studies he worked for 4 years in Orissa, India, with the village Reconstruction Organization which aimed to assist village communities after being devastated by cyclones. Since then he has been in Nepal, living largely in one community for over 4 years and involved in general development activities there, as well as being specifically concerned with assessing the effectiveness of community Biogas Systems.

John Finlay, C. Eng., MI Prod E., worked in the engineering industry in U.K. for 17 years in various positions including value analysis, and organization and method study. He has been working in Biogas research in the Development and Consulting Services since 1974, and has presented papers on this subject in various countries. He has also compiled and technically edited the United Nations book 'Guidebook on Biogas Development'. His particular concern has been reliable cattle dung biogas plants and accessories suitable for village use which are low cost but also efficient.

David Fulford, B. Sc., Physics from Bristol University, U.K. In previous assignments, he has worked as scientific officer at RAP, Farborough, researching on fuel system for aircraft. He was also research assistant at the University of Reading, where his interests were in the Humphrey Pump and development of appropriate technology for developing countries. After joining the Biogas programme at the Development and Consulting Services, he researches on the wet type gas meter and the Humphrey Pump. He has published various papers and reports in this field.

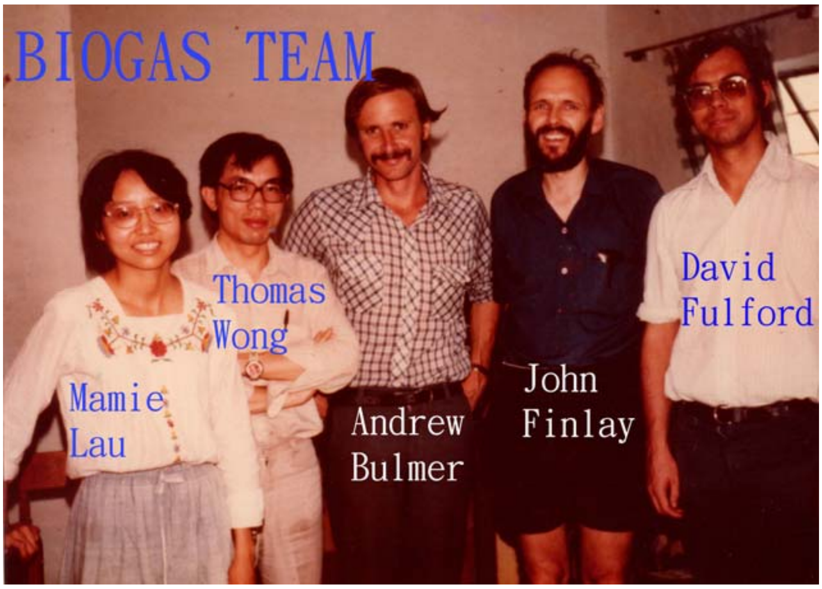
Mamie M. Lau-Wong, B. Sc., Ph.D., received her doctorate in Chemical Engineering at Cornell University, U.S.A., where she specialized in culturing aerobic and anaerobic micro-organisms for industrial purposes, and computer simulation of fermentation processes in living ruminants. As consultant to the Development and Consulting Services of the United Mission to Nepal, she has been engaged in Biogas research and training, presented papers in Biogas Conferences, and published various papers in this field. She is also involved in the production and field testing of nitrogen-fixing bacterial fertilizer for cereal crops.

Preface to the 2013 edition of
Biogas – Challenges and Experience from Nepal

With treasured memories, I embarked on preparing an electronic version (2013 edition) of this two-volume book as a tribute to two distinguished persons: Mr. John Finlay and Dr. Thomas KH Wong, who had served on the Biogas Team of the Development and Consulting Services (DCS) of the United Mission to Nepal (UMN).

Right after our marriage, Thomas and I set off for Nepal in January 1980. Our adventure began with an intensive and arduous 6-month study of the Nepali language that climaxed with the Village Stay. We soon joined the Biogas Team in Butwal in the southern Terai of Nepal. It comprised of five members, who enriched the Team with their diversified expertise and experience.

Photo taken at the DCS office in Butwal



The team leader John Finlay, being a ‘practical’ man, specialized in improving the building and design of biogas plants, gas stoves and lamps. Corrosion and leaking of the gas drum was a major problem of the Indian type design; whereas the Chinese dome design required good masonry skill that was hard to find. When we joined the team, John had started to experiment on the ‘plug -flow’ design (introduced by Prof. Jewell of Cornell University where I did my PhD), and developed it into what John called the ‘Tunnel Plant’, which was simpler to build and easier to maintain.

Dr. David Fulford, another senior member on the team, often impressed me with his burst of creative ideas and his passion for the Humphrey Pump. I still recall the occasions when we crossed streams and valleys on his motor bike to do trouble-shooting for biogas plants in the hills and villages.

Then there was Mr. Andrew Bulmer, whom I saw rarely as he stayed at the Madhubasa village for developing a community biogas plant there. Being patient and courteous, Andrew was ideal for this job.

Now Thomas, with his expertise in finance and operational management, served as consultant and director on the Board of the Gobar Gas tatha Krishi Yantra Bikash Pvt. Company (in short, the Gobar Gas Company), set up jointly by the UMN and the Nepali Government back in 1977. The capital costs of the plants were subsidized by the Agricultural Development Bank of Nepal with grants from agencies like UNDP. Thomas later became the Assistant Economic Development Secretary of the UMN.

Gobar Gas Company staff

Meanwhile, after setting up a research laboratory at the Gobar Gas Company, I recruited and trained up the Research Scientist, Mr. Govinda Devkota. As gas production drops with surrounding temperature, research areas have included methods and devices to enhance gas production in cold climates. I also performed economic and financial analysis of biogas systems, and compared them for different scenarios: cooking, lighting, as well as income generating activities such as using biogas for milling, hulling and irrigation.

By 1987, over 2000 plants had been built by the Gobar Gas Company. The seeds that our Team planted flourished, as other biogas companies and international projects have sprung up since then. By 2011, some 250,000 plants had been installed, benefiting over a million people across the country, and saving a colossal amount of fuel-wood and trees. Our pioneering efforts had helped to spark off the biogas industry in Nepal, and left a legacy that made biogas technology viable and accessible to the Nepali people, up to this very day.

This 2-volume manuscript, first published in 1985, is a comprehensive collection and record of the work, ideas, experience and drawings of the UMN Biogas Team. I hope the data, designs and methodologies will be useful to others working in this field.

January 2013

Dr. Mamie Lau-Wong
Co-author and currently Principal Officer
Environmental Protection Dept. of the Hong Kong Government

PREFACE

For the past 30 years, the United Mission to Nepal has sought to meet the basic needs of people in Nepal, related to the areas of medical, educational and economic development. Its personnel have come from many different lands with various qualifications and skills, working toward the enablement of people by offering opportunity and training. There has been a mutual learning and sharing experience, resulting in projects and programmes which emphasise service towards others and the equitable sharing of benefits among the less advantaged and privileged.

Biogas is one area of the development and sharing of appropriate technology which is geared to making renewable energy resources available to those who need them. For the past 7 years, the Development and Consulting Services of UMN, at Butwal, has assigned and supervised the research and development of improved biogas plants and appliances, striving to make this equipment more efficient, effective and economical. Design work and production of biogas plants and appliances have been closely monitored by DCS engineers and technicians in the laboratory and workshops, as well as in the field. Testing of the performance of installed biogas plants and related equipment has been oriented to the customers on the farms of Nepal and it has been carefully monitored to ensure not only quality control, but also quality of operation.

This book describes the concept, purposes, implementation, constant revision, and implications of the whole process and its history. Amply illustrated and informative, the book records the achievements (and failures) of a dedicated task force which has persisted in a quest for advancing a technology, despite limited facilities. They have also gone beyond the mere mechanics and technicalities to address the economic, social and management aspects of biogas technology in the context of Nepal as a culture and society seeking development goals.

May I take the opportunity to commend the authors of this material for so ably documenting the biogas story and for the untiring efforts they have made. Commended also are the Tradesmen and Technicians of Nepal, without whose help much would have not been accomplished. This book is a testimonial to a joint venture of Nepali and Expatriate Cooperation at DCS in Butwal.

Kathmandu
January 1984

Al Schlorholtz
Economic Development Secretary
United Mission to Nepal.

ACKNOWLEDGEMENT

Since its commencement in 1974, the biogas research, development, and extension work undertaken at the Development and Consulting Services has been financially supported by three agencies:

The United States Agency for International Development (Grant No. : 498-0251 (357-0139) (OPG) Nepal).

The Mennonite Central Committee, U.S.A., and

The Canadian High Commission Small project Fund.

We would like to express our grateful appreciation to their assistance.

Written materials and diagrams used in Ch, 2, 5, 6, 7 and 9 in Vol. I are partly based on the "Guidebook on Biogas Development" published by the United Nations Economic and Socia1 Commission for Asia and the Pacific. Their permission for the use of the material is gratefully acknowledged.

Besides the four authors, significant research and deve1oplment were accomplished by Mr. Nick Peters. He pioneered in adapting the concrete dome p1ant for Nepal and developing the plastering system for making the dome gas tight.

Last but not least, credit goes to the staff of the Gobar Gas tatha Krishi Yantra Bikash Private Ltd., and to the many other Nepalis and expatriates whose cooperation has contributed considerably to this work.

* * * * * * * * *

Each chapter in this book represents the opinion of its individual author, and it may not necessarily reflect the opinion of the United Mission to Nepal or the other authors.

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BIOGAS RESEARCH AND DEVELOPMENT PUBLICATIONS AND DRAWINGS

Available at the Development and Consulting Services, or the EDB Service Office, United Mission to Nepal, P.O. Box 126, Kathmandu, Nepal.

BOOK AND REPORTS

United Mission to Nepal (1985) Biogas - Challenge and Experience from Nepal Vol. I and II.
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Paper reprints or microfiche available from National Technical Information Pbosf`b

Springfield, Virginia, 22161, U.S.A.
The upper code is required for ordering reports. The lower code is a cost code, PC for paper reprints, and MF for microfiche on film.

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PB83 - 162107 (PC A03/MF A01)	Finlay, J. (1978). Operation and Maintenance of Gobar Gas Plant. Finlay, J. (1980). 500 Cattle Dung plants Built in Nepal in 5 Years: from Design Office to Field and Back Again. Paper presented at International Symposium on Biogas, Microalgae, and Livestock Wastes, Taipei. Finlay, J. (1978). Efficient, Reliable Cattle Dung Gas Plants. Paper presented at UN ESCAP.
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<u>Paper Series</u> :	Lau-Wong, M. (1985). Studies on the Dynamics of Biogas Processes. No. 1 - 5. (1) Modelling of Biogas Processes. (2) Analysis of the Kinetic Data of 3 Plant Designs Installed in Nepal and the Effect of Retention Time & Temperature. (3) The Effect of Slurry Moisture Content. (4) The Effect of Pressure on Gas production. (5) Prediction and Optimization.

DRAWINGS

Floating Steel Drum Design

(Nominal Gas Production) :	100cft	200cft	350cft	500cft
Gas plant construction - straight type	D221/1	D228/0	D241/1	D161/1
Gas plant construction - taper type	D225/0	D220/0	D239/1	D169/1
Gas Holder manufacturing details	D163/0	D164/0	D240/0	D256/1
Concrete floor construction - straight	-	-	-	D168/1
Concrete floor construction - taper type	D124/1	D125/1	-	D170/1
Water (condensate) removing device for gas pipes	D329/1	D329/2	D332/2	D332/2

Drawing No.

Special Night Soil Plant, 350cft

Gas plant construction - straight type	D231/1
Gas holder manufacturing details	D230/0
Night soil plant site layout	2000-142/3

Fixed Concrete Dome Design

(Digester volume, m^3) :	10	15	20	--->50 (not yet tested)
Gas plant	D333/1	D334/1	D336/1	D335/1
concrete dome construction templates	D338/2	all same as 10 m^3		
Agitator (slurry mixer) manufacturing details	D337/2	D337/2	D337/2	-

Extended concrete dome gas plant

Gas plant	2000-143/1
Steel moulds	2000-144/1

Tunnel Design

TP8 (7.7 m^3) gas plant construction, using bricks for walls	D452/1
Gas outlet pipe, manufacturing details	D437/3
Gas outlet pipe, simplified, manufacturing details	2000-119/2
Steel mould for curved roof pieces, manufacturing details :	
Frame 2000-114/2 Details of frame 2000-115/2	Base plate 2000-116/2

Appliances and Accessories

Hand tool for mixing slurry	D354/3
Slurry mixing machine construction	D229/2
Slurry mixing machine manufacturing details 0121/2	D121/2 and D166/2
Gas burner, family size, 0.45 m^3 (16 cft) per hr. :	
manufacturing details	D221/1
castings	D222/2
Gas burner, large size, 0.90 m^3 , plus 0.45 m^3	2000-111/1
Drain cock for condensate removal - galvanized iron pipe (1/2")	D453/3
- cast iron type (1/2")	D459/3
Main gas valve (l/2")	
Gas tap for connecting rubber pipe to burner (1/2")	2000-108/3
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Gas lamp : assembly	2000-113/2
manufacturing details	2000-112/1
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meter box and counter	2000-127/1
counter details	2000-128/4

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'Biogas -- Challenges and Experience from Nepal' comprises two volumes : Vol. I is a practical guide for field workers, whereas Vol. II includes more theory and research work.
The authors of each chapter are listed below.

Cover design: by Mamie Lau-Wong

Volume II

CONTENTS

Chapter 1 THE DEVELOPMENT OF BIOGAS TECHNOLOGY

D. Fulford

Biogas technology has not had a smooth history. While the idea of producing a fuel gas from cattle dung and vegetable wastes has been known since the end of the last century, it was regarded more as a scientific curiosity than of any use. The exception has been during times of war in Europe, when energy from other sources was limited. Otherwise, supplies of oil and electricity were cheap and plentiful, especially in the West, so further work on the development of biogas was considered irrelevant. The few small biogas programmes that did start in Europe, in France, West Germany and Italy, in response to energy problems during and after the Second World War, quickly faded away (van Brakel).

In the 1950s and 1960s, as part of a growing concern for the environment and for conservation on the part of a few enthusiasts who were questioning the fast growth philosophy of the Western nations, biogas again found a place. It became almost a symbol of the new "zero growth" approach to life, as a non-polluting, renewable energy resource, that could free men from their dependence on centralised energy, and its control on people'slives (NAI).

Unfortunately, the enthusiasm of these conservationists for biogas was based on the work of very few practical pioneers, who happened to publicise their results. L. J. Fry had built a plant is South Africa, that used the dung from 1,000 pigs to produce gas to run a 13 HP adapted diesel engine (Fry). Harold Bates, in Britain, used gas from chicken manure to run his car (Bell). The view of biogas was romantic and idealistic, but somewhat impractical.

One place where biogas technology remained a serious interest was at the Indian Agricultural Research Institute at Delhi (Idnani). Research and development work was inspired by a new sewage treatment plant near Bombay, in 1937. The work at IARI inspired Jashbai Patel, as well as others, to design full-scale biogas plants that could be used by farmers. Unfortunately, even this work had its weaknesses : both the early IARI, "Delhi", and Patel, "Gramlaxmi", designs used a counterbalanced gas drum, which was supposed to increase gas production by keeping the gas under negative pressure. This system jammed easily and was potentially dangerous, as air could enter the gas holder and cause an explosive mixture (Singh).

The oil price rises of the early 1970s made the rest of the world begin to take the ideas of the conservationists more seriously, including the use of biogas technology. Unfortunately, they discovered that this "ideal" energy resource suffered from many problems (Pyle). Biogas enthusiasts had not considered the technical and other difficulties in setting up an unfamiliar technology. Early attempts to popularise biogas technology, either through small commercial concerns in the Western world, or through development programmes in the less developed countries, proved less successful than expected. The result of over-selling an idea that does not live up to expectation is disillusionment. Government planners and aid administrators became rather suspicious of biogas technology and were less willing to give it strong support. Even in India, where the biogas programme has usually had good support, there was a period in the late 1960s and early 1970s, when the programme had reduced priority and emphasis. Only in China has the early failures, apparantly, not stopped its enthusiastic adoption by large numbers of people (Thery). This may be changing (Tam).

Despite these initial set-backs, several groups have been prepared to face up to the practical problems of getting this appropriate technology from the stage of being a "good idea" to one in which it has the potential to help people in developing countries. There is an increasing growth in the number of research programmes on biogas technology in different parts of the world, both in developed and developing nations (Bente, ECDC, UNESCO). In India, the programmes in the Khadi and Village Industries Commission, Bombay (Patankar) and in the Planning, Research and Action Division (PRAD), in Lucknow and Ajitmal (Lichtman), have been given a new impetus by the Indian government, and new programmes have started elsewhere (Reddy, TATA). Elsewhere in Asia, Taiwan has a research programme (Chung Po), as does Korea, Japan (Subramanian) and the Philippines (Maramba). The Environmental Sanitation Information Centre of the Aisian Institute of Technology in Thailand has a keen interest (Tam). The United States government has sponsored several research programmes (Jantzen) and efforts are increasing in Britain (Meynell), Germany (BORDA) and other developed countries.

Biogas is now being recognised for what it is : a useful new technology that is still under development, not a magical solution to the energy problems of the world. As this development work progresses, and new discoveries and inventions are made, biogas will have a small, but growing impact on world energy resources, especially in rural areas of developing countries that are not easily served by centralised power supplies, such as electricity.

1.1 Challenges of Biogas Technology

The problems that faced the early attempts to popularise biogas were not so much difficult, as unexpected and complex. Biogas, as a subject of academic study, is very difficult to define clearly, as it includes many different specialist subject areas. It is almost impossible to limit the study of the problems of biogas systems to any one of these areas.

The process by which biogas is made is microbiological as it uses methanogenic bacteria. The biochemistry of anaerobic fermentation is very complex and the details are far from fully understood (Zeikus, Wolfe, Mah). The practical problem of making cheap, but effective biogas plants is one of civil and mechanical engineering. A container must be constructed to hold the slurry of bacteria and feedstocks, and a system devised for catching and storing the biogas, as it is given off. Once biogas is produced, suitable, cheap gas appliances must be designed to use it.

The economics of biogas technology is very important; people will not use a new technology, however good, if it costs more than the alternatives. It also has sociological implications : biogas is called "gobar" gas in Nepal and India as "gobar" is the word for cattle dung. The cow is a holy animal to the Hindu, so gobar is an acceptable source for cooking fuel. Pig dung and human faeces are not acceptable feedstocks for a biogas plant for many Hindus, although the gases produced from them are the same.

Since biogas plants use animal dung and agricultural residues as feedstocks, and produce a fertilizer as well as a fuel gas, it may belong properly, to the subject of agriculture. The main users of the technology are farmers. The use of the effluent of a biogas plant brings in the subjects of soil science and horticulture. In China, where composting of all agricultural residues, including human faeces (night soil), is held in high esteem (FAO, van Buren), the use of biogas plants for producing good compost is more important than the fuel gas produced.

The ogranisation of a biogas programme, both for research and development and extension, has proved difficult (see Volume I, Chapter 13). In India and China, for example, large numbers of biogas plants have been built, but the failure rate has been high. Over 90,000 biogas plants have been built in India (Ellegard). There were reports of about 30% failure rate in a survey conducted in Gujurat state in 1975 (Moulik). The problems of organising larger scale community and institutional plans seem to be even greater. The above study showed that only 6 out of 25 institutional plants, built for groupes such as ashrams, were working, a failure rate of 76%. A major reason for failure quoted was a lack of interest by the concerned heads of the institutions. A much publicised community plant built by PRAD (with money from UNICEF) (PRAD) has run into problems of organisation (Roy), and the people have stopped using it.

When an organisation : a government department or an aid agency, plan to start a biogas programme, they are faced with a set of closely related problems that demand a very wide range of skills and experience to deal with them. A biogas team cannot employ experts to cover all the fields, so those involved in biogas technology must be "generalists", with skills in various field.

1.2 Economic Challenges

The economics of biogas is an area which has received much attention (Pang, Barnett, Prasad, Makhijani etc.). While the running costs of a biogas plant are low, the capital costs per unit of energy produced is fairly high. This is a factor common to most alternative energy technologies, because the energy density in biomass, or wind or sunlight, is much lower than for coal, oil, nuclear energy or even hydropower . The physical dimensions of a plant to extract that energy must be larger per unit of energy produced. Conventional energy plans also rely on economies of scale to extract large amounts of energy in large centralised units. Alternative energy technolgies tend to be diffuse; plants are very small and scattered, and this also increases the capital cost per unit of power produced.

Example 1.1

Approximately 0.33 litres of oil isused to produce 1 kW.hr of electricity, either in a diesel generator or in an oil-fired power station. The same energy requires 667 litres of biogas, from 60 kg of cattle dung or 120 litres of slurry (mixed with water). The biomass occupies 360 times the volume of oil for the same potential energy.

The cost of an oil-fired power station is roughly $1,900 per kiloWatt (1982 prices), for medium scale units (around 5 MW). The capital cost of a similar size of hydropower station is about the same.

A biogas unit, producing 2 cu.m of gas a day costs around $700 (in 1982). If this amount of biogas were used to drive a biogas fuelled generator set, it would produce 3 kW.hr per day. This gives a capital cost of $5,600 per kW, almost 3 times higher.

The above example does not include the cost of distributing the power from central power stations to rural areas. A biogas plant can be built in a rural village, where the energy is needed. If the costs of power transmission to rural areas is included, the capital economics of biogas look much better (Prasad). In a study in South India (Makhijani), it is suggested that a biogas fuelled generator set could give electricity to villagers at 6 to 8 cents (US) per kW.hr, while electricity from a central coal-fired or diesel generating plant would cost 8 to 13 cents, at 1973 prices. Government subsidies, for both electricity and biogas, tend to upset this type of analysis.

1.3 Technical Challenges

Economics puts a severe constraint on technology. It is relatively easy to make a biogas plant that will produce biogas and fertilizer; there are many designs available. The more difficult task is to make a design of biogas plant that is both effective and cheap enough for potential users to afford. It may be possible to make one or two low cost plants, by using scrap materials, but the technology used in a national biogas programme must be reproduced for thousands of plants, and must be made by workmen with suitable training.

At the present time, it seems easier to make a complex technical unit than a simple one. Specialised materials, devices and control systems, including microprocessors, are available that allow units to be designed to do almost anything. Information on these new ideas is becoming more easily available. Most biogas units designed in the developed world, especially USA, Europe and Japan, tend to reflect this complex approach, with the addition of slurry pumps, temperature control systems and the use of specialised materials, especially plastics. While some of these designs are for research plants, where different parameters need to be automatically monitored, this whole design philosophy is inappropriate for rural areas of the developing world. Simplicity, low cost and the use of locally available materials are the priorities.

The design of appropriate technologies for rural farmers in a developing country demands a lack of sophistication. An appropriate technical unit has to be made from a limited selection of materials, which are also of variable quality and difficult to fit to defined specifications. It becomes difficult for designers and engineers to rely on design data and principles learned in a developed country. It is necessary to go back to basic scientific and engineering principles and start again. It can be argued that simple, appropriate technology demands more knowledgeable and better skilled scientists and engineers than the more sophisticated, but routine, technology of the developed world. Appropriate technologists not only need a wide knowledge, they also need a good understanding of the basics of their subjects.

1.4 Organisational Challenges

The advocates of appropriate technology tend to be engineers, so the technical side is often emphasised to the neglect of other areas, especially those of organisation and management. In the enthusiasm to develop a technology, such as biogas, and prove that it does work for local people, the management of a programme can be left to chance. In the words of a management consultant, who once visited DCS, the result can be a "crisis management situation".

In this approach to management, decisions are made only when they have to be, such as when problems occur. Since these problem solving decisions are not well planned, they can give rise to further problems, which require further decisions. These later decisions tend to partially conflict with the earlier ones, as they are made to overcome the problems resulting from these early decisions. The result is a series of 'crises' that become more difficult and frequent as the programme gets bigger and more complex. The neglect of well planned management in the early stages of a biogas or other appropriate technology programme, can give rise to administrative problems later on in the programme.

A well organised, well planned programme can work well, even if the technology is inadequate. The fast expansion of the programme in China, despite poor technology, is an example of this (Thery). This early Chinese biogas plant designs (van Buren) were poor and difficult to make gas tight, but the highly organised commune system allowed the programme to progress rapidly.

For an effective programme, both the technology and the organisation must be good. Ultimately, however, it is the organisation and management of a programme that determines its long-term success. A biogas programme, whether it involves only research and development, or extension as well, should be carefully planned in the early stages, as the programme is set up. The managers and technicians who are to be involved in the running of the programme should be appointed and trained early on in the planning process, so they can do the detailed planning of the programme. Technical and extension staff should be trained in administration, book-keeping and personnel management, as well as in the technical aspects of biogas, so they know how to run their various sections of the programme.

Once a good organisation has been set up and is running well, attention can be devoted to other aspects, such as the introduction of a new technology or the setting up of new areas of work. Bad organisation means that administrative crises are always taking attention and energy away from other matters, so the progress of the programme is slowed, or even destroyed.

1.5 Marketing Challenges

An "appropriate technology" must be appropriate to the people who are to use it. While a new technology may seem impressive to the engineer who is developing it, the attitudes of the people who buy it are far more important. Many new technologies can be "solution looking for problems".

Biogas has been publicised mainly as a domestic fuel, especially for cooking, but many people in a developing country see biogas as too expensive to be suitable for this purpose. The fuels that biogas replaces, such as wood, agricultural residues and dried cow dung, have a very low direct cash cost to the user, even though the long-term "cost" may be very high, in terms of deforestation and reduced crop production. If a local farmer uses biogas in place of these fuels, he cannot save the money, in cash, required to pay for the biogas plant.

The use of these traditional fuels have a high, long-term cost to the nation, as deforestation leads to soil-erosion and flooding in the monsoon, and drought in the dry season. Vegetable matter and dung, that should be returned to the soil to uphold fertility is being burnt (UNESCO). This national effect has been recognised by the Indian government for many years, in terms of 25% or even 50%, subsidies for biogas technology. His Majesty's Government of Nepal is also recognising the problem, and is giving subsidies for biogas as part of a programme to increase food production.

An alternative approach to the extension of biogas is to emphasise its relevance for economic development in rural areas. Biogas offers a supply of energy to rural areas that cannot hope to have energy from centralised supplies. Gas can be used to run engines which can be used for income earning activities, such as cottage industries and irrigation pumping. If this approach is adopted, farmers can earn income, as cash, from their biogas plants, which can be used to pay for the capital cost of the biogas plant and other equipment. This approach has been shown to work in practice (Volume I, Chapter 11 and Volume II, Chapter 9), even when some of the gas is being used for cooking.

The difficulty of this semi-commercial use of biogas is that a large size plant is needed, which requires the dung of many animals, or a large quantity of agricultural residues to run it. The majority of small farmers in developing countries do not have enough animals, or have access to enough suitable feedstocks, to set up such a plant on their own. The smallest size of dual-fuel engine that is commercially available in India has a capacity of 3 HP (about 2.3 kW). This needs 1.3 cu. m. of biogas an hour, or about 9 cu. m. to run for 7 hours a day. A plant to produce this amount of biogas (an SD500 or an EP50) costs about $2,700 to buy in Nepal and requires 20 to 30 cattle to run it, if only cattle dung is used as a feedstock.

There are several ways in which such a semi-commercial biogas system could be run. An entrepreneur could set up the system, buying in dung and other agricultural wastes to run it, and selling fertilizer as well as the products of his cottage industry. Another way is for a whole community to run the cottage industry as a cooperative venture. Each family would contribute feedstocks and receive fertilizer, while also gaining the benefits from the semi-commercial enterprise.

1.6 Community Organisation

There is a growing interest in the concept of groups of people owning biogas plants as a cooperative venture (see also Chapter 9 and Volume I, Chapter 12). The effectiveness of such a group approach has yet to be proved in practive. Even institutional biogas plants have had poor success in India (Moulik), and the administrators of these institutions are more educated and motivate than village people and should be able to organise the use of the new technology.

The problems that face the organisers of community biogas projects are now being analysed more carefully (Roy, Bulmer), and they seem to result from a wrong approach by the implementing agency, rather than from technical difficulties, or even a lack of organisation within the community. The failure of the biogas project in the village of Fateh-singh-ka-Purwah in Uttah Pradesh, North India (PRAD), for example, was mainly due to misunderstandings and confusions by the villagers as to their responsibilities in the project. A contributing factor to disagreements in the community over the plant were political and family divisions that had been present in the village long before the biogas plant was built (Roy).

The success, or otherwise, of community development projects depends very much on the approach of the agency implementing the project, especially on the attitudes of the extension agents who approach the community with a view to setting up the project, such as a community biogas plant. If a new technology is given to a village before they are ready to accept it, then they tend to resent it as coming from outside, and have little motivation to ensure that it continues to work. Too often, the challenge of community biogas has been only seen as a technical one, with the village people considered only as one variable in the total equation. A more successful approach must see villgers as real people with feelings and thoughts (Bhasin).

Village people should be helped to make a new technology their own. If they can be motivatedto accept, or even desire, a new idea, even to the extent of putting a lot of work and even money (e.g. through a loan) into the project, then they will be deeply committed to making the new system work. (FFHC).

Motivation takes a long time : villagers need to consider a new idea and really understand it and all its implications before they can make up their minds. They need to see the new technology in terms of their own situation; they need to know to what it commits them, what extra work and cost it involves and exactly how they would benefit from it. They need to be confident that the new system will actually help them and not be another expensive failure. Small farmers cannot afford to lose the little they have, and they are suspicious of new things that might be a drain on their meagre resources.

Community biogas can work, but only if it can be organised in a way that enables the village people themselves to be positive that they will gain from having and using it.

1.7 Commercial Biogas

The use of biogas as a fuel, within a commercial operation, is not new. Many sewage processing plants collect the gas given off by digestion and use it to run stationary engines and to run vehicles (van Brakel). This approach has been extended in China where wastes, collected from cities and the surrounding countryside, are digested in central digesters and used to run electricity generating units (Chen, UNIDO). Over 600 of these units have been set up (ITDG).

Another approach is to use wastes from processing industries, that can be digested to biogas to fuel the operation of that industry. This is being done in China; for example brewery wastes are being digested to form biogas to fuel the brewery (FAO). Research is continuing in Japan, USA and India to find ways in which wastes from paper mills, food processing units and other such industries can be used to supply energy instead of causing pollution (Ashare, TATA).

Integrated farming systems, that use biogas as an essential part of their operation are a fairly new idea, although Maya farms in the Philippines have been doing this for years (Maramba). In this system, a herd of animals, e.g. pigs or cattle, is the basis for the commercial operation, while biogas, made from their dung, is used to supply the energy needs of the operation. The effluent from the biogas plant can be used to feed fish and ducks in ponds, as well as algae, which can be harvested as animal feed. The water from the ponds, containing the remaining effluent, as well as the waste from the fish and ducks, is allowed to overflow, to irrigate and fertilize vegetable plots and crops for animal feed. The principle behind an integrated farming system is to make the "waste" from one activity, the input to another (Xinbu, Yang, Soong).

On the more general level, biogas may be incorporated into the general running of an agricultural system. Energy is required to process crops and animal products : for threshing grain, dehusking rice, milling flour, making milk into cheese, butter and ghee. Energy is also required to pump irrigation water and to drive mobile machinery such as tractors. Biogas may be used to partially or wholly replace diesel or other fuels for these jobs.

1.8 Biogas Development in Nepal

The way biogas technology developed in Nepal, illustrates the multidisciplinary nature of the subject. Many of the above points were discovered "on the way" and not even considered at the beginning.

The pioneer of biogas technology in Nepal was a Belgium, Father B. R. Saubolle, S. J., who was a teacher in St. Xaviers School in Godavaria, at the edge of the Kathmandu Valley. He built a demonstration plant in about 1955, run with dung from a small herd of cows owned by the school (Saubolle), as well as a smaller plant in his own home. It proved an attraction to many visitors, including local farmers, government officials (many of whom had sons at the school) and aid administrators. Two plants were built by people in Kathmandu, inspired by this example, and they are still running today.

In 1968, the Khadi and Village Industries Commission of India built a plant for an exhibition in Kathmandu, and gave it to the Department of Agriculture, HMG/N, so they could do experiments.

In 1974, the Energy Research and Development Forum, set up at Tribhuvan University to advise HMG/N planners on energy issues, recommended that biogas be considered an alternative energy resource for Nepal (ERDG). The Biogas Development Committee was set up. The Department of Agriculture, with the cooperation of the Agricultural Development Bank of Nepal (ADB/N), made a programme to build 250 biogas plants during the "Agricultural Year" of 1975/76 (HMG/N). The Nepali financial year goes from mid-July to mid-July, while the calendar year is from mid-April. The Agricultural Year was the Nepali financial year of 2031/32.

The Department of Agriculture arranged for several workshops to make biogas drums according to the KVIC design of biogas plant from India. The extension agents (Unior Technical Assistants - JTAs) of the department were to act as sales agents persuading farmers to buy these biogas plants, with a zero interest loan from ADB/N. The JTAs also had to find local builders to build the plants and obtain the steel gas drums from the manufacturers.

In 1974, the Development and Consulting Services of the United Mission to Nepal built 4 biogas plants to the Indian KVIC design. They were looking for new products that could be made in the Butwal Technical Institute's Mechanical Workshop (now formed into Butwal Engineering Works, Pvt, Ltd). A small demonstration plant, that was also made, was borrowed to be shown at an exhibition held to celebrate the Coronation of King Birendra in 1974.

During the Agricultural Year, BTI and DCS were asked to be contractors to take biogas drums and also to install biogas plants under the Department of Agriculture's programme. Other drums were made by Balaju Yantra Shala in Kathmandu and the Agricultural Tools Factory in Birgunj.

In the Agricultural Year, a total of 196 plants were built, according to the records. DCS built 95 of these, and helped with the installation of 14 more. During 1976 a joint 2-year programme : "Studies of Energy Needs in the Food System", was set up by the Department of Agriculture and American Peace Corps, with funds from USAID, which included a strong emphasis on biogas (Karki). 4 Peace Corps Volunteers were involved, mainly with the training of Nepali personnel in biogas and in the setting up of community biogas plants (see Chapter 9).

In 1977, DCS and ADB/N agreed to set up the Gobar Gas tatha Krishi Yantra Bikash (Pvt) Ltd. (2034), together with the Fuel Corporation of Nepal. UMN had a policy of setting up private limited companies, an organisational model that would allow local people to continue technical programmes on a self-supporting basis. The Company organisation was based on the DCS extension programme for the Lumbini zone of Nepal, of which Butwal was at the centre. The Gobar Gas Company set up Sub-Branch Offices and Sales and Service Centres in about 9 strategic places in Nepal, mainly in the Terai (plains).

The first few years of the biogas programme had shown up some technical weaknesses in the Indian KVIC design of biogas plant, so a Research and Development Programme was set up under DCS to try to improve biogas plant designs (see Chapter 2).

At the time of writing (December 1983), over 1,300 biogas have been built in Nepal, mainly by the Gobar Gas Company. The Company is continuing to build plants, at the rate of about 250 per year, although this number should be increasing. After a time of apparent disillusionment with biogas technology, the Department of Agriculture is offering subsidies for some biogas plants, as part of a programme to increase crop production in Nepal. They now see biogas digesters as important for improving the effectiveness of natural fertilizers, such as cattle dung and crop residues.

As in other places, biogas technology proved to be much more difficult to develop than expected, but it is now finding its place in Nepal.

Volume II - Chapter 2

Chapter 2 THE FUNDAMENTALS OF BIOGAS PROCESS

Chapter 2 THE FUNDAMENTALS OF BIOGAS PROCESS M. Lau-Wong

2.1 The Biogas Microflora

In recent years tremendous effort has been initiated in the construction of biogas systems in various developing countries. However, disproportionate attention has been given to the ultra-structure and construction of plants while the study of the internal process is much neglected, partly because the latter is less straight forward and obscured by unknown factors. Nonetheless, a proper understanding of microbial interactions, nutritional requirements, bio-chemical reactions and kinetics of the process is a prerequisite to the choice of design and operation parameters (e.g. retention time, slurry solid content) for maximising output.

Methane generation from insoluble complexes can be generalised into the following stages :-

Anaerobic digestion with methane generation

Insoluble organic compounds

(e.g. lignocellulose, polysaccharides, carbohydrates, lipids, proteins)

↓ HYDROLYSIS

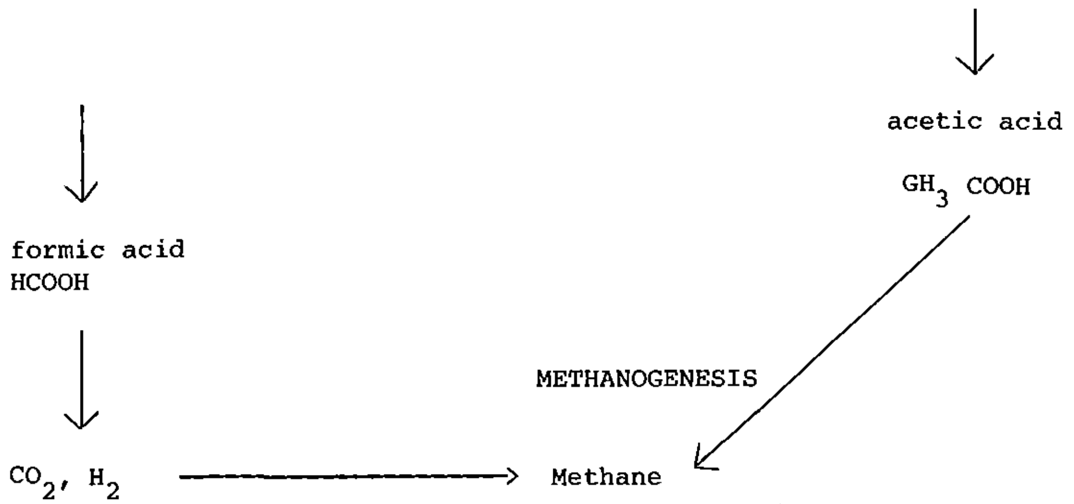
Soluble organic compounds

(e.g. oligo-sacchardes, monosaccharides, short chain fatty acids, alcohol) with formation of H_2, CO_2, and NH_3

↓ ACIDOGENESIS

Volatile fatty acids

(mainly acetic and propionic acids, with some formic and butyric acids)



Anaerobic digestion reduces the bulk of waste and sewage by solubilising the insoluble polymeric substances. The whole process can be visualised as a relay :-

1. Hydrolysis performed by the first team of bacteria e.g. Clostridium thermocellum metabolises cellulose to glucose.

2. Acid formation by bacteria from the same or another group e.g. Clostridium thermoaceticum converts glucose to acetic acid.

3. And finally, methane production from carbon dioxide and hydrogen.

These are three distinct stages and each group of bacteria has its own pH preference: neutral or slightly alkaline for hydrolytic and methanogenic bacteria, and acidic pH (4 to 6.5) for acid formers. A fermenting slurry develops its own buffer and it usually settles down to a compromising pH between 6.5 and 7. In peat bog where the pH is low (around 4), methane can still be detected.

Microbial Interactions

Methanogens thrive in mixed cultures but are difficult to isolate into pure cultures. This may be due to their strict anaerobic requirement, and probably to their need for microbial interactions.

Hydrolytic and acid bacteria can be facultative (live in the presence or absence of oxygen) or an aerobic (live in environment without oxygen), whereas methanogens are obligate anaerobes which are killed upon contact with oxygen. Aerobic and facultative organisms both utilise oxygen as terminal electron acceptor. In the absence of oxygen, the latter can also utilise nitrate or sulphate (in the case of sulphate-reducing bacteria). In a digester, these bacteria assist methanogen by exhausting oxygen from the environment. The methanogens are at the end of the relay and in return remove the acidic end products by converting them to methane. The interrelationships among these micro-organisms in the biogas or ecological systems are thus indispensable.

It is not surprising that for the first few days after start-up, the digester would have a negative pressure inside. Aerobes and facultative organism first deplete the oxygen, forming carbon dioxide which is more soluble than oxygen in the slurry. Thus the presure is reduced. As the more slow growing methanogens thrive, they convert the carbon dioxide to methane, and as more insoluble carbon substrates are metabolised (a slow process as well), more methane is found. Gradually, a positive presure is built up in the digester.

Significant interactions were observed in the presence of complex substratas when essentially methane, acetate, and carbon dioxide are found as the end products. But in the presence of simpler substrates, free hydrogen, carbon dioxide, acetic acid, and other end products such as formate, succinate, lactate, and ethanol are formed, indicating a reduced role of methanogen in the interaction. (Zeikus, 1977).

Experiments have been performed to enhance methane production with microbial interactions. A mixed culture of specific bacteria and enzymes has been claimed to decrease the lag phase and hydrogen sulphide content of the gas produced, with gas production rate and methane content (over 87%) notably higher than other processes (Canber Industries, Canada, personal communications). In China (Lin, etal, 1981) hydrogen-producing bacteria of the families Enterbacteriacea and Bacillaceae have been isolated and studied. When they are inoculated with an enriched culture of methane producing bacteria, the methane content increased remarkably to 80% in 1 week, whereas a control without the hydrogen bacteria had only 65% methane. The CO_2 also decreased to a level too low to be detected by gas chromatography.

Methanegenic Bacteria

Methanogens are strict anaerobes (killed upon contact with oxygen), non-spore formers; and their habitat includes garden soil, lake sediment, mud swamp, sewage sludge, ruminant feces, as well as gastrointestinal tracts of animals. Thermophiles have been obtained from thermal springs in the Yellow Stone National Park in the United States. Since methanogens are obligate anaerobes, indiscriminate exposure of digester slurry to air can seriously reduce the methanogen population.

From physiological and nutritional point of view, methanogens come from very diverse origins. It appears that they are linked together only by their common methane energy-generating mechanism. All methanogens can utilize hydrogen as the sole reducing agent in the energy releasing step of methanogenesis and in cellular synthesis; some can use formate and others e.g. (Methanesarcina barkeri) methanol. In the energy generating process, oxidation of hydrogen is always coupled with the reduction of carbon dioxide, the terminal electron acceptor,to methane. All species can use carbon dioxide as the sole carbon source for cellular synthesis. Some can use carbon dioxide, while others use inorganic compound for energy. For example, Methanosarcina barkeri and some Methanobacterium can use carbon monoxide as energy substrate by first converting it to carbon dioxide.

The intergenus GC content is highly variable and even within the genus Methanobacterium, it varies from 27.5% of M. arbophilicum to 52% of M. thermoantotrophicum. They do not have cytochromes for electron transport, but all contain Coenzyme M (2-mercaptoethane - sulphonic acid) and a fluorescent pigment Factor 420, fluorescense occuring when its oxidised form is excited by ultraviolet rays. Owing to their diversity, methanogens are classified according to their ultrastructure into four genuses (Zeikus and Bowen, 1975).

Taxonomy of Methanogens : Family : Methanobactereace

Genus	Morphology	Substrate for energy and growth
Methanobacterium	rod shaped, often curved	H_2, CO_2, formate
Methanococcus	cocci, in pairs, single, or chains	H_2, CO_2, formate
Methanosarcina	irregular cell packets	H_2, CO_2, methanol, acetate
Methanospirillum	curved, forming helical filaments	H_2, CO_2, formate

2.2 Nutrient requirements of methanogens

Carbon, hydrogen, oxygen, nitrogen, sulphur, and phosphorus (C, H, O, N, S, P) are basic elements essential for the building up of cells and metabolism. In methanogens, carbon serves the additional purpose of being an electron acceptor (CO_2 ---> CH_4). Nitrogen is a constituent of protein, enzymes, and nucleic acid, and is usually lacking in ligno-cellulosic materials.

Up until now, surveys on nutritional requirements of methanogens are limited to only a few species, and the role of vitamins for most species in largely unknown. For those studied, the effect of vitamins can be nil or stimulatory, required or not required. Yeast extract (1 g/l), folic acid (0.2 mg/l), Vit B6 (0.09 mg/l), and Vit B12 (0.001 mg/l) were stimulatory when acetate was used as substrate for methane generation (Parkin and Speece, 1980).

Methanogens invariably use only ammonium as a source of nitrogen, and nitrogen gas, amino acid, and other nitrogeneus compound cannot take its place. Amino acids can be stimulatory for some species like Methanobacterium ruminantium and Methanospirillum hungatti, but not for Methanobacterium thermoautotrophicum which is autotrophic. If urea is supplemented in the feed, it has first to be broken down by other microbes to ammonium before it can be utilised by the methanogens.

Sulphur at 0.85 mM is essential for the degradation of cellulose to methane. Sulphide or cysteine can be utilised by some species whereas Methanosarina barkeri needs both. At 9 mM of sulphur, all inorganic sulphur compounds except sulphate inhibit both cellulose degradation and methane formation. (Khan and Trotter, 1978).

It was noted in some studies that stable methane generation was not maintained on an acetic acid - mineral salt medium until solids - free digested sludge was added. The sludge presumably provides some undefined growth factors for the methanogens. CoM, 2-methylbutyrate, and fatty acids like acetate are essential for rumen methanogens. (Zeikeus etal, 1975).

2.3 Biochemical Reaction and Kinetics

In methane formation, carbon dioxide is reduced by hydrogen and the reaction common to all methanogens is :-

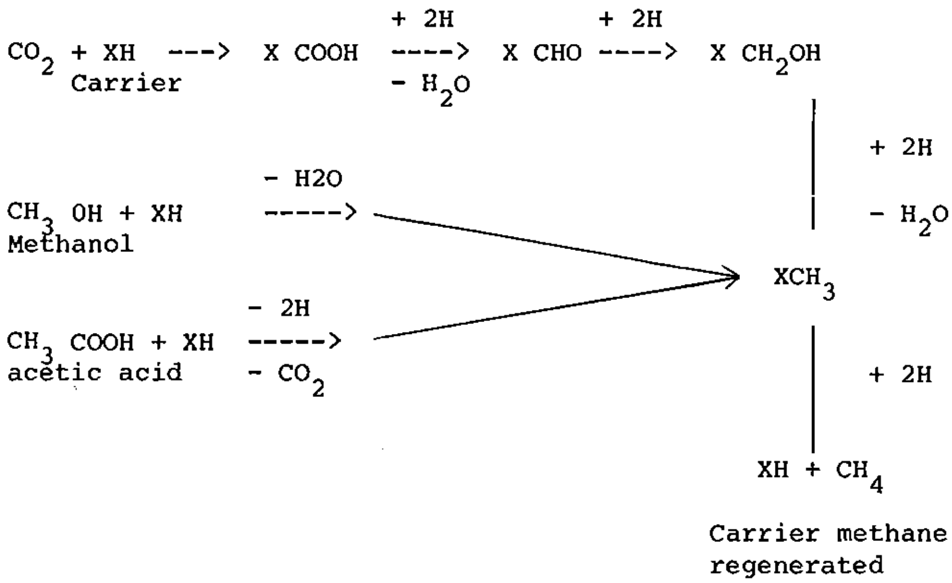
$$CO_2 + 4H_2 \text{ ---- } 2H_2O + CH_4$$

In the course of fermentation of complex substrates, volatile fatty acids such as acetic, propionic, butyric, and lesser amounts of formic, lactic and valeric acid are produced. The higher carbon acids are initially broken down to acetic and propionic acids which become the precursors of about 85% of the methane generated. In an unbalanced process, there are also the acids that prevail (Tappounni, 1979). In sewage sludge, 70 - 80% of methane arises from H_2 - CO_2 and acetate. Interestingly, gaseous hydrocarbons such as ethane, propane, and butane are not produced, indicating that all metabolites are probably coverted to the same precursor of methane.

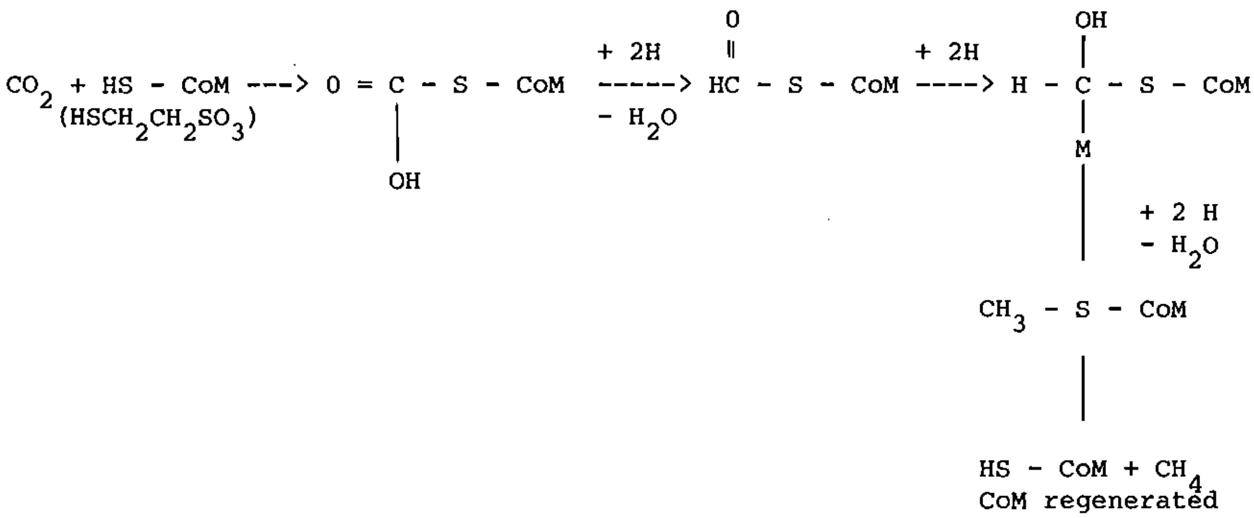
The details of the mechanism for the reduction of carbon dioxide to methane still remain to be elucidated. The discoveries of Coenzyme M or CoM and F420 did indeed shed some light on the understanding of the mechanism. They seem to be unique in methanogens. Tetrahyrofolate, B12, and CoM have been suggested as candidates for methyl group transfer (Stanier etal, 1976). However, the levels of formyltetra-hydrofolate synthetase and methylene tetrahydrofolate dehydrogenese were too low to be of significance in the species studied (Stadman, 1967).

Vitamin B12 is high in sludge (about 3000 mcg/kg dry sludge) and it was postulated that B12 acts as methyl carrier for CoM for cells grown on methanol, with KTP providing the energy. More work is needed to confirm this (Baylock, 1968).

F420 is involved in hydrogen metabolism. Extreme sensitivity of methanogens to oxygen may be due to the oxidation of F420. In Methanobacterium ruminatium, F420 facilitates the oxidation of hydrogen and formate coupled with the reduction of NADP to NADPH. Barker (1956) proposed a unifying mechanism for the reduction of methanogenic substrate. Instead of being reduced by H_2 directly, they are bound to one or more carriers and reduced to methane with regeneration of the carrier. Later on, CoM was proposed as the carrier.



Using CoM as the carrier, Gunsalus (etal, 1976) proposed the refined version which is similar to above,



Thermophilic digestion enhances methane production rate since thermophiles have the fastest growth rates. Methanobacterium thermoautotrophicum has the shortest doubling-time (the time taken for cell population to double) of less than 3 hours at temperatures above 70^oC grown in an inorganic mineral salt medium. Isolated from sewage sludge, it grew well up to 80^oC (Zeikus and Wolfe, 1972). Doubling-time for Methanobacterium arbophilicum culture grown in mineral salt medium supplemented with vitamins is 10 hours; for Methanospirillum hungati in a complex medium it is 17 hours. Under optimal cysteine and sulphur concentrations, the generation time of Methanosaccina barkeri is 7 - 9 hours. At mesophilic temperature (365^oC), the doubling-time for methane fermentation of acetic acid is 33.9 hours. In high solid or dry batch fermentation of corn stover, the rate is 1.75 and 3.5 times faster at 55^oC than at 35^oC and 25^oC respectively. The difference for wheat straw is not as dramatic (Jewell etal, 1981). The usual retention time of 1 month for digestion at mesophilic temperatures can be reduced to 1 week at thermophilic temperatures.

Kinetic studies help to determine the rate limiting step in the sequence :

Hydrolysis, acidogenesis, or methanogenesis. The specific growth rates, Umax, and generation or doubling time d, ($d = \ln 2/\mu\ Max$) for various phases and substrates were reported as follows :

Table 2.1 Kinetic Constants for different stages in anaerobic digestion

Substrate	Phase	μ max, hr^{-1}	d, hr	Temperature °C
glucose *	acid	0.30	2.3	36.5
sewage sludge *	acid	0.16	4.3	36.5
cellulose *	acid	0.07	9.8	35.0
acetic acid *	methane	0.02	33.9	36.5
glucose #	acid	0.33	-	30°C, pH6
glucose #	acid	0.51	-	37°C (Optimum mesophilic)
glucose #	acid	0.71	-	52°C (Optimum thermophilic)

* Source = Ghosh and Klass, 1978

\# Source = Zoet meyer, etal, 1979

Acid formers such as Streptococci and Bacteriods are more fast growing than methanogens. Thus for a balanced process, acid formation should be in step with its conversion to methane by the slow growing methanogens.

In digestion of simple carbohydrates such as glucose, sewage sludge, and cellulose, methane formation from volatile fatty acids is rate limiting since the corresponding specific growth rate is lowest, at 0.02 hr^{-1}.

For highly lignocellulosic compounds which are resistant to degradation by enzymes and limited in exposes surface, hydrolysis step can be limiting.

However, if the methanogen population is scanty and lacks viability, acid will accumulate and methane formation will be limiting instead.

Sometimes, thick slurry or scum formation at the surface can prevent rapid release of gas from the slurry. Studies are needed to compare the rate of release of gas to the rates of reaction.

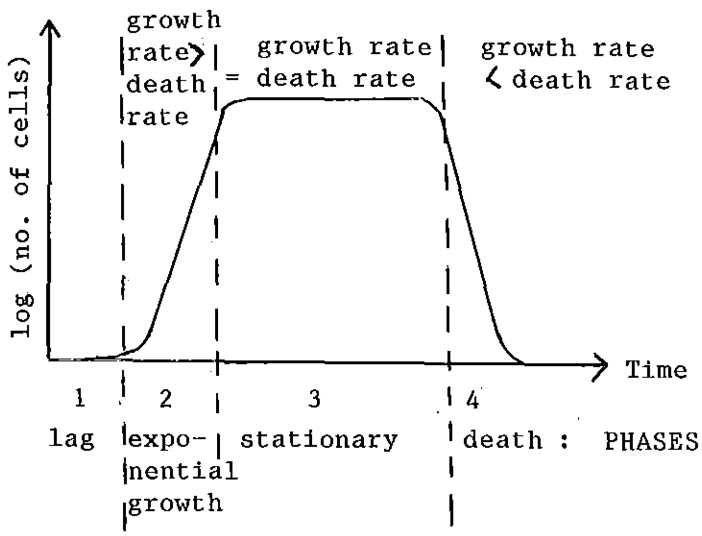
2.4 Types of Biogas Processes

A close analogy can be drawn for fermentation in a biogas digester and that in the rumen of a ruminant. The gastrointestinal tract of a true ruminant is a complicated affair. It comprises the rumen-reticulum where feed is fermented, abomasum where enzymic digestive processes similar to that in monogastric take place, omasum where water and some nutrients are absorbed, and the intestines. The rumen microflora is similar to the biogas microflora, and ruminant feces should therefore contain the set of microbes required for methane generation.

One notable difference between digestion in a digester and digestion in a ruminant is that the living animal can regurgitate long pieces of fibrous feed, chew them down to a proper size for enzymic actions and reswallow them in a ball-like boluses. Whereas fibrous substrate for a digester has to be first comminuted artificially before feeding. The rumen is stratified into three layers - the top hardpack layer of long fibrous materials, the intermediate layer with ruminated feed, the fluid layer of finer particles. Fermentation takes place in the intermediate and fluid layer. A biogas digester, which lacks the discrimination and co-ordinated actions of muscles in a ruminant, would be in serious trouble if it is stratified as in a rumen. This nevertheless can occur if long pieces of straw are added as substrates or the slurry is too diluted.

At the start-up of plants, a lag phase is almost inevitable when the microflora attempts to establish itself. In a batch process, in which no material enters or leaves except for gaseous products, the lag phase is followed by a period of maximum growth (μ = Umax) called the exponential growth phase. Thereafter, the population declines as the death rate exceeds the growth rate. The lag period can be shortened if the batch is inoculated with the proper microbial culture.

Fig. 2.1 Growth in a batch process



Other processes include the continuous stirred tank reactor (CSTR) which is highly popular in fermentation industries, and plug flow reactor in which mixing is retricted. In practice, the biogas systems encountered in laboratories and research stations are modified versions of these reactors. For the gas plants built in Nepal, feeding of substrate is semi-continuous, usually once a day, and mixing is not uniform since agitating devices may be absent or not in use.

The application of fixed film reactor or anaerobic filter for methane generation has been a recent development. These reactors are basically vertical columns filled with materials with large surface areas for the adherence of bacterial film. Chunks of glass, plastic, clay, stone or even bamboo rings have been tested as film adhering materials. Clay pipes provide excellent surface for film establishment. Glass gives the lowest rate and highest variability, and the film, once removed, was difficult to re-establish (Von Den Berg and Lentz, 1979). Substrate is pumped in from the top of downflow reactors, or pumped up in upflow reactors which act partly as fluidized bed. The rate at which the bacterial film is formed on the surface is variable, depending on the nature of the support material.

In one experiment, dilute pig slurry (below 1% total solid) was fed to an upflow reactor filled with limestone chippings. 90m^3 biogas per day was produced from the 9.46 m^3 digester at a low retention of 0.5 to 5 days and temperature 30 - 35^{o}C. Construction cost was low and clogging was not a problem as long as the feed was low in solid content (Newell, 1979). In Thailand where bamboo rings (1 1/2 inch diameter and 1 inch long) were used, bacteria developed as a thick black slime on rings and as flocs in the interstices in upflow reactor. Pig dung was first diluted and screened through 2 mm sieve before feeding. After ten months of operation, there was no visual signs of degradation in the rings and their expected life is 2- 3 years. One significance is that the low retention time (average 5 days) allows a smaller volume of digester, half the size of conventional ones, and construction cost was 30% lower (Chavadej, 1980).

In summary, the advantages of fixed film reactor are that agitation is not required, the rates of methane generation is high, and the retention time is low permitting the construction of a smaller and cheaper reactor.

As for disadvantages, this process is only applicable to low solid waste (less than 1%). Higher solid was requires dilution and settlement of solids or sieving through screens. Unless this procedure is properly observed, the chance of clogging in the spaces between the supporting material is very high. A plant installed in China was clogged up after several months of operation (ASSET, 1981).

Another reason for the requirement of liquid feed is that diffusion of substrate to the bacterial film is more effective for soluble matters than solids. Lignocellulosic residues have low cell soluble matter (about 10 to 15%) and degradation proceeds more rapidly if microbes are adhered on it. The proximity decreases the time needed for diffusion of hydrolytic enzymes to the fibrous substrate and diffusion of products back to the micro-organism. The low retention time and adherence of the microbes to supports in fixed film reactor are therefore unsuitable for highly insoluble lignocellulosic materials.

The use of fixed film reactors are also limited by the life expectancy of the supporting materials and the stability of the bacterial film. Films are usually slow to develop and difficult to reestablish after failure.

Two Phase Anaerobic Digestion

As methane generation from complex substrate is mediated by two groups of bacteria that have their own environmental preferences, separating them in two phases can optimise conditions for both acidogenesis and methonogenesis. Acid formers have a faster growth rate than methanogens and the retention time needed to maximise both stages differ greatly. At 5% glucose the generation time for acidification and methanation are 3.6 hours and 36 hours respectively; that of Cellulose hydrolysis is even higher, at 1.7 days. A higher flow rate to satisfy the acid formers can therefore result in total washout of the methanogens.

In a two phase system daily methane production per kg VS is almost 4 times that of a one phase system and methanogens can cope with shock loadings of acids better in the second stage. Because of the slow growth ratio of methanogens, recirculation of biomass in necessary (Zoetemeyer etal, 1979).

Phase seperation can be simulated in a plug flow system, which theoretically allows no mixing of contents in different cross-sections of the longitudinal reactors. This process enables acid-forming bacteria to be enriched in the initial section of the reactor and methanogens in the latter part. The tunnel design operates only partially on the plug flow principle, since mixing caused by displacement of slurry destroys true plug-flow effect.

2.5 Effluent as Fertilizer

The fertilizing value of effluent from biogas plants has been commented frequently in the literature, although field trials of its effectiveness compared to chemical fertilizer, manure, and compost have not yet been properly performed and documented. In the choice of plots for trials, care should be taken to note the nature and fertilizer of the soil, and avoid plots that have had a history a fertilizer application. Organic fertilizers tend to leave their residual effects in the soil; manure, biogas effluent, and compost can have effects lasting for two to three years.

During fermentation, carbon in the substrate is consumed. Part of it is incorporated into the microbial cells as building material and remains in the slurry while the rest is metabolised to methane, carbon dioxide, volatile fatty acids, or other soluble metabolit es. The gases escape from the slurry, leaving it more dilute with less carbon and solid matter. Nitrogen, on the other hand, is assimilated into cells but rarely reduced to nitrogen gas in the system.

Although nitrogen fixing bacteria have been detected in some systems (El-Halwagi, 1980) the total amount of nitrogen remains fairly constant. Its concentration in terms of dry matter actually increases, not so much because of production by nitrification, but becasue of the net decrease in solid matter as fermentation proceeds. Table 2.2 lists some typical NPK values of manure and effluent obtained from our biogas plants in Nepal; note that the concentrations of nitrogen is almost 40% higher in the effluents.

Table 2.2 NPK values of manure and effluent, % by weight of air dried materials

Material	N	P_2O_5	K_2O	ash
Buffalo manure, fed on grass and rice husk	1.01	1.11	0.92	26.43 (n = 3)
Effluent from dome-type plant	1.41	1.18	1.48	28.64 (n = 6)
Effluent from tunnel-type plant	1.39	1.04	1.08	28.64 (n = 4)

While the net amount of nitrogen fluctuates slightly, the forms it takes vary considerably. In most cases, there is more ammonia (20 to 50%) and less organic nitrogen in the effluent than in the manure substrate. In a report from Egypt (El-Halwagi, 1980) the quantity per unit volume of volatile fatty acids, phosphates, and ammonia increased. In fact ammonia doubled becoming 25% of total nitrogen. Organic nitrogen decreased 20% but the amount per unit dry matter increased owing to the concentration effect described above. In other circumstances in the U.S. ammonia increased from 1/4 to 1/2, whereas organic nitrogen was reduced from 3/4 to 1/2 of the net amount. In India, ammonia in the effluent was found to be between 15 - 18% of total, nitrogen. (Subramanian, 1977).

Similar to manure, gas-plant effluent loses nitrogen in the form of ammonia if left outside for long before application. If it is too wet, leaching of soluble compounds especially nitrates will occur, and if too dry volatile compounds such as ammonia and volatile fatty acid will evaporate more readily. Furthermore microorganisms act on the area and protein converting them to ammonia.

$$CO(NH_2)_2 + 2H_2O \dashrightarrow (NH_4)_2CO_3 \text{ ammonium carborate} \quad (1)$$

$$(NH_4)_2CO_3 \dashrightarrow 2NH_3\uparrow + CO_3\uparrow + H_2O \quad (2)$$

The second reaction is accelerated by high temperature and alkaline conditions.

In the Philippines, effluent from biogas plants fed with livestock wastes such as hog manure are treated in aeration lagoons for about a month. The purpose is to allow toxic compounds present in the effluent to decompose in the ponds before being applied to crops. (Maramba, Sr. 1978).

Toxic compounds include hydrogen sulphide and their successful removal can be indicated the attraction of insects to the treated slurry. In Nepal, where cattle and buffalo dung is the common feed, this procedure is not a necessity. We have encountered cases where frogs dwell happily in the effluent in the outlet pit and plants sending their roots down the inner sides of the outlet pit.

2.6 Effect of Anaerobic Digestion on Pathogens

Another side benefit of biogas plant besides the provision of fertilizer is sewage treatment. In biological treatment of waste, the initial step known as primary treatment involves settling out of solids. In secondary treatment, suspended matter and soluble organic matter can be removed by one of the following methods :-

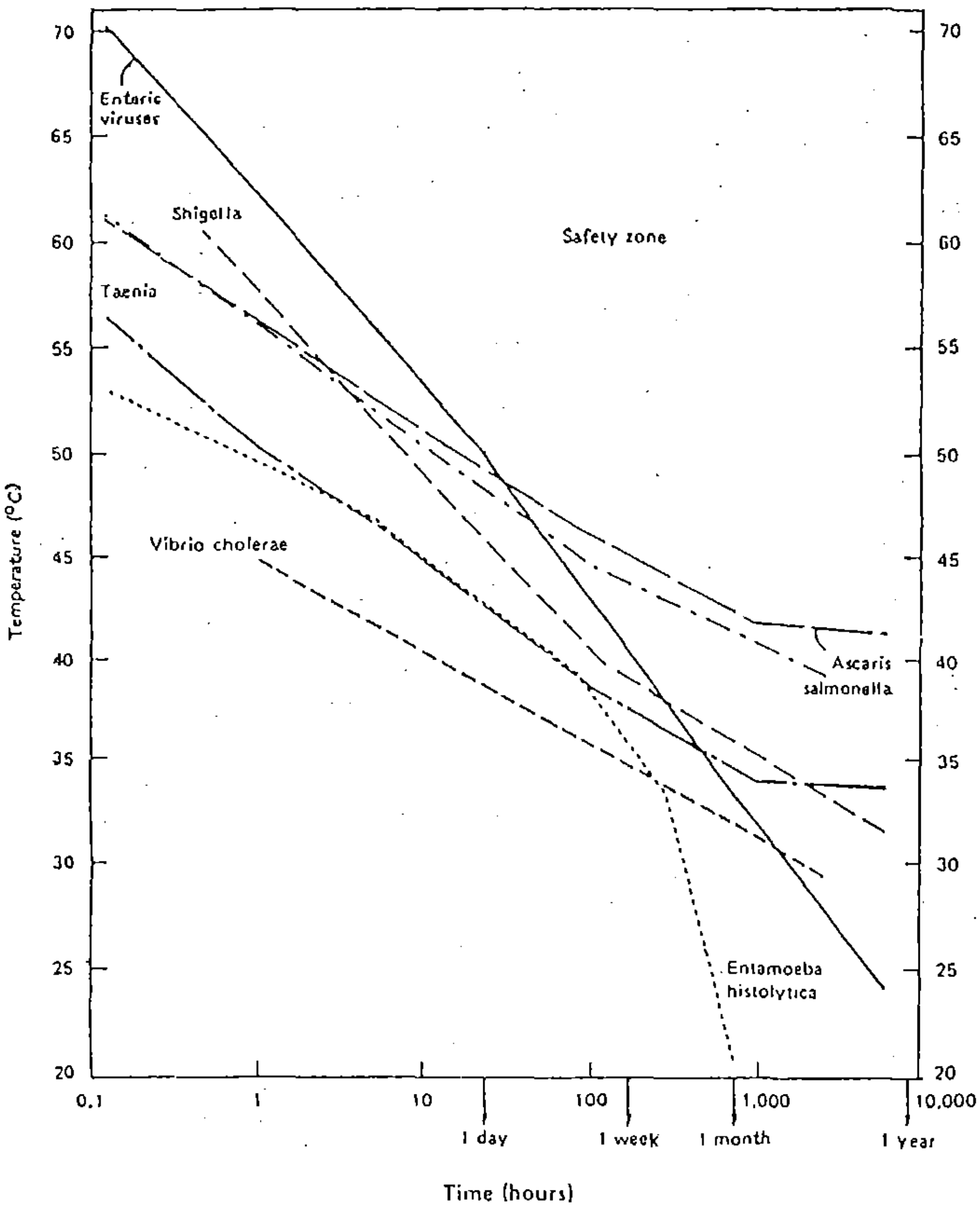
1. Stabilization pond.
2. Oxidation ponds or aerated lagoons, some with algae for providing oxygen. Cost is low and appropriate where land is available.
3. Activated sludge or continuous-flow aerate biological reactor, usually with recycling of sludge.
4. Fixed film reactor with downward or upward flow (see 2.4) Trickling or percolating biological filter is a special case with downward flow of substrate.
5. Anaerobic digestion with or without methane recovery.
6. Composting.

Time and temperature are the two important parameters governing the success of waste treatment. Fig. 2.2 depicts how the survival of different kinds of pathogens are related to these parameters. The upper right hand corner is the safety zone, where at a certain combination of temperature and time, all pathogens are virtually eliminated. The most resistant pathogens are enteric viruses and ascaris eggs; they are the last ones to be eliminated. In anaerobic digestion at 35^{o}C and at a retention period of 20 - 30 days, the population of Ascaris eggs is substantially reduced but not totally destroyed. At 40 - 50^{o}C, complete destruction is almost ensured. In a well-drain pit, storage for one year essentially eliminates all pathogens at low temperature.

In a biogas digester, where the temperature is usually below 30^{o}C and retention time between one and two months, removal of pathogens from night soil is never complete, and caution must be taken to treat the effluent in stabilization ponds before application to crops as fertilizer. In China, inlet pipes are made to open near the bottom of the digester, so as to allow parasite eggs drop to the bottom and have longer retention periods. Even so, it was found in China that Ascaris or round worm eggs only loses 53% of their viability after 100 days.

Salmonella is another pathogen renown for its resistance to waste treatment. Studies done on S. heidelberg indicated that retention time and not so much PH is the crucial factor for extermination. There are conjectures that competition with other organisms in the digester threatens the survival of Salmonella. However, when Salmonella was inoculated into sterilised effluent from digesters, the viable counts dropped from 6×10^5 to 10^2 in two cases and zero in another, indicating compounds in the effluent itself are probably inhibitory to their growth. (Anaerobic Digestion Poster Papers, 1980).

Fig. 2.2 Influence of Time and Temperature on Selected Pathogens in Night Soil and Sludge



Note: The lines represents conservative upper boundaries for pathogen death - that is, estimates of the pathogen time-temp. combinations required for pathogen inactivation. A treatment process with time-temp. effects falling within the "safety zone" should be lethal to all excreted pathogens, with the possible exception of hepatitis A virus which is not included in the enteric virused in the fig. at short retention times.
Indicated time-temp. requirements are at least :
1 hour at $\geqslant 62^{o}C$, 1 day at $\geqslant 50^{o}C$, and 1 week at $\geqslant 46^{o}C$.

Source : R. Feachem and others, 1981.
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2.7 Properties of Biogas

Biogas usually comprises 50 - 70% of methane, CH_4, and the rest is mainly carbon dioxide, CO_2. In the Indian subcontinent, biogas generated from gobar (cattle or buffalo dung) contians only 50 - 55% of methane. Small amounts of other gases such as nitrogen are also present. Hydrogen and carbon monoxide may be present, usuall below 1%. The corrosive gas hydrogen sulphide H_2S is also produced in trace quantities by sulphate reducing bacteria.

Both Methane and hydrogen are combustible, though the contribution of hydrogen to the calorific value of the gas is negligible because of its small quantity. Removing the incombustible carbon dioxide would increase the calorific value of the gas.

Methane is well-known for its property of forming explosive mixture with air between 5 to 14% methane or 8.1% to 21.3% biogas (assuming 60% methane content). In enclosed space, violent explosions can occur. Accidents are not unheard of , but are usually induced by extreme carelessness such as lighting a flame inside an anaerobic digester or testing the combustibility of gas at taps situated in small pits. With a bit of knowledge and common sense, operation of biogas plants and appliances is rather safe.

Using biogas for cooking is as convenient as using butane gas, though in all cases, proper precautions such as adequate ventilation should be observed. Biogas contains a minute amount of hydrogen sulphide, which is not only poisonous but is also a nuisance because of its corroding action on engines and gas taps, especially those that contain lead. Hydrogen sulphide is characterised by its rotten eggs odour and should not be inhaled unnecessarily : Above 10 ppm, it starts to irritate the eyes and above 20 ppm, the lungs and mucous memberanes, and above 600 ppm, death may occur. Unfortunately, olfactory (sense of smell) fatigue develops after prolonged exposure to the gas and its dangerous presence may not be detected.

Substrates with high amount of sulphur generate biogas with more hydrogen sulphide. The percentage of H_2S generated from cattle dung in Nepal is below 0.001% tested with the lead acetate method. The amount should not exceed 0.07% by volume when used for engines, or else it has to be scrubbed.

Powdered hydrated ferric oxide (rust) reacts readily with hydrogen sulphide forming ferric sulphide. Upon exposure to atmospheric oxygen, ferric oxide is regenerated; this reaction is very vigorous with tremendous heat generation and admittance of air should be controlled carefully.

$$Fe_2O_3 + 3H_2S \longrightarrow Fe_2S_3 + 3H_2O$$

$$2Fe_2S_3 + 3O_2 \longrightarrow 2Fe_2O_3 + 6S$$

Wet scrubbing can also be used, 3 volumes of H_2S in 1 volume of water at one atmosphere and 20°C. Carbon dioxide is also partially removed.

Volume II

Chapter 3 **THE EFFECT OF OPERATIONAL PARAMETERS ON SYSTEM DYNAMICS**

M. Lau-Wong

3.1 The Purpose of Modelling

In order to enhance the performance of a biogas process and to prevent process failure, kinetic study of the dynamic behaviour of the system is indispensable. A common tool in kinetic study is the construction of mathematical models for describing the system's characteristics. Successful models enhance understanding of system behaviour by shedding light on the role and interactions of various operational parameters for the process. By adjusting the parameters, control of the process and prediction of system behaviour under different sets of conditions can be achieved accordingly. This ultimately leads to improvement of plant design and refinement of operational practices.

A model should reflect the essential features of the real process, but not be bogged down by trivial details. It should also be tested against real data. So far most good kinetic data have been generated from bench-scale reactors and pilot plants in research stations under carefully controlled environments. Field data, if existent, usually do not lend themselves readily to analysis. True, tests on gas plants operating under field conditions give more realistic results, but these same conditions create immense difficulties when one comes to data analysis. Many environmental factors are often beyond one's control : temperature and moisture content of substrate (e.g. animal dung) vary from month to month and a true steady state of the system can never be achieved. Moreover, input quantities of dung and water are not measured out as exactly in the field as in research laboratories. All these factors together contribute to a greater degree of randomness in the data.

A simulation model on anaerobic digestion has been developed by Graef and Andrews for fine process control (1974). In our study of gas plant operation under field conditions in Nepal, where sophisticated facilities are lacking and feedback is minimal, it is more practical to use a less elaborate model but one that includes the essential operational parameters (such as temperature and retention time) that are still within our control and monitoring. In the following sections simple models for various plant types will be discussed.

3.2 Parameters Affecting Gas Output

In the literature, gas production from substrates is often given in terms of the unit weight of the substrate or volatile solids in the substrate. This presentation is too simplistic and sometimes quite misleading. Since output is dependent on numerous factors, such as temperature, retention time, input quality, concentration of substrate, slurry water content, pressure, pH and digester volume, it is crucial to specify the conditions and subject them to the same frame or reference before meaningful comparisons of diversified substrates can be made. If animal dung is used as feedstock, one must take into account its moisture content, which varies for different animal species and period of exposure after defecation. In a hot climate of low relative humidity, dehydration of dung occurs rapidly, especially under sunlight. The same applies to plant feedstocks which vary in water content and digestibility at different stages of maturity.

3.3 Modelling the Dynamics of Various Reactor Systems

Biogas systems encountered in research stations, laboratories or in the field usually adopt one of the following basic designs :-

1. Batch Reactor - from which nothing is removed (except gaseous products) and to which nothing is added after the initial inoculation of medium.

2. Completely Mixed Continuous Stirred Tank Reactor (CSTR) - also known as Chemostat, to which substrates, and possibly cells, are continuously fed and from which effluent is constantly removed.

3. Semi-continuous Mixed Reactor - similar to CSTR, except that substrate is fed at intervals and mixing may be intermittent.

4. Plug Flow Tubular Reactor (PFTR) - a longitudinal or pipe-like reactor to which feed is fed and effluent is removed continuously. In the ideal case, there is no variation of axial velocity over each cross-section. Ideal plug flow can be approximated by the movement of fluid through large pipes or channels. At each plane of the channel, fluid moves at constant velocity with no mixing or interaction with fluid in the neighbouring plane.

5. Horizontal Displacement Reactor - a modified version of the PFTR that allows mixing by displacement of slurry between digester and outlet pit. Input is semi-continuous. An example is the Tunnel design.

6. Fixed Film Reactor or Anaerobic Filter - a vertical reactor filled with supporting material which has a large surface area for the adherance of bacterial films. The substrate is pumped either up or down; agitation is eliminated; and it is more applicable to dilute non-particulate substrates (see Chapter 2.4).

Modelling of the Batch Process

At the end of a lag period (where $t = t_o$), the rate of disappearance of the substrate is proportional to its concentration :-

$$\frac{dS}{dt} = - kS.$$ (See Table 3.1 for notation).

Integrating, with $S = S_o$ at $t = t_o$:

$$S = S_o \, e^{-k(t-t_o)}.$$

At the end of the Retention Period R :

$$S = S_o \, e^{-k(R-t_o)}.$$

The substrate converted between the time : t-1 and t is :

$$S_{t-1} - S_t = S_o[e^{-k(t-t_o)}].(e^k - 1).$$

This value, the daily amount of substrate converted, is variable and dependent on t, being smaller as time increases (Figure 3.1). The gas produced daily (between t-1and t) is :

$$G = C_1 \, C_2 \, f \, (S_{t-1} - S_t) \, V$$

$$= C_1 \, C_2 \, f \, V \, S_o \, [e^{-k(t-t_o)}]. \, (e^k - 1).$$

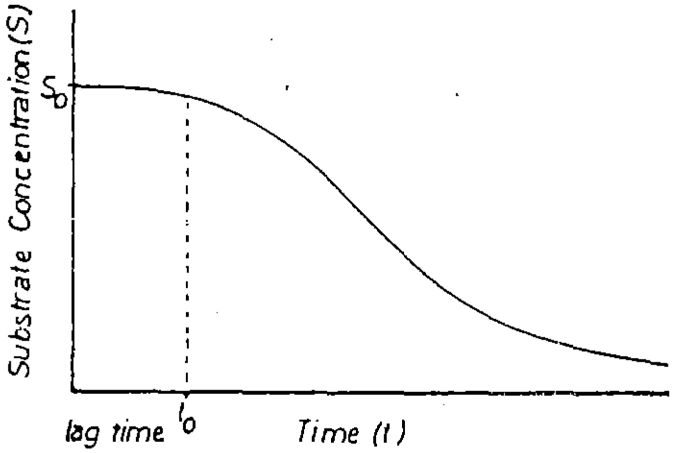


Figure 3.1 Batch Process : Substrate Concentration vs. time

Modelling of the CSTR Process

At steady state, the substrate concentration S in the reactor is constant and equal to that in the effluent (Figure 3.2).

Doing a mass balance on the substrate in the reactor :
Mass in - Mass out = Mass converted in the reactor :

$$F \, (S_o - S_e) = kSV = kS_eV,$$

or : $$S_o - S_e = kS_eR, \quad \text{since } R = \frac{V}{F}$$

$$\therefore \quad S_e = \frac{S_o}{1 + kR}$$

$$\text{Rate of Gas Production (G)} = C_1\, C_2\, f(S_o - S_e)\, F$$
$$= C_1\, C_2\, f\, V \frac{S_o\, k}{1 + kR}$$

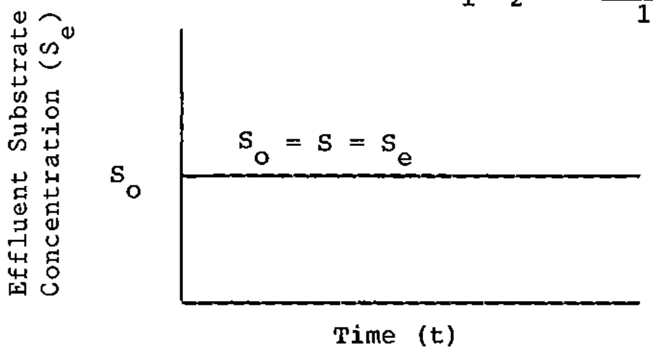


Figure 3.2 CSTR and Semi-CSTR : Substrate Concentration in effluent vs. Time

Symbol	Meaning	Units
S_o	Initial Concentration of Substrate : in feed for batch processes, in influent for continuous processes.	$kg.m^{-3}$
S_e	Substrate Concentration in Effluent	$kg.m^{-3}$
S	Substrate Concentration in Reactor	$kg.m^{-3}$
R	Hydraulic retention time	day
F	Flow Rate of contents in Reactor	$m^3.day^{-1}$
V	Working Volume of Reactor	m^3
⟨VS⟩	Volatile Solid Content of Substrate (organic matter)	kg
f	Fraction of Volatile Solids in Substrate = 1-ash fraction	-
G	Rate of Gas Production (usually at STP)	$m^3.day^{-1}$
C_1	Gas Output per Unit Mass of Digestable ⟨VS⟩	$m^3.kg^{-1}$
C_2	Fraction of digestible volatile solid in substrate	-
P	Interval between feeding of Substrate in semi-continuous reactors	day

Table 3.1 Symbols Used in the Mathematical Models

Modelling of a Semi-Continuous Mixed Reactor

A semi-continuous process combines features of both continuous and batch reactors. Substrate is fed at intervals p, and for simplicity mixing is assumed to be accomplished instantaneously. At steady state, substrate concentration in the effluent is constant (Figure 3.2), but the concentration S inside the reactor fluctuates with time (Figure 3.3).

S is highest immediately after input, denoted : S_a

S is lowest right before input, denoted : S_b

Let the amount of input at each period be : V_o

Retention Time : $R = V/\frac{V_o}{p}$ or $V_o = \frac{Vp}{R}$

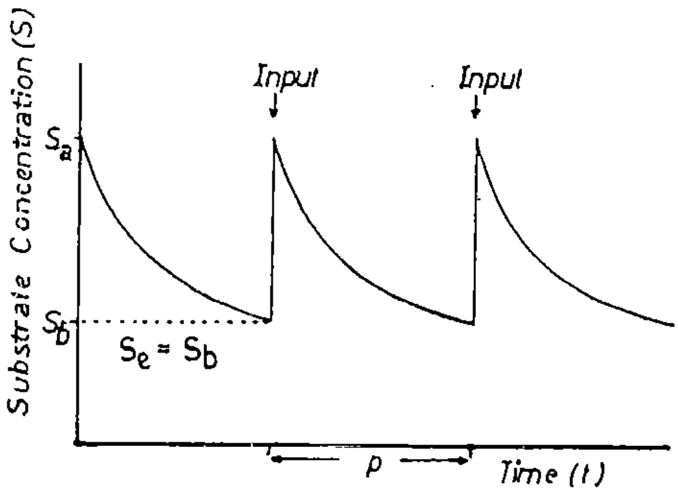


Figure 3.3 Semi-continuous Mixed Reactor : Substrate Concentration in reactor vs. time

In the event of input of substrate, effluent of a volume V_o and of concentration $S_e = S_b$ is displaced from the outlet, before it has a chance to mix with the incoming fresh substrate.

After mixing of the influent with the reactor slurry, each having substrate concentration S_o and S_b and volume V_o and $(V - V_o)$ respectively, the resultant concentration of the mixture is :

$$S_a = \frac{S_o V_o + S_b (V - V_o)}{V} = \frac{S_o p}{R} + S_b \left(1 - \frac{p}{R}\right) \quad \ldots (1)$$

After each input, however, fermentation proceeds batchwise and S_b is related to Sa by the batch equation :

$$S_b = S_a e^{-kp} \quad \ldots. (2)$$

Solving for S_b from (1) and (2) gives :

$$S_b = \frac{S_o}{e^{kp} - 1 + \frac{p}{R}} \left(\frac{p}{R} \right)$$

Usually when the period p is small compared to the retention time R, the expression (3) for S_b can be simplified.

p << R is equivalent to $\frac{p}{R}$ ----> 0 ; Since R is finite, p -->0

$$\lim_{p \to 0} S_b = \lim_{p \to 0} \frac{S_o}{\left(\frac{e^{kp}-1}{p} \right) + \frac{1}{R}} \quad \frac{1}{R}$$

Applying L'Hopital's rule to $\lim_{p \to 0} \frac{(e^{kp} - 1)}{p}$ gives k

and $$\lim_{p \to 0} S_b = \frac{S_o}{(k + \frac{1}{R}) R} = \frac{S_o}{1 + kR}$$

This gives the same substrate concentration as in the effluent from a CSTR. Therefore if the retention time is long compared to the feeding interval p, a semi-continuous process can be approximated by a continuous one.

Rate of Gas Produciton, G :

$$G = C_1 C_2 f \left(\frac{S_o - S_e}{R} \right) V = \frac{C_1 C_2 f V S_o}{R + \frac{p}{e^{kp} - 1}}$$

Again, as $\frac{p}{R}$ ---> 0, $G = \frac{C_1 C_2 f V S_o K}{1 + kR}$

Modelling of the PFTR Process

A plug flow process can be visualised as a batch process with the time axis in the batch reactor translated to a length axis in the tubular reactor. By transforming time t, to length l, the graph of reactor substrate concentration (Figure 3.4) is identical to that of a batch (Figure 3.1).

t and l are related by the relationship :

$t = \frac{l R}{L}$ where L is the total working length of the tubular reactor.

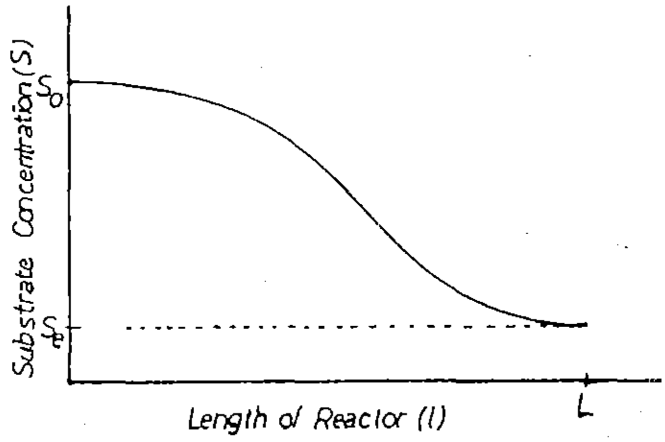


Figure 3.4 Plug Flow Reactor : Substrate Concentration vs. Length

At steady state, effluent substrate concentration S_e, is constant and is given by :

$$S_e = S_o \, e^{-kR}$$

On the other hand, concentration in the reactor S varies at different cross-sections along the length of the reactor, but is independant of time at steady state.

Rate of Gas Production ;

$$G = C_1 \, C_2 \, f \, \frac{(S_o - S_e)}{R} \, V$$

$$= C_1 \, C_2 \, f \, V \, S_o \, \frac{(1 - e^{-kR})}{R}$$

Modelling of the Semi-continuous Plug Flow Reactor Derivation is the same as that for the PFTR, as long as there is no mixing of fresh substrate with the reactor contents.

3.4 The Effect of Retention Time

In the optimisation of a biogas process, differentiation between rate and efficiency is important. Both are intimately related to retention time, and in a process, one but not both, can be maximised. Rate of substrate conversion and rate of gas production are proportional and either can be used to specify the rate of the process.

Specific Gas Production Rate : $g = \frac{G}{V} = C_1 \; C_2 \; f \; \left(\frac{S_o - S_e}{R}\right)$

Substrate Conversion Rate : $r = \frac{S_o - S_e}{R}$ per unit reactor volume

The rates : g and r are therefore related by the constants : $C_1 \; C_2 \; f$ which depend only on the nature of the substrate.

Dilution rate D and retention time R are related by :

$$D = \frac{1}{R}$$

It can be shown by kinetic analysis that as D increases or R decreases, conversion rate increass until a maximum is reached; after that, for a further increase in D, a precipitous drop in the rate follows, plummeting to zero as wash-out occurs (Figure 3.6). The efficiency of substrate conversion can be represented by gas production per unit volatile solid :

$$g' = \frac{\text{daily gas production}}{\text{daily VS input } (\langle VS \rangle)} = \frac{G}{\langle VS \rangle}$$

$$= \frac{G \; R}{f \; V \; S_o} = C_1 \; C_2 \; f \; V \; \left(\frac{S_o - S_e}{R} \right) \frac{R}{f \; V \; S_o}$$

since $R = \frac{V}{F} = \frac{V}{\frac{\langle VS \rangle}{f} \; S_o} = \frac{f \; V \; S_o}{\langle VS \rangle}$,

$$g' = C_1 \; C_2 \; f \; \left(\frac{S_o - S_e}{f \; S_o} \right)$$

Substrate conversion efficiency : E, is defined by :

$$E = \frac{S_o - S_e}{f \; S_o} ,$$

Thus : $g' = C_1 C_2 f E$ and g' and E are related by the constants : $C_1 C_2 f$.

For the CSTR and its approximations :

Substituting for S_e : $E = 1 - \frac{1}{1 + kR}$ and as $R \longrightarrow \infty$, $E \longrightarrow 1$.

Therefore, the higher the retention time, the greater the efficiency; but then substrate conversion rate is traded off in favour of efficiency. Normally, when substrate is abundant, one would optimise the process by operating at the retention time that gives the maximum rate. But when substrate is scarce and gas consumption rate is below the maximum gas output rate, more of the substrate can be consumed (i.e. the efficiency can be increased) by extending the retention time.

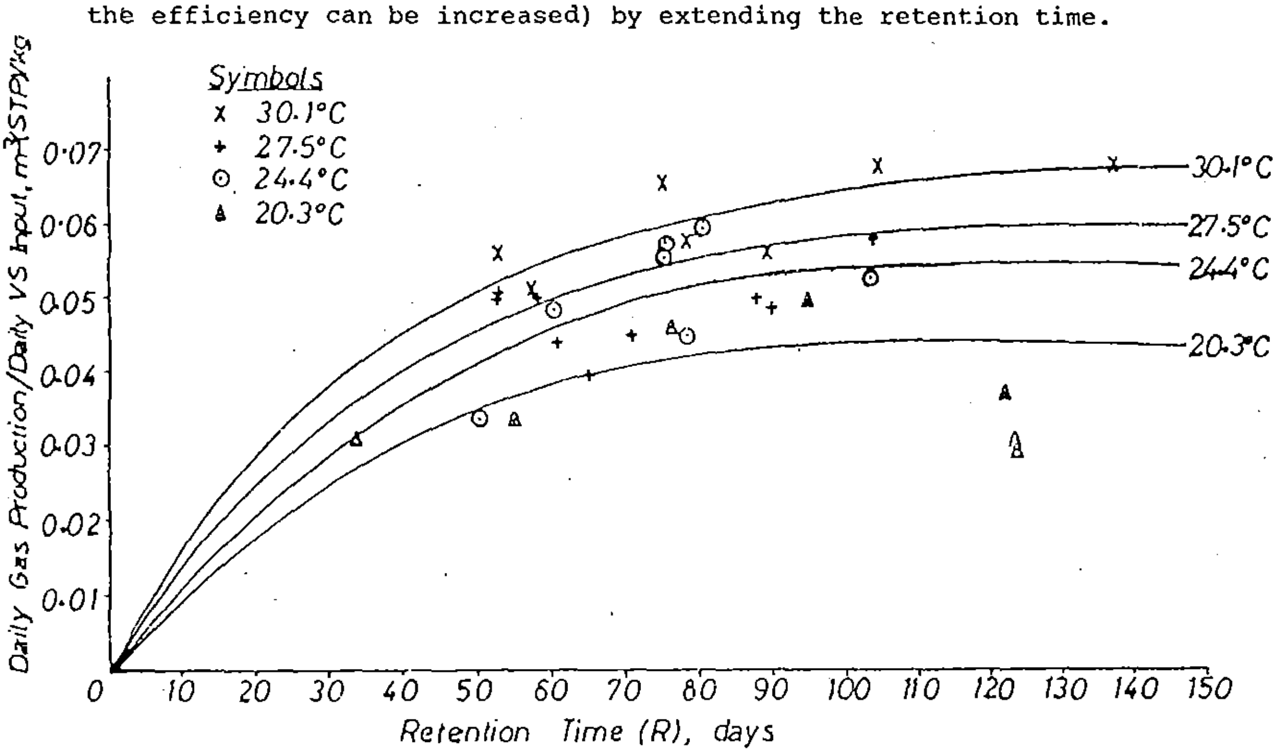


Figure 3.5 Gas Output per unit Volatile Solids Input vs. Retention Time

As an illustration, the gas output (at standard temperature and pressure) per kilogram of volatile solids in buffalo dung is given in Figure 3.5 for different temperatures. The data were collected from semi-continuously fed biogas plants (of the steel drum, concrete dome and tunnel designs) operated for a period of two years. As retention increases, gas production per unit volatile solids and consequently efficiency tend to level off asymptotically.

In Figure 3.6, the rate of gas production was plotted against retention time. For comparison of cases with dfferent substrate input and slurry moisture content, the rate was obtained by dividing daily gas output by substrate concentration and reactor volume. The curves for differnet temperatures, ranging from $20^{\circ}C$ to $30^{\circ}C$ are convex, reaching maximum at their respective retention time R_{max}. The curves slope gently beyond the maximum, as retention time exceeds R_{max}. On the other side of the maxima, however, the curves drop precipitously, signifying wash-out of the microflora. AT the temperature range shown on the graph, R_{max} occurs between 20 and 30 days. At higher temperatures, R_{max} is lower, so the plant can be operated at a lower retention time.

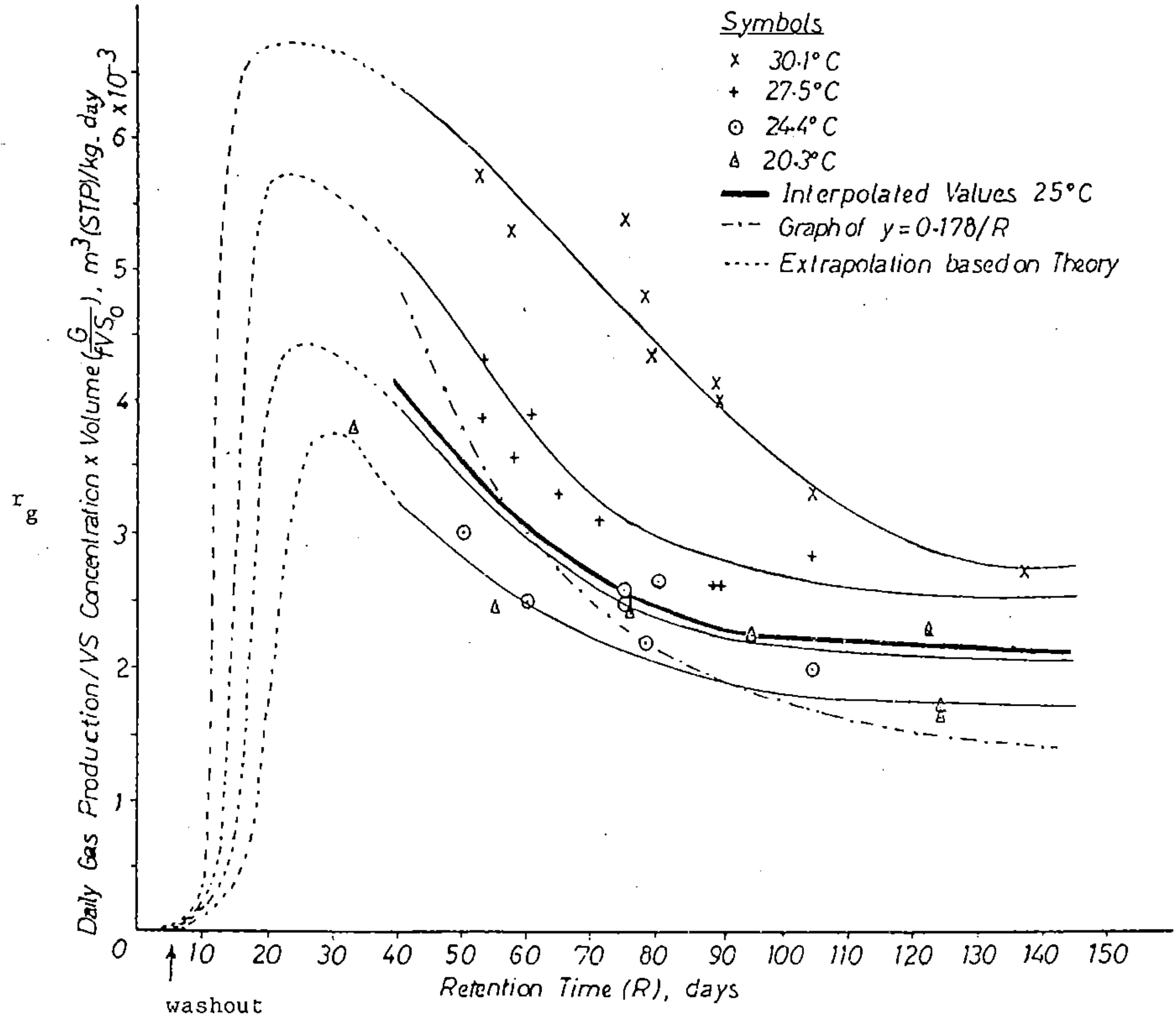


Figure 3.6 Rate of Gas Production vs, Retention Time

The data points obtained from the field trials all lie on the gentle slopes of the graph. The reason is that, of operation of plants in villages, the adoption of a retention time close to the maximum is not advisable, since a decrease in temperature can shift R_{max} to the right, resulting in a wash-out.

3.5 The effect of temperature

The reaction rate of a biogas process is strongly dependent on temperature. The relation can be described using the Arrhenius equation :

$$K = A \exp\left(\frac{-E_{act}}{RT}\right)$$

where : k is the reaction rate constant,
A is the frequency factor, a constant for the reaction,
E_{act} is the activation Energy,
R is the Gas Contant (= 8314 Joules.kg.mole^{-1}.$^{o}K^{-1}$),
T is the Absolute Temperature (^{o}K).

The equation can be transformed to :

$$In(k) = \frac{-E_{act}}{RT} + In(A)$$

A plot of ln(k) against 1/T will give a straight line with slope : $-E/R_{act}$ and intercept : In(A). These constants can therefore be determined experimentally by measuring k at different temperatures.

For a biological system, straight-line-relationship holds as long as the temperature is within the normal range that can be tolerated by the system. At high temperatures, denaturation of proteins and enzymes and eventually death of cells will occur.

Micro-organisms can be roughly divided into three catagories according to their temperature preferences :-

Psychrophilic (cold loving) organisms usually have their optimum growth temperatures below 15^{o}C, and may still grow at 2^{o}C, but at a much slower rate.

Mesophiles (middle loving) have their temperature optima between 20^{o}C and 40^{o}C; most biogas plants are operated in the mesophilic range.

Thermophiles (heat loving) usually have their temperature optima above 45^{o}C.

If the interval between feeding is short compared to the retention time R, the semi-continuous mixed process can be described by the equation :

$$G = C_1 C_2 f V \frac{S_o k}{1 + kR}$$ from section 3.3

Rearranging to determine C_1C_2 and K :

$$R = C_1 C_2 f \frac{V S_o}{G} - \frac{1}{k}$$

R and S_o are adjustable parameters in the process and the dependant variable G, the daily gas production, can be measured experimentally. The fraction of volatile solids or organic matter f, can be obtained by ashing the substrate at high temperature. The product of the two unknown constants : C_1 and C_2 and the kinetic constant : k can therefore be found from gas production measurements by plotting a graph of R verses the variable $\frac{f\ V\ S_o}{G}$. The slope gives C_1C_2 and the intercept $(-\frac{1}{k})$.

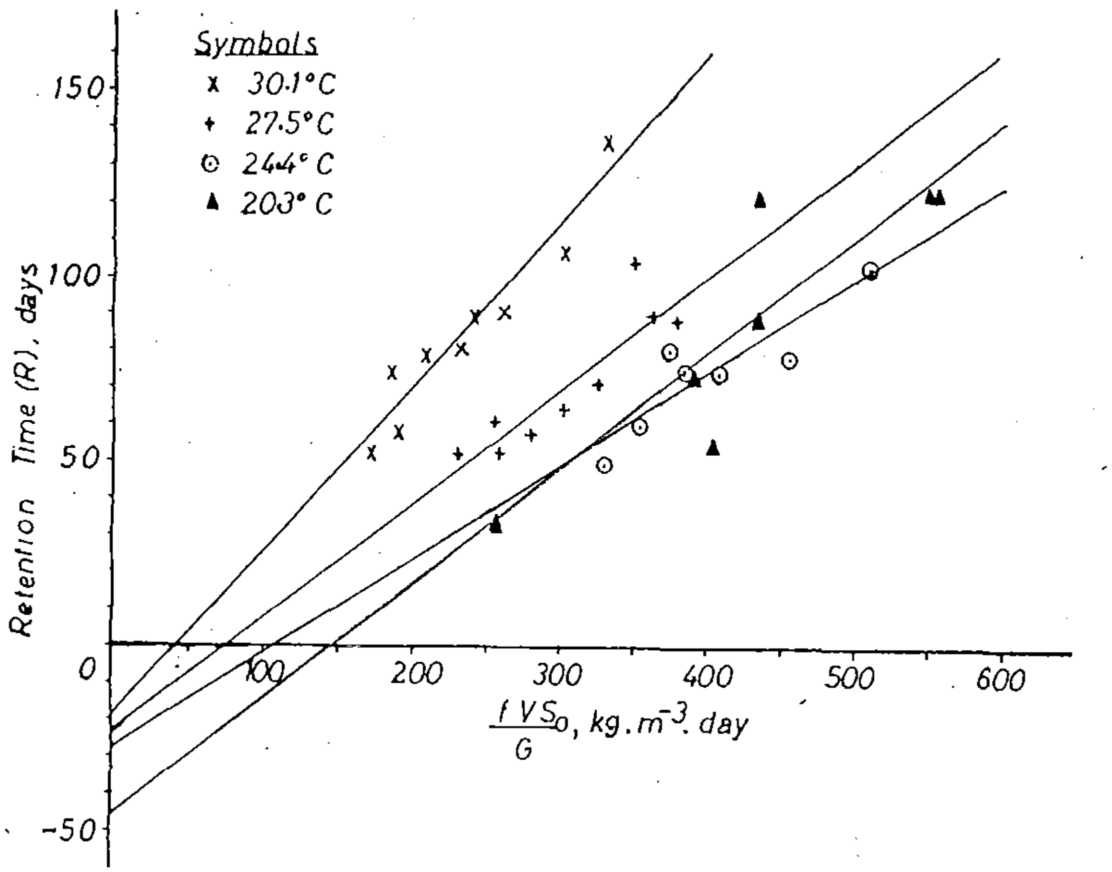


Figure 3.7 Plot of Kinetic Data as a Straight Line Graph

Data were recorded for various types of biogas plants, operated over a period of two years and plots were made for 4 temperatures of the above variables. The value of V, was taken to be the mean slurry volume for displacement digesters, where the slurry volume varies with the volume of gas stored. The plots were made for 30.1, 27.5, 24.4, and 20.3°C and the least squares method was used in obtaining the regression equations and unknowns : C_1C_2 and k. The results are shown in Table 15.2 and plotted in Figure 3.7.

T (^{o}C)	C_1C_2 (m^3/kg dVS)	k (day^{-1})	r	f	Regression Equation
30.1	0.45	0.052	0.95	0.73	R = 0.33 X - 19.34
27.5	0.31	0.044	0.90	0.74	R = 0.23 X - 22.73
24.4	0.25	0.036	0.91	0.61	R = 0.15 X - 27.78
20.3	0.31	0.022	0.88	0.74	R = 0.23 X - 45.45

Table 3.2 Regression Analysis of Kinetic Data from Field Plants

$$X = \frac{V S_o}{G}$$

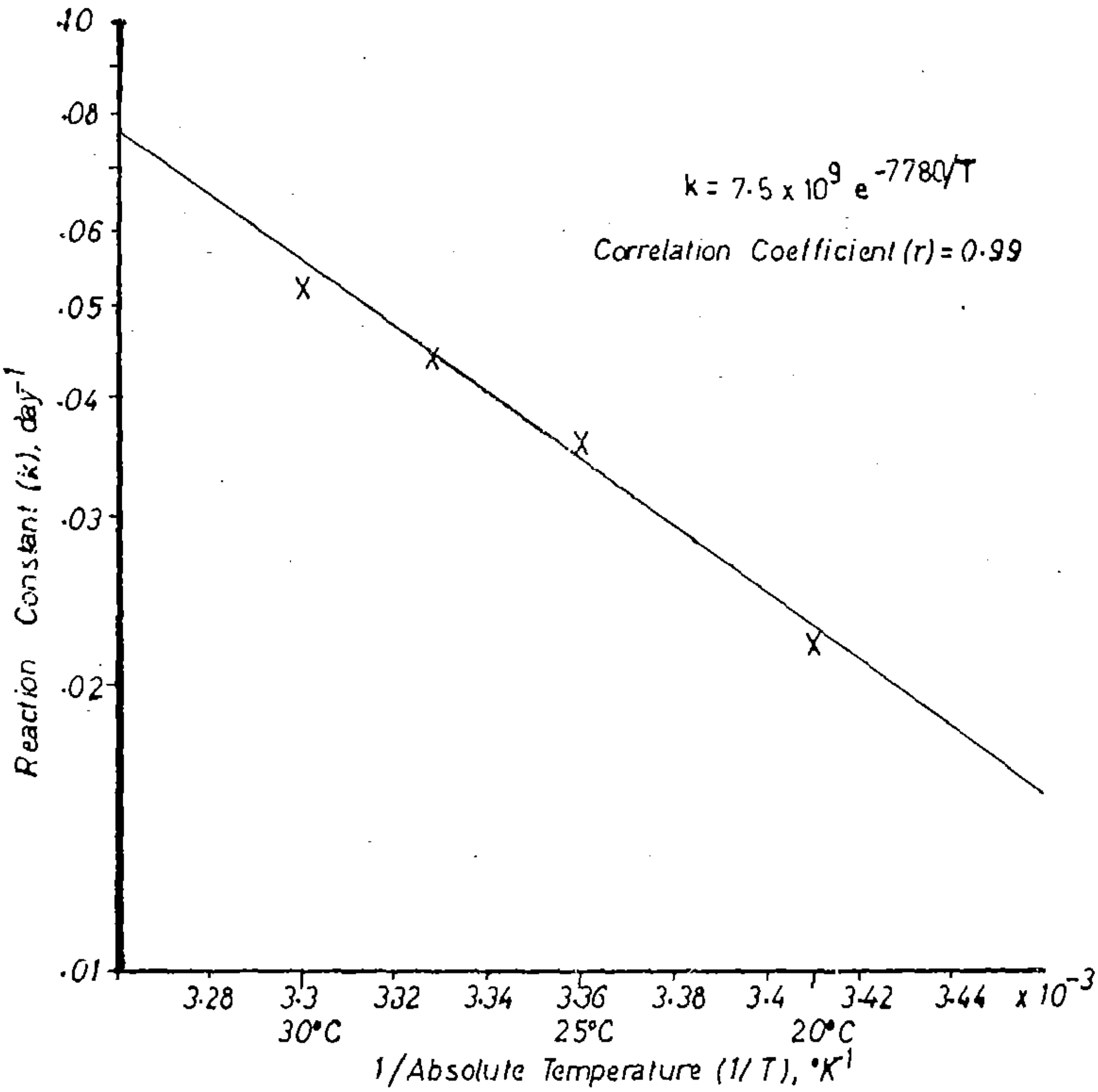


Figure 3.8 Reaction Constant vs. Inverse of Absolute Temperature

The value of f is obtained from ashing dung at 550°C for 4 hours. The correlation coefficient r is high in all cases and the model, though simple, can be used to explain the relationship of the rate of gas production and the other factors in most cases. When ln(k) is plotted against $\frac{1}{T}$, a straight line regression is obtained : Figure 3.8.

Using the least squares method : $A = 7.5 \times 10^9$ and $\frac{E_{act}}{R} = 7780$:

$$K = 7.5 \times 10^9 \exp\left(-\frac{7780}{T}\right)$$

The correlation coefficient r is very high (0.99), showing the strong relationship between the reaction rate constant k and temperature T.

In the southern plains (the Terai) of Nepal, a decrease in digester temperature from a summer maximum of 31°C to a winter minimum of 20°C can cause a reduction of k by 60% and a reduction of daily gas output by 30% to 50%.

Note that the values of C_1C_2 or in fact C_2 depend on temperature and the nature of the feed. The higher the lignin content in the feed, the lower the fraction of digestible volatile solids since lignin is hardly decomposed anaerobically. The quality of the feed varies all year round, being poorest during the dry season when the animals feed on straw or whatever scrubby vegetation that is left. Thus the values of C_1C_2 shown in Table 3.2 appear to have no obvious relationship with temperature.

3.6 The effect of moisture content in slurry

There has been much speculation on the effect of thick slurry (high total solids or low moisture content) on gas output. Experiments performed in India on batch systems ranging from 5% to 12% initial total solids showed that total gas output (over a period of 4 weeks) is maximum between 7% and 9% solids (Idnani et al, 1974). Below 5%, separation of solids occurs and at 12% solids, gas output was only 60% of that at 8% after 4 weeks. It was explained that the high concentration of solids delayed fermentation and the corresponding high viscosity prevented rapid evolution of gas.

In another study, methane production from mesophilic anaerobic fermentation proceeded relatively uninhibited at high solids content below 30%. In fact, the rate of conversion and efficiency were about equal at 10% and 20% initial solids. Neither the rate nor the efficiency were significantly inhibited by solids content up to 32% of the total wet weight. However, when a 40% value was reached, methane formation almost ceased (Jewell et al, 1981).

These results prompted the use of semi-solid or high solid batch fermentation for methane generation by the Jewell group. Since more gas is produced per unit volume, a smaller reactor is possible. More heat is also generated per unit volume and in cool regions, a small reactor volume would require less insulating material.

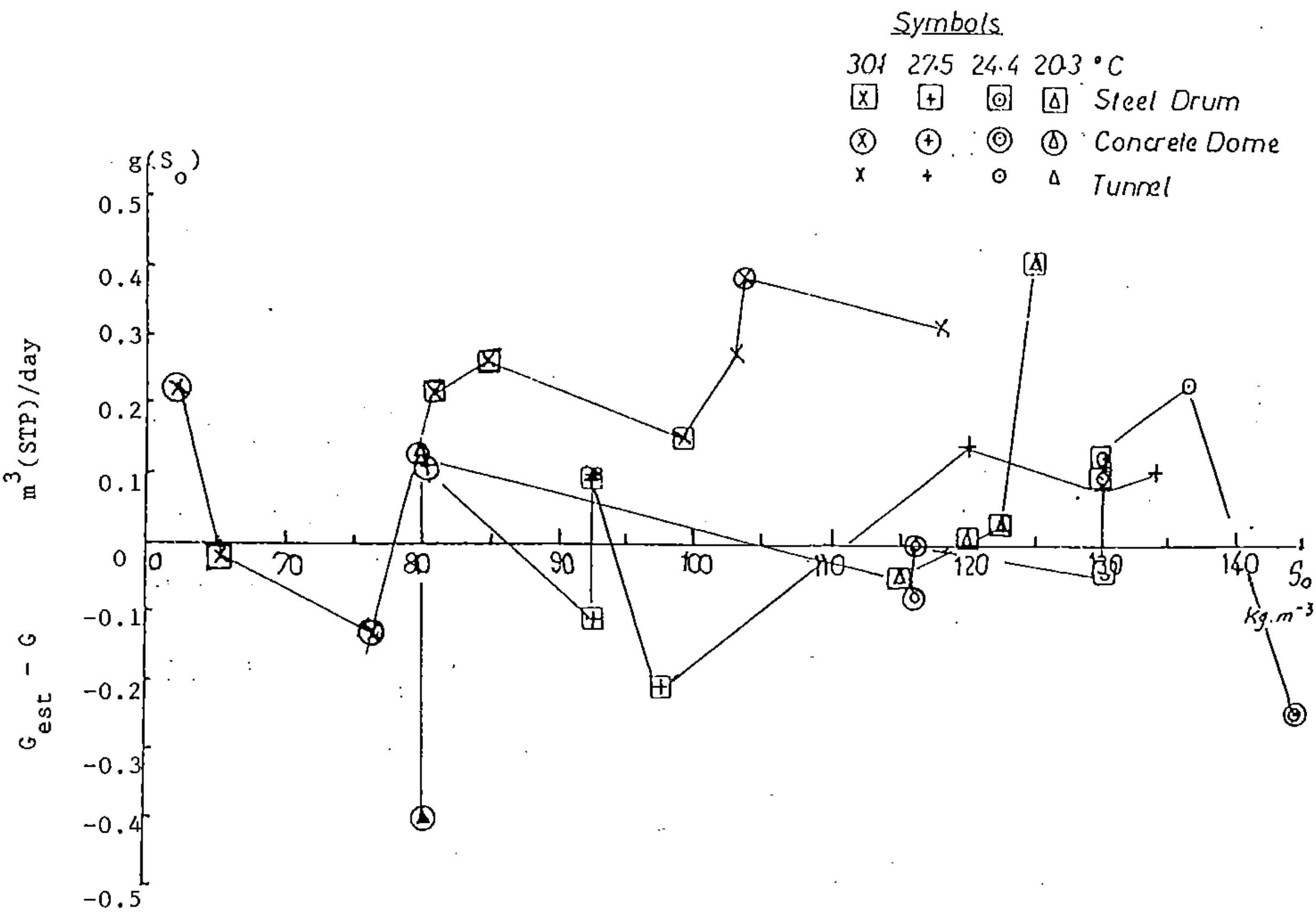


Figure 3.9 Effect of Influent Substrate Concentration on Gas Production Graph of $g(S_o)$

In investigating the effect of moisture content on gas output for the 3 types of semi-continuously fed plants (Drum, Dome, and Tunnel), kinetic data were collected and analysed as shown in the proceeding sections where by regression, the estimate of daily gas production, G_{est}, was found :

$$G_{est} = C_1 C_2 \text{ f V } S_o \text{ k}/(1 + \text{kR})$$

This estimate, G_{est}, deviates from the actual gas production, G, both given at STP. It is the purpose of our analysis here to determine whether the deviation can be ascribed to the effect of slurry moisture content.

Note that the concentration of substrate in the influent, S_o, is an indicator of slurry moisture content in the digester. In our field experiments, the moisture content in the slurry is 1 to 2% less than that in the influent. Because of incomplete mixing inside the digester, it is convenient and adequate to use S_o as an indicator of moisture content of digester slurry.

The deviation of G as measured, from its estimate G_{est} as calculated from the regression equation, can be due to the effect of slurry moisture content, randomness, or other unknown factors. If moisture content alone causes any appreciable effect, G may be expressed in the form :-

$$G = C_1C_2 \; f \; V \; S_o \; k/(1 + kR) \times f(S_o)$$

$= G_{est} \times f(S_o)$ where $f(S_o)$ is some meaningful function of S_o.

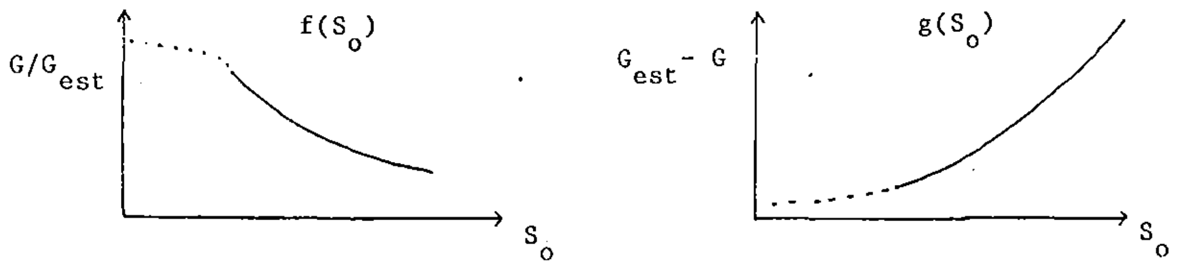
This gives $\underline{f(S_o) = G/G_{est}}$

Another likely possibility for the relationship between G and G_{est} is:

$G = G_{est} - g(S_o)$ where $g(S_o)$ is some meaningful function of S_o

This gives $\underline{g(S_o) = G_{est} - G}$

An intelligent guess of the shapes of $f(S_o)$ and $g(S_o)$ versus S_o is given below. They are exponential functions within a certain range of S_o, and conceivably they vary with temperature.



Thus, if slurry moisture content exerts appreciable effect on gas production, we might be able to determine $f(S_o)$ or $g(S_o)$ for different temperatures, by plotting G/G_{est} versus S_o and $G-G_{est}$ versus S_o. The graphs for the four temperatures ranging from to 20 30°C are depicted in Fig. 3.9 and 3.10. Using curvilinear regression on the data points, the regression equation for each temperature, the corresponding correlation coefficient, r, were calculated, and test of significance were performed.

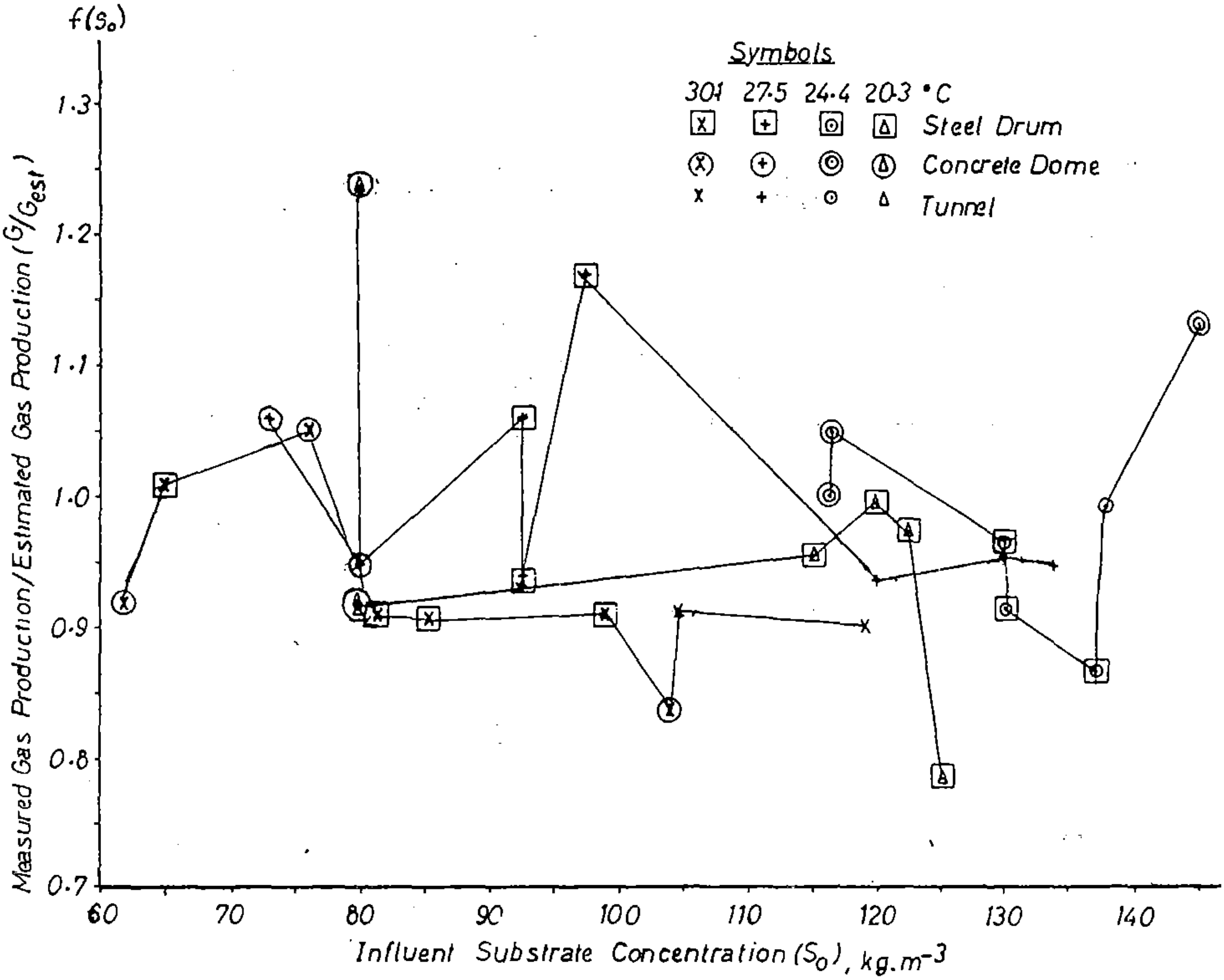


Figure 3.10 Effect of Influent Substrate Conc. on Gas Production, Graph of $f(S_o)$

At 30.1°, the exponential regresssion equation for $g(S_o)$ is :

$$g(S_o) = 0.793 \times 1.004^{S_o - 1}$$

r = 0.58 non-significant at the 5% level (d.f. = 7)

The regression equation for $f(S_o)$ is :

$$f(S_o) = 1.14 \times 1.002^{-S_o}$$

r = 0.66 just non-significant at the 5% level (d.f. = 7)

At 20.3°C, regression analysis gives

$g(S_o) = 0.624 \times 1.005^{S_o} - 1$ with $r = 0.39$, non-significant at 5%

$f(S_o) = 1.245 \times 1.0025^{-S_o}$ with $r = 0.40$, non-significant at 5%

For the other temperatures 24.4 and 27.5°C, the correlation coefficients for both $g(S_o)$ and $f(S_o)$ were even lower (as obvious from Fig. 3.9 & 3.10) and not worth reporting.

The highest correlation occurs at 30.1°C. It appears that $G/G_{est} = f(S_o)$ gives a better description of the relationship since r (0.66) is higher than that of the equation $g(S_o) = G_{est} - G$. However, it still does not (barely) make the 5% significance test. Even if it does, 56% ($1-r^2$ in %) of the variation of G/G_{est} cannot be explained by its relation with S_o.

In other words, at the influent moisture content between 6 to 14.5%, and temperature range 20 - 30°C, the deviation of G from G_{est} cannot be explained by the variation of slurry moisture content. In fact, the deviations are small, as evident from the high correlation coefficients for field data (Table 3.2). They can well be due to randomness in environmental and operational parameters, such as daily random fluctuation in substrate and water input, dung dry-matter, and digester temperature.

In the Steel Drum, Concrete Dome, and Tunnel designs of biogas plants, movement of slurry caused by semi-continuous feeding, and in particular, by displacement of slurry in the latter two designs, probably facilitate the evolution of gas bubbles in the slurry. This would make the effect of slurry thickness less pronounced.

3.7 The effect of Pressure

The effect of pressure is two-fold : it can alter the composition as well as the total output of biogas. Carbon dioxide is soluble in water readily while methane is not. At high pressure, the solubility of carbon dioxide increases proportionally much more than that of methane, with the consequence that the gas will contain a higher percentage of methane.

It was postulated that given the same conditions, drum type plants, which operate at a lower pressure (between 60 and 90 kg/m^2 or mm Water Guage) would deliver more gas than a displacement type plant, the pressure of which is variable up to 1200 mm WG.

How high does the pressure has to get before it can exert substantial effect?

Tests were performed at different times on displacement type plant. In the first experiment with a tunnel plant, gas was allowed to accumulate for one day before being released for measurement. In this way, pressure could build up to as high as 1100 mm (WG). This was compared with the gas production from the plant when it was measured twice daily, since the pressure remained always below 780 mm (WG).

In the second experiment, a dome type plant was connected to a gas meter, so that any gas produced would run through the meter and pressure would not build up (above 40 mm WG). This result was compared with the gas production when measurements were made twice daily. The results are given in Table 3.3. Interestingly, pressure within the testing range has negligible effect on gas output.

Plant Type	Gas Measurement	Pressure (mm WG)	Temp. (^{o}C)	Gas prod. (m^3)	No. Reads
Tunnel	Once daily	variable max : 1100	20.5	1.53	2
	Twice daily	variable max : 780	20.5	1.63	2
	Once daily	variable max : 1100	21.1	2.16	2
	Twice daily	variable max : 780	21.1	2.11	2
Dome	Twice daily	variable max : 1200	24.5	1.74	7
	Meter	Fixed max : 40	24.5	1.67	6

Table 3.3 Effect of Gas Pressure on Gas Output

According to one study in Egypt (El-Halwage, 1980), as operating pressure was elevated, the percentage of carbon dioxide decreased while that of methane increased, reaching a value of 75% methane at a constant pressure of 370 mm (WG). There was also a concomitant decrease in total output of gas, but the total methane output was hardly altered.

On the other hand, our experiment on dome-type plants showed imperceptible differences at the operating pressure range of the plant (Table 3.4).

Pressure, W.G.	Methane, %	Standard Deviation
Constant, 50-100 mm	50.7	2.7
Variable, Max. 850 mm	51.3	4.4
Variable, Max. 1900 mm	52.0	0.8

Table 3.4 Effect of pressure on methane content of biogas from concrete dome plant

From these results, it appears that displacement type (concrete dome and tunnel) which operate at variable high pressures do not suffer a lower gas production, nor do they deliver gas richer in methane than low pressure plants. As pressure is released during gas consumption, dissolved gas in the slurry is also released and the resultant average gas composition would turn out to be similar to that of low pressure plants. Results would perceivably be different if the plants have been operated at constant high pressure (as in the Egyptian study) which supresses the release of dissolved gas from the slurry.

3.8 Discussion of Results

Field tests on the three types of semi-continuously fed biogas plants (drum, dome, and tunnel) built in Nepal indicate little difference in their kinetic behaviour. This result is unexpected as they differ in their positions relative to ground level, in the digester configuration and in the mechanism of slurry displacement (used in the some and tunnel types, but not the drum). These factors should exert considerable effects on slurry agitation and mixing. Lacking the displacement mechanism, the drum plant has the least amount of mixing, although some manual mixing is often sone, by rotating the drum. In the tunnel plant, mixing by displacement is limited by its longitudinal shape, so that there are obvious gradients of the percentages of methane, carbon dioxide, hydrogen and gas output along the entire length of the plant (Figure 3.11). Temperature gradients in the slurry and daily inflow of feed also contribute to mixing, but it is far from uniform in any of these designs. Despite the apparent incongruity, however, analysis indicates that all three processes can be described by a simple unifying model - that for a CSTR - provided that the retention time greatly exceeds the feeding interval. The intrinsic differences between the three processes are small enough to be masked by day to day random fluctuations in the operating conditions.

Another assumption in the model, is the attainment of steady state by the process. However, owing to seasonal fluctuations in temperature and dung dry matter content, the systems can at best attain only quasi steady state. To take this into account, refinement of the model is possible (by careful daily monitoring of various parameters and computer simulation). For practical purposes, this would not be worth the expense as we find the simple model serves well in prediction under field conditions.

Let us now examine the effect of each parameter :-

pH : when the process is in full swing, the slurry produces its own buffer to maintain the pH between 6.5 and 7.0. Adjustment is not necessary, unless the pH drops below 6.5, indicating imbalance in the process.

Variable High Pressure : variations up to 1200 mm (WG) appear to have little influence on total gas output or methane content.

Solid or dry matter content : variations between 6 to 14.5% in the feed (or 5 to 13% in the slurry) do not retard the evolution of gas from the slurry. However, to facilitate flow and mixing in a semi-continuous process, the influent dry matter content should not be more than 14%.

Temperature and Retention time : are the more crucial factors affecting gas production. Reaction rates can decrease by 60% and gas output by 40% to 50% when the temperature falls from 30^{o}C to 20^{o}C. The decrease in gas yield can be compensated by building a larger plant, but to economise on construction cost, digester temperature should be maintained at least 25^{o}C throughout the year (see Volume 1 Chapter 10 and Volume 2 Chapter 6).

The efficiency of conversion increases indefinately with retention time while the rates of conversion or gas output reach their maximum at a certain retention time (R_{max}), depending on the temperature and the nature of the substrate (Figures 3.5 and 3.6). The higher the temperature, the smaller is R_{max} : being 15 to 20 days at 30^{o}C and 30 to 35 days at 20^{o}C. Operation at a retention time equal to R_{max} is conceivably ideal, but it is also precarious. A drop in temperature will shift R_{max} to the right, causing a sharp drop in gas production rate and possibly a washout. Total washout will not occur when cattle dung is used as a substrate, as methanogens are always present. However, at high dilutions, these slow growing organisms would be unable to proliferate.

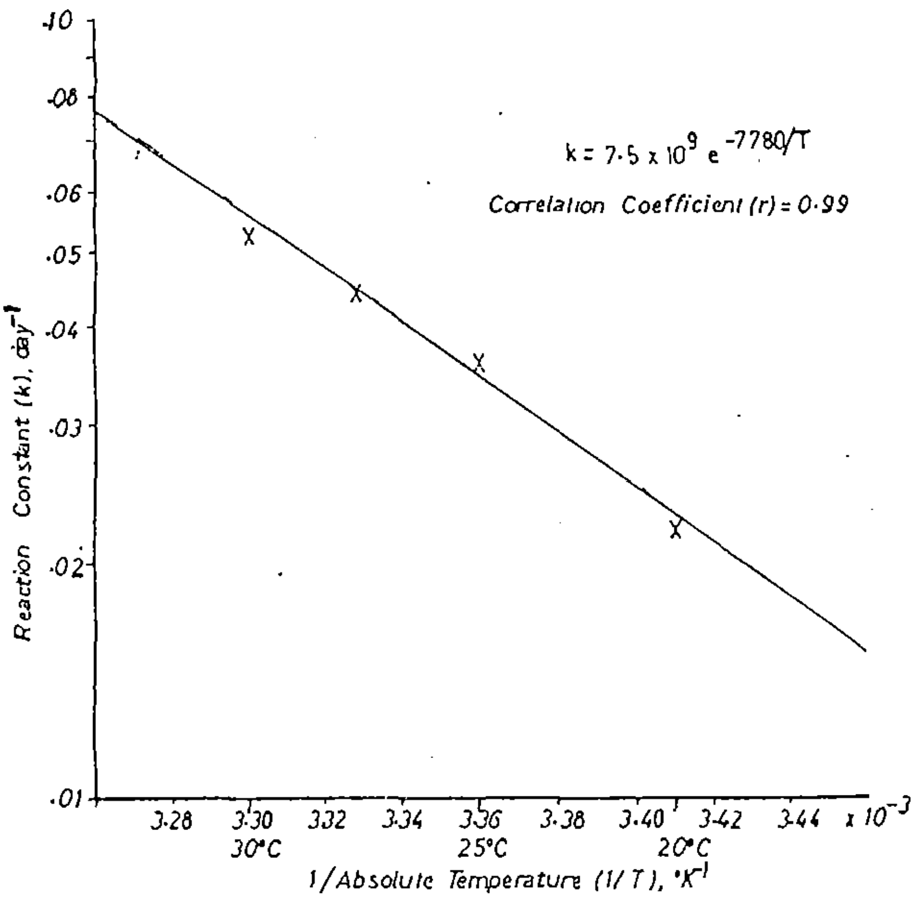


Figure 3.11 Proportions of Different Gases Along the Length of a Tunnel Plant

3.9 Prediction and Optimisation

The model can be used practically to predict and optimise the operation of biogas plants. This can be shown by the use of examples.

1. What is the daily gas output for a drum type biogas plant with 7.1 m^3 digester volume at 25°C, with the recommended daily input of dung and water being 60 kg each? The dry matter of the dung is assumed to be 20%. At present many plants are operated under these conditions.

   (a) First find the retention time : R

$$R = \frac{\text{Digester Working Volume V}}{\text{Daily Input Volume}}$$

The density of the slurry is about 1 kg/litre.

Input volume = 60 x 2 = 120 litres,

$$R = \frac{7.1 \times 10^3}{120} = 59.2 \text{ days.}$$

(b) From the graph 3.6, the rate of gas prduction r_g can be read from the interpolated curve at 25°C :

At R = 59.2 days :

$R_g = 3.0 \times 10^{-3}\ m^3.kg(VS)^{-1}.day^{-1}$ at 25°C.

(c) The daily gas production G is give by :

$$R_g = \frac{G}{S_o\ V\ f} \quad \text{.... (1)}$$

$$\text{where } S_o = \frac{\text{Substrate Input (kg) x Dry Matter (\%)}}{\text{Total Input Volume (litres)}} \times 10 \quad \text{... (2)}$$

$$= \frac{60 \times 20}{120} \times 10\ kg.m^{-3} = 100\ kg.m^{-3}$$

f = 0.74 for dung from grass-fed ruminants,

Thus : $G = R_g\ S_o\ V\ f = 3.0 \times 10^{-3} \times 100 \times 7.1 \times 0.74$
$= 1.58\ m^3$ gas (STP)/day or
$= 1.72\ m^3$ gas at 25°C.

At 30°C, the same calculations would give : $r_g = 5.6 \times 10^{-3}$ and $G = 2.95\ m^3$ gas (STP)/day.

If the influent dry-matter is increased form 100 to 130 $kg.m^{-3}$, (i.e. less water is used, but dung input remains unchanged).

At 25°C, $R = \frac{7.1 \times 10^3}{92.3} = 76.9$ days,

$r_g = 2.55 \times 10^{-3}$ at 25°C and

$G = 1.74 m^3$ gas (STP)/day.

Thus, when a thicker slurry is used, the retention time is longer and more gas is produced.

2. A smaller plant can actually be built to yield the same amount of gas 1.58 m^3 daily, at 25°C by using a higher dry matter content in the influent, say : $S_o = 130\ kg.m^{-3}$ (13% dry matter).

Assuming only 60 kg dung is available

Total input = $\frac{60 \times 20 \times 10}{130}$ using formula (2),

= 92.3 kg or $92.3 \times 10^{-3} m^3$.

Now r_g is a function of R, say f(R) :

$$r_g = \frac{1.58}{130 \times V \times 0.74} = f(R) \text{ using formula (1)}$$

Since $V = 92.3 \times 10^{-3} \times R/r_g = f(R) = \frac{0.178}{R}$.

R can be solved graphically from this equation by plotting the curve

$Y = \frac{0.178}{R}$ on the same graph and finding the intersection with the $25^{o}C$ r_g curve.

The curves intersect at R = 58 days and V = 5.4 m^3

Alternatively, teh graph $r_g = f(R)$ can be estimated by regression analysis and R can be solved numerically.

By increasing the dry matter content of the influent, the retention time is reduced from 59 to 58 days, the digester volume is reduced from 7.1 m^3 to 5.4 m^3 and water for mixing is saved. S_o is increased from 100 to 130 $kg.m^{-3}$ or the dry mater from 10% to 13%, while the dung input and the gas output remain the same. Therefore, by increasing the dry matter content in the slurry, the construction cost as well as water can be economised.

3. Now. $1.53m^3$ (STP) of gas is not usually enough for the daily consumption by a family of 6 persons. Based on the daily requirement of gas one can adjust the following factors to optimise the cost :-

   (a) Digester Volume - affects the capital cost;

   (b) Input dung - affects the operation cost;

   (c) Input water - affects the operation cost.

   The scarcity of water for mixing does pose a problem when the water source is distant or limited during the dry season. The minimum amount of water to give a dry matter content of 13% is used in the following calculations.

   Economic analysis (Volume 1 Chapter 11) showed that the cost of gas plant is a bottleneck for biogas extension. The recurring cost of dung is relatively insignificant in affecting the economics of the biogas plant. However, in practice, gobar is a limiting factor in most village situations.

Now, given a daily gas requirement G, to meet this requirement, Daily gas production $G = r_g \times S_o \times f \times V$

$$= f(R) \times S_o \times f \times V$$

$$= \frac{f(V \times 10^3 \times S_o)}{W_g \times DM} \times S_o \times f \times V$$

Where W_g is the dung input in kilogrammes and DM its dry matter content in % (20% in this calculation).

Dung input W_g and digester volume V are the two indepentent variables that can be manipulated.

Consider the two situations.

(a) If the availability of dung is unlimited, one would built the smallest size of biogas plant that could deliver the required daily volume of gas (say 2.8 m^3 at STP) at the lowest temperature of operation.

If the plant can be maintained at or above 25°C throughout the year, the maximum rate of gas production is :-

$4.5 \times 10^{-3}\ m^3.kg[VS]^{-1}.day^{-1}$ at R = days.

Applying formula (1) : $V = \frac{G}{S_o\ f\ r_g}$

$$= \frac{2.8}{130 \times 0.74 \times 4.5 \times 10^{-3}}$$

$= 6.5\ m^3$ (minimum digester volume)

The amount of input would be :

$F = \frac{V}{R}$ = 260 litres/day

and $W_g = \frac{F\ S_o}{DM \times 10}$

$$= \frac{260 \times 130}{200}$$

= 169 litres/day (169 kg/day).

If the plant can be maintained at 30°C throughout the year:

$r_g = 6.75 \times 10^{-3}$ at R = 20 days when r_g is maximum

$V = 4.3\ m^3$, total input = 215 litres/day, dung = 140 kg/day,

If a retention time of 50 days is used $r_g = 6 \times 10^{-3}$: (30^oC)

$V = 4.85m^3$, total input = 97 litres/day, dung = 63 kg.

Since the difference in the volume of the plant is not great, the lower dung input would be preferred.

(b) If dung is limited, to say 60 kg/day, what is the minimum digester volume required?

To meet a daily biogas requirement of 2.83 m^3/day, at $S_o = 130\ kg.m^{-3}$, the calculation proceed as in 2 :

$$r_g = \frac{2.8}{130 \times 0.74 \times V}$$

$$= \frac{2.8}{130 \times 0.74 \times R \times 92.3 \times 10^{-3}}$$

$$= \frac{0.315}{R} = F(R).$$

Solving for R graphically gives :

at 25^oC R = 135 days and V = $135 \times 92.3 \times 10^{-3} = 12.5\ m^3$;

at 30^oC R = 55 days and V = $55 \times 92.3 \times 10^{-3} = 5.1\ m^3$.

Therefore if the plant can be maintained at 30^oC all the year round, a digester volume of $5.1m^3$ is sufficient.

However, if only 25^oC can be maintained, the digester volume has to be increased to $12.5m^3$. The lower the operating temperature, the larger the digester volume has to be in order to deliver the required volume of gas at limited availablity of substrate.

	Temp. $(T)^oC$	Digester Volume (v), m^3	Mass Dung (W_g), kg	Ret. Time (R), days	Gas Output (G) m^3
(a)	25	6.5	169	25	2.8
	30	4.3	140	20	2.8
(b)	25	12.5	60	135	2.8
	30	5.1	60	55	2.8

Table 3.4 Results of Calculations based on Model

(a) Substrate unlimiting - digester volume smallest and r_g maximum.

(b) Substrate limiting (60 kg gobar/day).

Appendix to Figure 3.7

For each temperature, the type of plants and the number of readings are given in ascending order of data points along the x-axis.

Temperature

30.1°C	Plant type	C	S	S	C	T	S	T	S	C
	No. readings	19	6	6	24	19	23	25	13	12
27.5	Plant type	C	T	C	S	S	S	S	T	T
	No. readings	13	10	13	10	4	3	12	13	15
24.4	Plant type	S	T	C	C	C	S	S		
	No. readings	2	18	6	7	28	2	2		
20.3	Plant type	S	S	S	C	S	C	C		
	No. readings	2	2	3	37	17	24	11		

The codes are : S -- Steel Drum
C -- Concrete Dome
T -- Tunnel

Chapter 4 EXPERIMENTAL APPROACH TO BIOGAS TECHNOLOGY D. Fulford

The initial biogas extension programme in Nepal was based on the standard KVIC steel drum design of biogas plant (ESCAP). Several design weaknesses were quickly discovered in the course of the construction of the first 95 plants by DCS in 1974/5 for farmers in the Terai region of the Lumbini zone of Nepal. The water table in many places was high, so that the deep holes for the standard straight plant were difficult to dig, as they kept filling with water. The flexible plastic gas outlet pipe at the top of the drum became brittle after a few months in the strong sunlight and had to be replaced regularly. The steel gas drums started to corrode.

These design weaknesses were of the type that could only be discovered by building a number of plants for customers and then making follow-up visits to these customers afterwards. The replacement of the plastic hose was only a real problem to farmers who lived in remoter areas and had to spend time going to a town where a new piece could be purchased. Such farmers also did not have the screwdrivers and spanners needed to loosen the hose clips to change the hose. The depth of the straight design only became a problem where the water table was high . These two weaknesses were reduced by modifying the design (see Volume I, Chapter 2). The steel drum was also designed to use less steel and to be lighter in weight.

These experiences set the pattern for the work of research and development in DCS. Emphasis was laid on the field testing of new ideas in a local setting, with local people. While there are many design of biogas plants available (ESCAP, Maramba, Pyle), very few designs will work well in the severe economic and environmental conditions in Nepal.

4.1 Follow-up

The first 95 biogas plants built by DCS were visited 3 times by DCS research staff (Finlay). Once the Gobar Gas Company was set up, their field staff also made yearly follow-up visits to these plants. The first visit was made soon after the last of these plants was completed. It was discovered that 7 of the 95 plants had cracks in the brickwork, mainly due to poor backfilling behind the brick walls. These plants were repaired and the masons taught to do backfilling more effectively. 9 of the 95 main gas valves, which were gate valves, were broken because the farmers tended to turn them the wrong way. These broken valves were replaced and plug cocks were ordered for use in the future. During these visits, any errors made by the owners in operating the plants, such as feeding with too little dung, were also noted and the correct procedures explained to the farmers.

One major problem revealed by all three follow-up visits, was that of the corrosion of the steel gas drums. Poor quality steel had been used in the manufacture of these drums and chlorinated rubber paint had been used to protect them. 86 of these tanks were showing signs of corrosion less than a year after they were installed. After the first follow-up visit, all of the drums were cleaned and repainted with bituminous paint (high build black). This reduced the rate of corrosion, but did not eliminate it.

4.2 Adaptive Research on Gas Storage Systems

Several attempts were made to develop a floating gas drum made from a material other than steel. A drum made from high density polyethylene sheet (3 mm), hot air welded together, was made for DCS by a company skilled in the process. The drum was damaged in transit, and cracked again, while in use after being repaired. HDPE tends to flex when it is treated by sunlight : it softens and expands. Since the top edge of the drum was made by welding two sheets in different planes together, the sheets cracked as they attempted to flex in different directions. This drum was more expensive than steel. Enquiries about the cost of drums made from glass fibre bonded with polyester or epoxy resins suggested that this type of drum would also be more expensive than a steel one for a customer in Nepal.

Another approach was to use a floating drum made from ferrocement (Raman, Fulford) : a sand/cement mortar(25 mm thick) reinforced with wire mesh. The first design that was made : a hemispherical shape (Figure 4.1) proved to be the strongest and most successful. Other, squarer shapes tended to crack more easily, especially near the corners, where stresses are concentrated. One very interesting design, which unfortunately did not work, used a trapezoidal gas container, which was hinged at one end (Figure 4.2). It proved difficult to seal the corners of the gas holder against leaks.

All ferrocement gas holders were very heavy and difficult to transport and to put in place. the first few were made in DCS and taken to site Shear legs and a chain hoist were required to lift them over the digester pits. Lifting and transporting these drums put severe strains on the ferrocement walls and several cracked before they could be used.

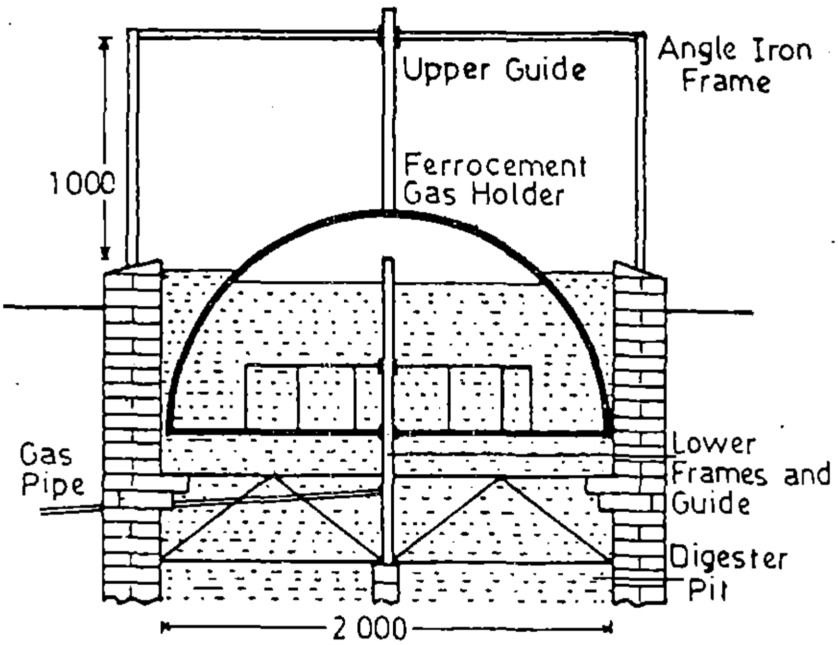


Fig. 4.1 A Design of Hemispherical Ferrocement Gas Holder

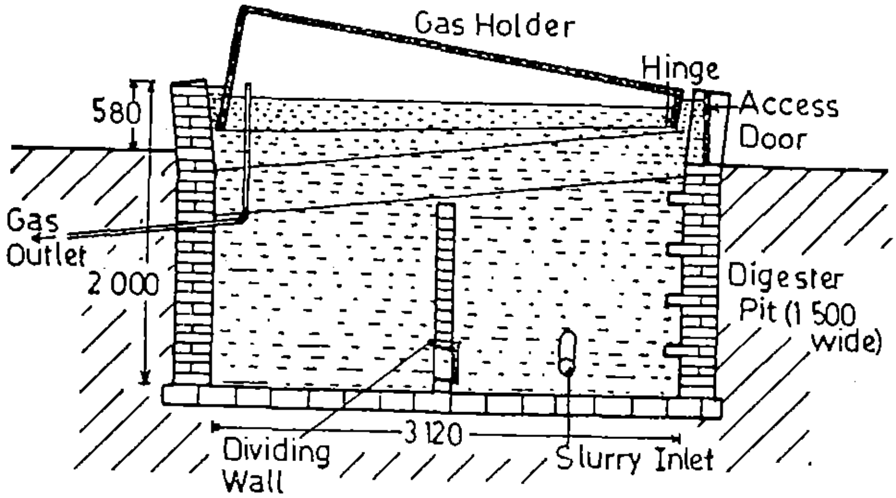


Fig. 4.2 Hinged Trapizoidal Ferrocement Gas Holder

Another problem was the sealing of the inside of the cement structures to make them gas tight. Cement plaster is slightly porous to biogas, even when it is well made. The use of chlorinated rubber paint proved ineffective, as it tended to flake off the surface when immersed in the slurry. Epoxy paint did work, but it was difficult to dry out the cement plaster to the point that the paint would adhere to it. Also the use of such paints, with strong smelling and toxic solvents, was very difficult in an enclosed space, such as inside a gas drum. Labourers were quickly affected by the fumes and could work only for short periods.

The alternative designs of gas holders were made for farmers in the field. The customer was told of the experimental nature of the design and usually paid a reduced price for the plant. They were not at all happy if the experimental design failed, as most of them did. Usually the ferrocement drum was replaced with one made from steel, at DCS expense. In one place, a whole new conventional biogas plant had to be built. In another place, the customer wanted his money back. One of the hemispherical drums lasted 3 years, with yearly painting, before it was replaced with a steel one.

Such an approach was not helpful to the reputation of biogas technology in Nepal. Although new designs must be field tested, they should be first tested at a prototype level, before being offered to customers. A test site was therefore set up, where futher prototype designs of biogas plant could be built and thoroughly tested before field tests were started.

4.3 Displacement Type Biogas Plants

Alongside the attempts to make a floating gas holder from ferrocement, consideration was also given to the idea of a fixed gas storage volume and the use of displacement principle (see Volume I, Chapter 3). One plant was built to the early Chinese design (McGarry), which had a flat cover for the top. The cover also acted as the floor of the slurry reservoir (Figure 4.3). This design gave many problems : the slurry in the large reservoir tended to dry out in the sun, or became diluted when it rained. The use of a plastic tent over the reservoir to protect the slurry proved unsuccessful. Local children and animals very quickly destroyed the tent. The flat roof of the gas storage volume was difficult to make gas tight. Internal gas pressure lifted the roof slightly, so it flexed at the corners and cracked the cement plaster seal.

The design of biogas plant that eventually proved successful when tested by DCS, was based on the dome shaped displacement digesters, also developed in China (SPIIBD, van Buren). The first was built of brick masonry, including a brick dome, but it proved expensive (Fulford). The use of a concrete dome cast in-place overa mud mould was adopted as the standard DCS design (see Volume I, Chapter 3 for full technical details).

The sealing of the concrete continued to be a problem. Bitumen spread over the surface of the dome tended to form pin holes, if the concrete was even slightly damp. Eventually the idea of a plastic emulsion paint was tested (Chen). Advice from paint manufacturers (Indofil) suggested that acrylic paint was more stable than vinyl emulsion in a damp atmosphere. A locally available acrylic emulsion paint has now been used very successfully in over 550 dome type biogas plants. As an emulsion in water, it does not give off strong smelling and toxic fumes. It can be mixed into the cement plaster to give an impervious seal and the concrete does not have to be dry before this plaster is applied.

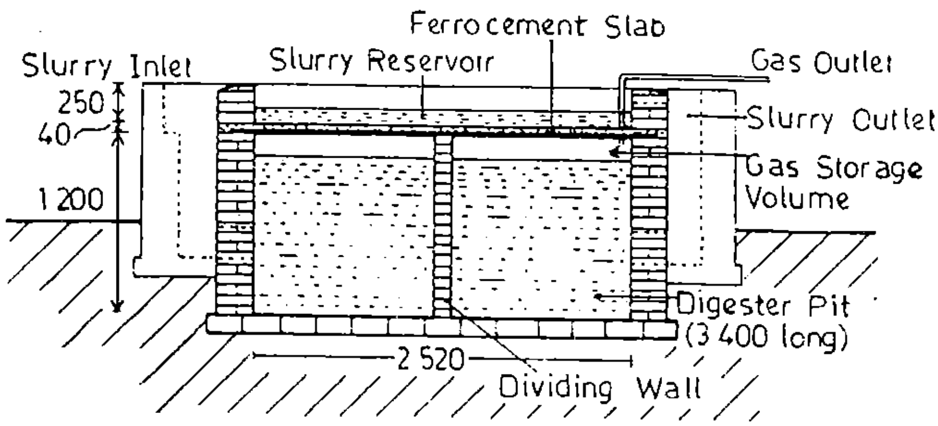


Fig. 4.3 Flat Roofed Displacement Digester

4.4 Field Testing of Dome Plants

Once the prototype dome plant worked on a test site, DCS was able to make careful plans for the field testing of this design, based on our previous experience. 12 plants were used as test sample, built for customers in the Pokhara area. The customers were expected to pay a market price for the new design, so as not to set a precedent for low cost, subsidised plants in the area. However, DCS set aside a 100% guarantee fund for each of these plants, so that failures could be put right quickly, if they occured. Several members of staff from the Gobar Gas Company helped in the building of these plants, so they could be trained.

Two follow-up visits were made to these plants by research staff, as well as the normal regular visits by the Gobar Gas Company extension staff (Shrestha, Devkota). The second visit also included 11 plants built by the Gobar Gas Company on a normal commercial basis (with a 7% guarantee charge, paid by the customer). All the plants were working well and there were no signs of leaking or cracking in the domes. The major problems were leaking from the main gas valves, which were not designed for the higher gas pressures from a displacement digester, and occasional blockage of the gas outlet by slurry. In some plants, the slurry seemed to be leaking through the digester, outlet and reservoir walls, as it was not overflowing from the plant in the same volumes it was put in. While the plaster lining of the dome was gas tight, due to the plastic emulsion, the plaster lining of the other parts of the plant was not water tight.

The problem of slurry blocking the gas outlet is related to the first problem of gas leaks. If the dome is filled with gas each day, slurry is displaced into the reservoir and overflows out of the plant. If gas leaks mean that the dome is not full of gas, the plant can be overfilled with slurry, allowing it to come out of the gas pipe. The gas outlet pipe was made larger and a removable cap fitted to the top, so the pipe could be cleared easily in later models. The level of the slurry reservoir floor relative to the top of the dome was also altered in later design drawings, so that the chance of the slurry level in the dome being too high was reduced. Work was also started on the design of biogas valves that would not leak at the pressures produced by displacement digesters (see Volume I, Chapter 6).:

The regular follow-up visits by Gobar Gas Company staff also pointed out some other problems. Some of the dome plants built in one area did not appear to store enough gas. One plant was emptied and the inside of the dome measured and it proved to be the wrong shape. The metal template, used to shape the mud mould, had been wrongly placed, so the dome was too wide and flat. The template was redesigned with vertical and horizontal struts that could be checked against a plumbline or datum string.

The problem of slurry leaking through the plastered walls was repeated in a few other places, mainly where the soil was sandy and porous. This has not fully been solved, although the use of a cement, lime (Calcium Hydroxide) and sand mortar (1:1:3) should be effective. Water Glass (Sodium Silicate) could also be used in the plaster mix (McGarry).

4.5 Tunnel Plant Experiments

The tunnel plant design was inspired by work done at Cornell university (New York) on plug flow digesters (Jewell). These digesters were supposed to be more efficient than mixed reactors and could use a thicker slurry (up to 15% solids). One plant was built on a test site, with a steel arched roof, divided into sections with baffles. The gas produced in each section could be measured separately. If it was found that most of the gas was produced in the middle part of the tunnel, the total length of the tunnel could have been reduced.

The tunnel plant is not a plug flow reactor, as there is horizontal mixing as the slurry is displaced by the gas stored or being used from the gas storage volume (see Volume I, Chapter 4). The results of a year's tests on this experimental tunnel plant and a dome plant on the test site, indicate that both designs behave in the same way, when fed similar amounts of feed (see Chapter 3). Biogas was produced along most of the length of the tunnel, except near the inlet, where the populations of bacteria were adjusting to the feed. A reasonable amount of biogas was still being produced from the slurry coming into the reservoir, indicating that the tunnel should be made longer, not shorter.

A second tunnel plant was built on the test site, to test the construction techniques. Various methods for fixing the plastics sheet lining to the gas storage volume were tested in this plant. The length of this test plant was too short for it to be used for gas production tests. Also slurry leaked through the plastered walls, so it could not be retained in the plant.

A test sample of 6 plants , built to a design based on these test site results (see Volume I, Chapter 4), were constructed for customers in the Butwal area. DCS set aside a 100% guarantee fund for each plant. The roof sections were all made on the test site and transported to the sites by rickshaw. One design weakness was discovered : part of the arched roof, which acted as floor for the slurry reservoir, lifted up under internal gas pressure. The use of a mass of weak concrete, keyed into the side walls above these sections, supplied the necessary counterweight.

All 6 tunnel plants appear to have worked well, with no leaks from the plastics lining. Staff of the Gobar Gas Company, however, question the commercial viability of the tunnel plant. If the roof sections are made in a central place, they would be difficult to transport to a remote site. If they are made on site, a mason and a helper would have to spend several days casting them, before the construction of the plant could be started. Company masons are also anxious that the plastic lining could be easily punctured while they are putting it in place. At present, the possible advantages of the tunnel design are insufficient to warrent a change from the present emphasis on the dome design, except in special circumstances.

4.6 Future Directions

The work of development of the tunnel plant has suggested another design of biogas plant that could help to fill a gap in the present range. The extended dome design (see Volume I, Chapter 14), which has domed ends with a tunnel section in between, could be made in larger sizes, up to EP95 (95 cu.m internal volume), producing about 20 cu.m of gas a day from 600 kg of cattle dung (from 40 to 50 animals). A smaller version of this extended dome design, also with the roof section cast-in-place, could be used in positions where the soil was too weak to support a dome plant, or where deep pits could not be dug because the water table was too high.

The staff of the Gobar Gas Company have been involved in the approach to research and development pioneered by DCS in Nepal and they will continue to follow this approach in their own work.

4.7 Lessons Learned

Ideally, the development of a new design of appropriate technology such as a biogas plant, should follow a natural progress. Once the requirements and specifications are defined, a prototype design can be made and tested in a laboratory or on a test site. Modifications are made to the prototype until it works well and can be produced fairly easily. A limited number of units are then made and sold to customers for field testing. The customers should pay a market price for their unit, but finance must be available to provide proper guarantees and protection to them. Close and careful follow-up is required, with a quick response to repair or to make modifications if failures occur, due to design faults or poor construction. This is essential in order to keep people's confidence in the technology and the extension organisation.

Once an effective design is complete, extension staff must be trained to make the units, so they can be sold on a commercial basis. Close cooperation between R & D staff and extension staff assists and speeds up this operation. An over-emphasis on either side, on R & D or on extension, can lead to weaknesses in the progress.

Chapter 5a EXPERIMENTAL TECHNIQUES

M. Lau-Wong

5a.1 Total Gas Output

The amount of gas produced daily by a biogas plant can be deduced if both the volume of the gas in the gas holder and the gas consumption of the appliances are known. The latter can be conveniently measured by commercial wet-type gas meters. These meters operate at low gas pressures (less than 200 mm W.C.) and therefore are suitable for steel drum type plants. For the Cement Dome and the Tunnel Plants, which operate at higher pressures, a pressure regulator can be connected in series with the meter to prevent gas leakage and inaccurate readings resulting from high pressure. DCS has made its own design of wet gas meters that operate at higher pressures (see Volume 2, Chapter 5).

Calculation of the Volume of Gas in the Gas Holder

1. Floating Steel Drum (see Fig. 5a.1)

   Measurements required :

   l_1 = height of the steel drum above slurry in the digester, metres.

   l_2 = gas pressure as indicated by water manometer, metre WC

   Plant dimensions required :

   r = internal diameter of steel drum, metre

   Since the drum has weight, the gas pressure inside is above atmospheric pressure, and consequently the slurry level inside the drum is slightly lower than that outside. The difference, l_2, can be measured with a water manometer connected to the gas pipe outlet. It is assumed that the specific gravity of the slurry is roughly equal to that of water, since the difference is less than 10% (Table A.1).

   Volume of gas V = $\pi r^2 (l_1 + l_2)$

   The unit of V is in cubic metre, m^3

2. Cement Dome (see Figure 5a.2)

   It is less straight forward to calculate the gas volume of masonry plants built underground than for steel drum plants.

Fig. 5a1 Floating Steel Drum

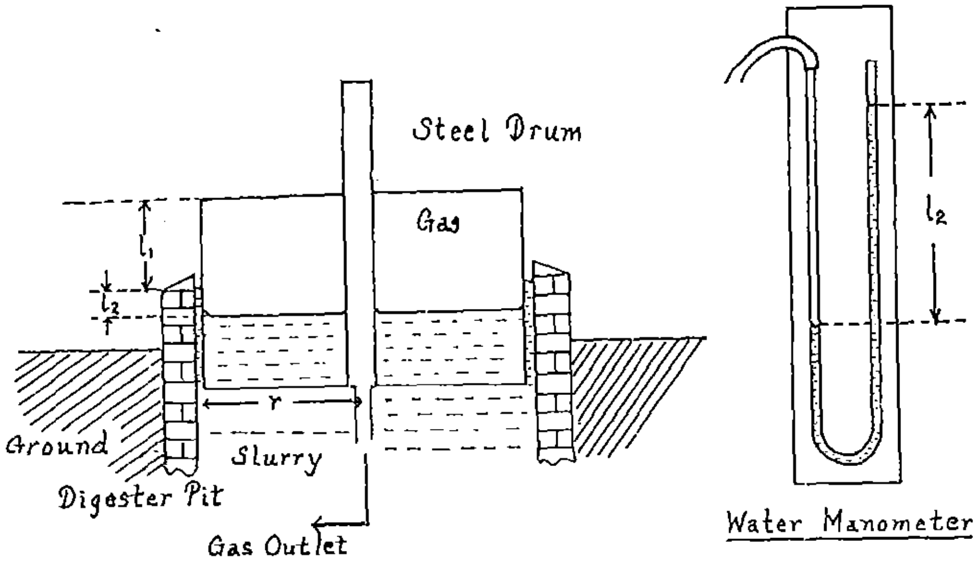


Fig. 5a2 Cement Dome

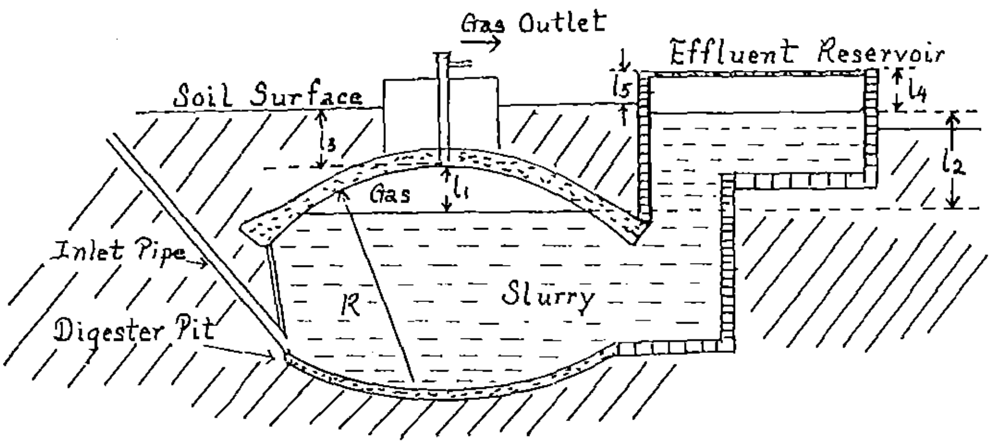
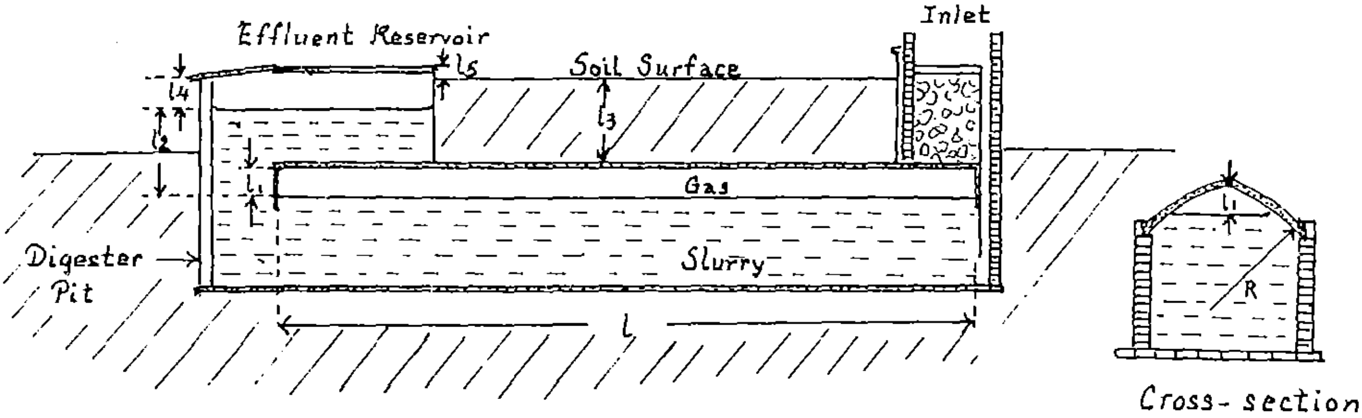


Fig. 5a3 Tunnel Plant



Measurements required :

l_2 = gas pressure measured by water manometer, metre

l_4 = depth of slurry in effluent reservoir, metre

Plant dimensions required :

l_3 = depth of the apex of the dome from the soil surface, metre

l_5 = vertical distance between the soil surface and the edge of the effluent reservoir, metre

R = radius of the domes, metre.

From these measurements, the vertical distance between the apex of the dome and slurry surface in the digester, l_1, can be found.

$$l_1 = l_2 + l_4 - l_5 - l_3$$

Volume of gas $V = l_1^2 (R - l_1/3)$

Unit of V in cubic meter

3. Tunnel Plant

All measurements are similar to that of the Cement Dome plant. Cross-sectional area, A, of the dome occupied by gas is

$$A = R^2 \cos^{-1} (1 - l_1/R) - (R - l_1)\ (2Rl_1 - l_1^2)^{1/2}$$

Since the plant has the same cross-section along its longitudinal axis (length l),

Volume of gas V = l x A (unit in cubic metre)

Conversion to Standard Temperature and Pressure (STP)

For comparison of gas production at different temperature and pressure, it is necessary to use the same standard of reference, such as the Standard Temperature (25^oC) and Pressure (1 atmosphere) or in brief STP. One atmosphere is equal to 10.363 metre WC at 25^oC. Assuming ideal gas law holds,

$$P_t\ V_{t/}\ T_t = P_1V_1/T_1$$

Where the subscript t denotes the STP state and the subscript denotes the state of the gas in the gas holder. P_1, V_1, T_1 can be measured. P_t = 10.363 mWC, T_t = 298^oK. Therefore, the STP volume, V_t, can be easily calculated :

$$V_t = T_t/P_t\ (P_1V_1/T_1)$$

Total Output

It is best to measure the gas volume at certain fixed time every day when the gas is not being used. The STP volume, V_t, of the gas in the holder is measured and calculated as shown above. V_t is used to subtract the STP volume of the previous day (say V_{t-1}). The amount of gas used by appliances (say V_R) is obtained from the meter reading and converted to its STP value as well. Therefore,

$$\text{Daily gas output} = V_t - V_{t-1} + V_R$$

Note that $V_t - V_{t-1}$ can be negative. To get a reliable estimate, daily measurements should be taken over a period of time, for at least a week, during which variables like feed input, temperature, and retention time are the same.

If a gas meter is not available to measure the gas consumption of appliances, a rough estimate of the gas production can be obtained by measuring the gas volume at the beginning and the end of an interval during which gas is not used. For example, if the gas volume measured at 8 pm is 0.8 m^3 and at 6 am the next day is 1.9 m^3. The gas produced in the 10 hour span is 1.1 m^3. Therefore, in 24 hours, the gas production is roughly 2.6 m^3.

5a.2 Gas Composition

Biogas comprises a variety of gases. Methane is the main combustible component, varying from 50% to a high of 80%. The rest is mainly carbon dioxide, with traces of hydrogen sulphide which is corrosive.

The most accurate method for determining the gas composition is by gas chromatography. A gas sample is passed through a column packed with material with different affinities for the different gas components. The components are thus separated and emerge successively with the carrier gas. A detector is located at the outlet of the column to measure the physical property of the gases. The time and sequence in which they emerge help to identify them, and the peak areas indicate their concentration. Two commonly used detectors are thermal conductivity and flame ionization detectors.

The ORSAT Apparatus

The ORSAT Apparatus is used for determining the percentage of CO_2, O_2, CO, H_2 in flue gas and furnace gas. It is less expensive than gas chromatographs, more simple to maintain, and reasonably accurate for measuring the composition of biogas.

The Apparatus consists of :-

(a) A 100 ml measuring burette with water jacket, connected to a levelling bottle filled with an acidic solution (2M H_2SO_4, sulphuric acid) saturated with salt. This solution prevents the absorption of water soluble and acidic gases.

(b) Absorption pipettes with 2-way stop cock (see fig. 5a4) :-
For the absorption of carbon dioxide, the solution required is 6M sodium hydroxide (240g NaOH/1000 ml distilled water). Potassium hydroxide can be used instead but it is more expensive.
Potassium hydroxide can be used instead but it is more expensive.
Oxygen is absorbed by an alkaline pyrogallol solution (10g pyrogallol/20 ml distilled water and 19 g NaOH/70 ml distilled water) prepared fresh every time.

(c) Absorption pipette with spirals of copper wire :
Carbon monoxide, CO, is absorbed in an ammoniacal cuprous chloride solution. Since the presence of CO is negligible, it is not measured.

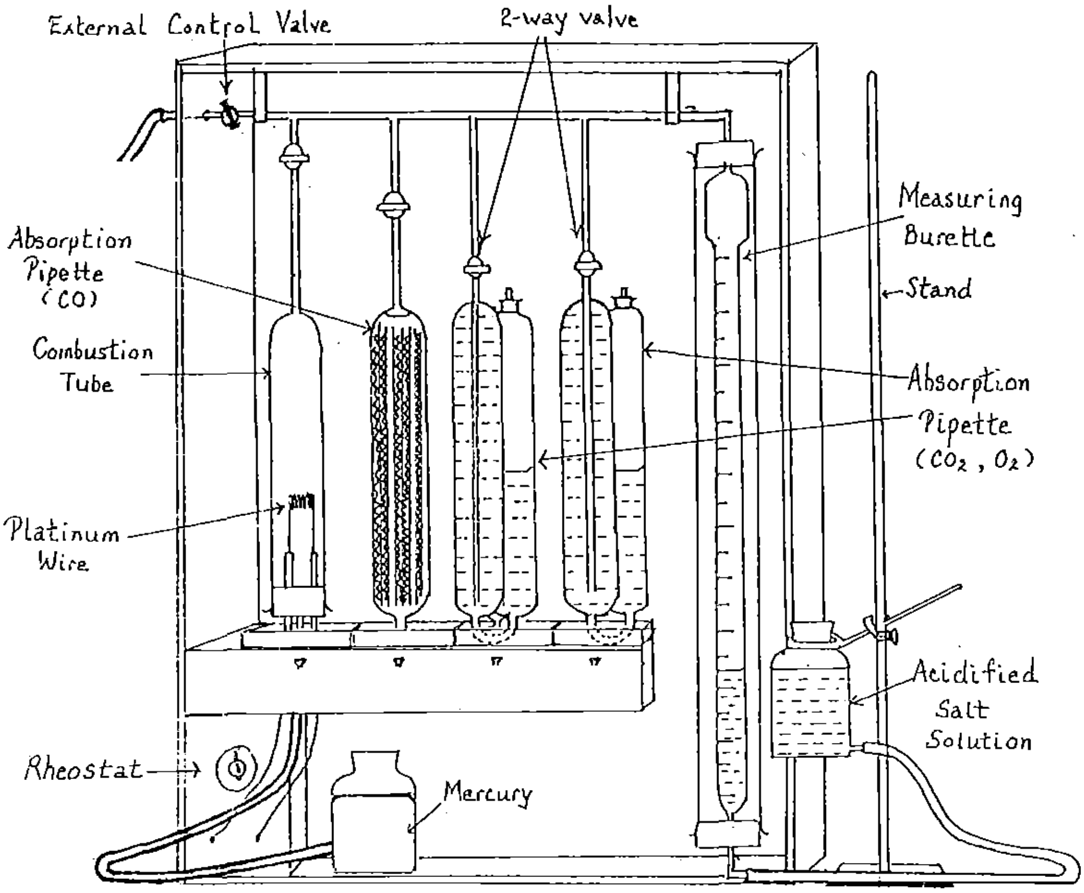


Fig. 5a4 The ORSAT Apparatus

(d) Slow combustion tube, for the determining of hydrogen and methane. The tube is fitted with a platinum spiral heated with a maximum of 4.5 V at the two terminals. A rheostat is used to adjust the voltage and thus the temperature of the wire. The gas volume inside the combustion tube is controlled with a levelling reservoir of mercury. Before the analysis, the tube is filled with mercury to a fixed level.

Procedure :-

(a) Leave the external control tap open and the taps of all the pipettes and combustion tube closed.

(b) A gas sample of 100 ml is passed into the burette by lowering the levelling bottle A that contains the acidic salt solution. Note that before any reading is taken at the burette, the meniscus inside should be adjusted to the same level as that in the levelling bottle.

(c) The external control tap is closed and the 2-way tap of the CO_2 absorption pipette is opened to a 'Y' position. The levelling bottle A is raised until all the gas in the burette is bubbled through the sodium hydroxide solution in the pipette. The scrubbed gas is then passed back into the burette and the reading is noted. This step is repeated 3 or 4 times until 2 consecutive readings are identical. Call this reading C_1.

(d) The scrubbed gas is returned to the absorption pipette. The burette is flushed with air several times by raising and lowering the levelling bottle A.

(e) 97 ml of air is passed into the burette, followed by 3 ml of residual gas. The mixture is then passed into the combustion tube by raising the levelling bottle A and lowering the mercury bottle. Note that the explosive limit of air-methane mixture is 5 - 15% methane. It is important that not more than 3 ml of gas (to be on safe side) is allowed to mix with air or else explosion may occur.

(f) Switch on the battery and adjust the rheostat until the platinum wire glows red. Maintain this for 2 minutes. As reaction occurs, water vapour forms and condenses on the glass of the combustion tube.

(g) The reduction in volume V after combustion is measured at the burette, and the carbon dioxide formed (C_2) is determined as described in step (2).

Calculations :-

During combustion, methane and hydrogen react with oxygen in the following reactions :-

$CH_4 + 2O_2 \text{ ----> } CO_2 + 2H_2O \downarrow$

x 2x x

$2H_2 + O_2 \text{ ----> } 2H_2O \downarrow$

y 1/2 y

x and y are the number of moles or volumes of the gases as indicated.

Reduction in volume after combustion = V = 2X + 1 1/2 Y...(1)

Since x = volume of CO_2 in the gas after combustion C_2 ml

The volume of hydrogen, y ml, can be found from (1) above, therefore, y = (V - 2x) 2/3 ml

In the original gas, the composition is :-

Carbon dioxide = C_1%
Methane (x ml in 3 ml residual gas before combustion)

$= \frac{C_2}{3} (100 - C_1)\%$

Hyrdogen (y ml in 3 ml residual gas before combustion)
$= (V - 2x)\ (100 - C_1) 2/9\%$

The sum of these three gases may not add up to 100%. The difference, which is usually small, is nitrogen or other inert gases.

Electronic Gas Analyser

This is a portable device for estimating the methane content in natural gas and for checking gas leaks. The principle behind makes use of the different thermal conductivities of methane in the sample cell and air in the comparison cell. Since the gas analyser has been calibrated for methane-air mixtures, it is not suitable for determining the compositon of biogas which comprise carbon dioxide and hydrogen. The thermal conductivity of the former is lower than that of methane while that of the latter much higher. With only methane and carbon dioxide in the sample gas, one can recalibrate the analyser with mixtures of varying composition of methane and carbon dioxide. However, hydrogen is likely to be present, and since it has a high thermal conductivity, a low percentage can affect the reading significantly. Recalibration is impossible since there is more than one unknown (hydrogen and carbon dioxide) involved.

Measurement of Hydrogen Sulphide

Hydrogen sulphide is accurately determined by gas chromatogrpahy. An inexpensive method for estimating its concentration is the use of lead acetate paper. It cannot be determined by ORSAT because of its minute amount, and if a lead acetate solution is made, it reacts with carbon dioxide as well forming a white precipitate of lead carbonate.

Lead acetate reacts with hydrogen sulphide to form lead sulphide, a dark brown precipitate. Strips of filter paper are soaked in lead acetate solution (11.1% wt..vol) and dried. The strip of paper is then suspended in a bottle and a fixed volume of gas (1 litre) is passed through it. The paper darkens and its intensity is a rough indication of the percentage of hydrogen sulphide in the gas. (House, 1978).

5a.3 Quantity and Composition of Input

The feed or input invariably contains a certain amount of moisture. Its wet weight, W_w, can be easily measured by a spring balacne or scale.

The dry matter, W_d, or solids content is obtained by drying samples overnight in a forced convection oven (oven fitted with a fan for drawing moisture out) at 100°C. A higher temperture will cause evaporation of volatile solids such as fatty acids, and the measured weight will be less than the actual one. For good sampling techniques, see Van Soest (1978).

Glass crucibles or beakers can be used for holding the sample. Since they reabsorb moisture once outside the oven, they should be cooled down in a dessicator before weighing. Another reason for cooling inside a dessicator is becaue weighing hot objects with a cold balance will add to the inaccuracy. If an electronic balance is available, weighing can be done more expediently and the hot weighing method is preferred, thus obviating the need for cooling in a dessicator. (Van Soest, 1978).

A dessicator can be made with an air-tight tin with a thick layer of silica gel at the bottom. An indicator of cobalt sulphate can be mixed with the silica gel. The blue cobalt sulphate crystals turn pink when hydrated with water. When the pink colour appears, the silica gel should be regenerated by heating at 150°C for several hours until the blue colour returns.

When the samples are cooled to room temperature, they should be weighed quickly in the balance. Triplicate or at least duplicate samples should be made to give reliable results.

Volatile Solids

Volatile solids or organic matter can be measured by ashing the oven dried sample in a furnace at 550°C for 3 hours. The ash that remained is weighed in the manner described above. It is inorganic matter such as silica or chemical salts.

Calculation :

Moisture content = $(1 - W_d/W_w)$ 100%

Solids content or dry matter = (W_d/W_w) 100 % = f_d

Volatile solids or organic matter = $(1 - W_a/W_d)$ 100%
(as percent of dry matter)

where :

W_w = wet weight of sample

W_d = dry weight

W_a = weight of ash

Water to Gobar Ratio

Having determined the dry matter content f_d of the feed, the amount of water required (M_w) to make a slurry of a desired moisture content can be calculated.

Moisture content in slurry = $M_s = f_d W_w/(W_w + M_w)$

The amount of water required is therefore

$$M_w = f_d\ W_w/M_s - W_w$$

Moisture Content of Gobar

In Nepal, the common feedstock is gobar (cow or buffalo dung). Since the moisture content of gobar varies with the climate, it is impossible to give workable recommendations of the water-dung ratio unless the moisture content of gobar is known.

In the Terai (southern lowlands), the dry matter increases from about 15% during the monsoon to 30% during the hot dry season from March to June. To maintain the same moisture content in the input slurry, the amount of water required during the hot dry season should therefore be twice that during the monsoon.

Other workers have done experiments to correlate the solids content with the specific gravity reading on a hydrometer (Idani, et. al. 1974). If the correlation is high, plant operators can be taught to add water to the feed until the desired reading is reached. However, in practice, we observed that the response of the hydrometer became erratic beyond 8% solids content, because of the presence of particulate matter in the slurry.

Since specific gravity increases with the solids content, another method to determine the latter is by measuring the weight of a known volume of slurry. Since a large variation in solids content only brings about a small change in specific gravity (Table 5a1), the weight has to be measured fairly accurately and would not be practical in a village situation.

Table 5a1 The specific gravity of slurry of different solids content

Sample Gobar	Water	Specific gravity	Solids content %
89.25 g	(75 ml), no water	1.19	24.2
same	62.5 ml	0.99	14.2
same	120 ml	0.98	10.32
same	125 ml	0.97	9.0

After defecation, the animal dung is exposed to the atmosphere and loses water at a rate depending on environmental factors such as the humidity, temperature, and rainfall. Thus, one can probably predict the solids content by knowing these climatic indicators. To investigate this hypothesis, the solids content of buffalo dung (less than one day old) was determined twice weekly from duplicate samples over a period of 20 months in Butwal. For correlation, climatic data were collected from a nearby metereological station (Table 5a2).

Table 5a2 Dry matter Content of Gobar and Climatic Data of Butwal

Month	Gobar dry-matter, % (Y)	Relative Humidity (H) 8:30	17:30	Mean %	Temperature (T) Max	Min °C	Mean	Rainfall (R), mm
Year 1981								
3	29.6	49.7	42.2	46.0	31.2	18.5	24.9	26
4	25.3	51.4	49.5	50.5	34.0	22.4	28.2	45
5	18.9	58.5	51.9	55.2	35.0	24.4	29.7	110
6	18.1	63.2	54.6	58.9	37.2	26.7	32.0	345
7	15.7	83.5	79.4	81.5	33.4	25.9	29.7	1101
8	16.1	82.0	81.6	81.8	33.1	25.9	29.5	1090
9	16.8	75.4	78.8	77.1	32.7	24.9	28.8	487
10	20.1	65.9	66.9	66.4	31.8	21.7	26.8	0
11	20.2	61.1	67.7	64.4	28.4	17.8	23.1	34
12	22.9	61.7	68.7	65.2	25.9	14.1	20.0	0
Year 1982								
1	24.4	67.8	68.4	68.1	24.8	14.0	19.4	16
2	27.6	70.4	59.7	65.1	24.4	13.2	18.8	2
3	28.1	58.5	52.0	55.3	29.1	21.7	25.4	83
4	25.1	50.5	37.6	44.0	35.5	22.8	29.2	19
5	23.9	46.4	38.4	42.4	38.2	24.8	31.5	47
6	18.3	81.0	72.6	76.8	34.4	25.3	29.9	547
7	14.5	81.4	75.5	78.4	33.6	25.9	29.8	683.5
8	14.5	76.7	81.8	79.3	33.7	25.9	29.8	513
9	14.6	78.0	77.5	77.8	32.0	24.2	28.1	426.5
10	16.9	64.3	67.4	65.9	31.6	21.9	26.8	14

Using the above data, the correlation coefficients, C, were calculated for all the combinations of any two of the four variables : gobar dry-matter (Y), relative humidity (H), temperature (T), and rainfall (R). All together, there are six correlation coefficients,and their values are given below :-

C(YR) = -0.685	C(YH) = -0.762	C(YT) = -0.533
C(RH) = 0.734	C(RT) = 0.501	C(HT) = 0.046

The correlation between Y and any of the three climatic variables is quite appreciable. The correlation between H and T is low, therefore these two variables must be included in the regression equation for the prediction of Y. The correlation between R and H and between R and T are both quite appreciable, so if the addition of R does not add much accuracy to the prediction, it can be omitted from the equation for the sake of simplicity. The test of the significance of R is shown below.

From graphs, Y can be shown to be inversely linear to T, and roughly proportional to 1/H and to R. A regression equation for Y is thus obtained with the three climatic variables.

$$\hat{Y} = 23.19 + 3.51 \times 10^{-3}R + 1267.01/H - 0.883T$$

$$r^2 = 0.87, \ r = 0.93$$

The overall correlation coefficient, r, is high, being 0.93.

T-test showed that both 1/H and T are significant beyond 0.1 %, but R is only significant at the 10 to 20% level and is therefore not as important as H or T.

If R is omitted, the regression equation becomes :

$$\hat{Y} = 23.29 + 1033.82/H - 0.7126T$$

$$r^2 = 0.85, \ r = 0.92$$

Since the overall correlation coefficient r decreases by only 0.01 (from 0.93 to 0.92), it is safe to omit R in the equation.

Thus for prediction of the dry-matter of dung, we can use :-

$$\underline{Y = 23.3 + 1034/H - 0.71T}$$

According to climatic records, there is no appreciable variation in the average monthly temperature and relative humidity over the last ten years. This equation is thus applicable in the Terai and places with similar climate. Extrapolation for Kathmandu which has a temperate climate has resulted in prediction of a wide error margin. However, this method can be applied for different climate and animal species provided that the appropriate data are known. Our experiments showed that the dry matter content of buffalo and cattle are similar, but that of the horse is higher (Table 3).

Table 5a3 Dry-matter content of animal dung in Kathmandu

Species	Month	Dry-matter, %
Horse	November	28.2
	December	26.6
Cattle	December	15.4
Buffalo	December	15.1

Measurement of NPK

The fertilizer value of dung and effluent slurry can be measured in terms of nitrogen, phosphorus, and potassium (NPK).

Ammonia and organic nitrogen are determined by Total Kjeldahl method (Perrin, 1953).

For the determination of phosphate, volumetric or calorimetric methods can be used (Standard Methods, 1955). Potassium can be determined by flame photometric method (Wander, 1942).

The details of these procedures will not be presented here, since there are standard methods with numerous references.

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Perrin, C.H. (1953) Rapid Modified Procedure for Determination of Kjeldahl Nitrogen. Analytical chemistry. Vol. 25(6) : 968.

Standard Methods (1955) For the Examination of Water, Sewage, and Industrial Wastes. Tenth Edition. American Public Health Association, Inc. 1790 Broadway, New York, USA :

Van Soest, P (1978) Forage Fiber Analysis. Agricultural Handbook No. 379. Agricultural Research Service, US Dept. of Agriculture.

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Chapter 5 METHODS OF MEASURING GAS PRODUCTION PARAMETERS

D. Fulford

5.1 Use of Gas Meters

Many different types of gas meter are available commercially, but most seem to be affected by the corrosive gases in biogas. A simple bellows type domestic gas meter was used by DCS, but the tinplate housings and the steel movement quickly became rusty and made the meter unusable. A wet type gas meter, with a rotary movement, was purchased, which has worked better. The brass counter movement of this meter, too, was affected by a slight leakage of biogas from the main shaft seal. It became covered in a black deposit (lead sulphide?) which interfered with its operation. The rotor, which was also made of brass, could not be inspected to see if it also was affected. If the rotor was held together with solder, which has a high lead content, it could be attacked by biogas, over time, resulting in degradation of the solder.

The wet type gas meter is designed to be an accurate laboratory tool, but there are limitations on its use. It is designed to work with low gas pressures, 150 to 200 mm WG. When the DCS meter was used with gas from a dome plant, a solder seal at the back cracked. The normal wet type meters tend to be expensive, but not very robust.

It was decided in DCS to design a version of the wet type meter that would not be corroded by biogas and could also take the higher pressures from displacement digesters. This type of meter uses a rotor that has 4 seperate chambers in it (Figure 5.2). Gas enters the first chamber (1) from a central gas inlet pipe, and water is displced out of the chamber into the body of the meter. The opposite chamber (3), then has more water in it, so is heavier and the rotor rotates under this imbalance of weight. Water then enters this chamber (3), through a central water passageway, displacing gas into the upper half of the meter body and into the gas outlet pipe. If the rotor is made carefully, so no gas can leak between chambers, the meter will accurately measure the volume of gas that passes through it.

5.2 DCS Plastic Gas Meter

The DCS meter (Figure 5.3) was made of acrylic plastic (Perspex, Plexiglass), which can be solvent welded using chloroform. The accuracy of this meter did not have to be very high, so the tolerances on the dimensions were not tight. The main bearings were made of nylon, which is self-lubricating, especially if immersed in water. Allowance had to be made for the nylon swelling when it absorbs water. The sealing of a rotating shaft through the walls of the meter proved difficult, so a magnetic drive for a revolution counter was chosen instead.

Acrylic plastic sheet can be softened by warming it to the correct temperature, so it can moulded to shape. If it is made too hot, the surface will tend to bubble and craze.

The curved walls of the rotor compartments are made by placing sheets of softened plastic (2 mm) between two shaped forms made of wood. When the sheets cool, they remain in the correct shape. Two acrylic sheets can be welded by holding them together and running chloroform between them with a brush or dropper. Chloroform is very volatile, so the joint dries quickly, it is also strong smelling and toxic, so it should be used in a well ventilated place. A glue can be made by dissolving small pieces of acrylic plastic in a bottle of chloroform. Holes should be filled by spreading on several thin layers of this glue, as a thick layer tends to trap air bubbles, which leave holes that can leak.

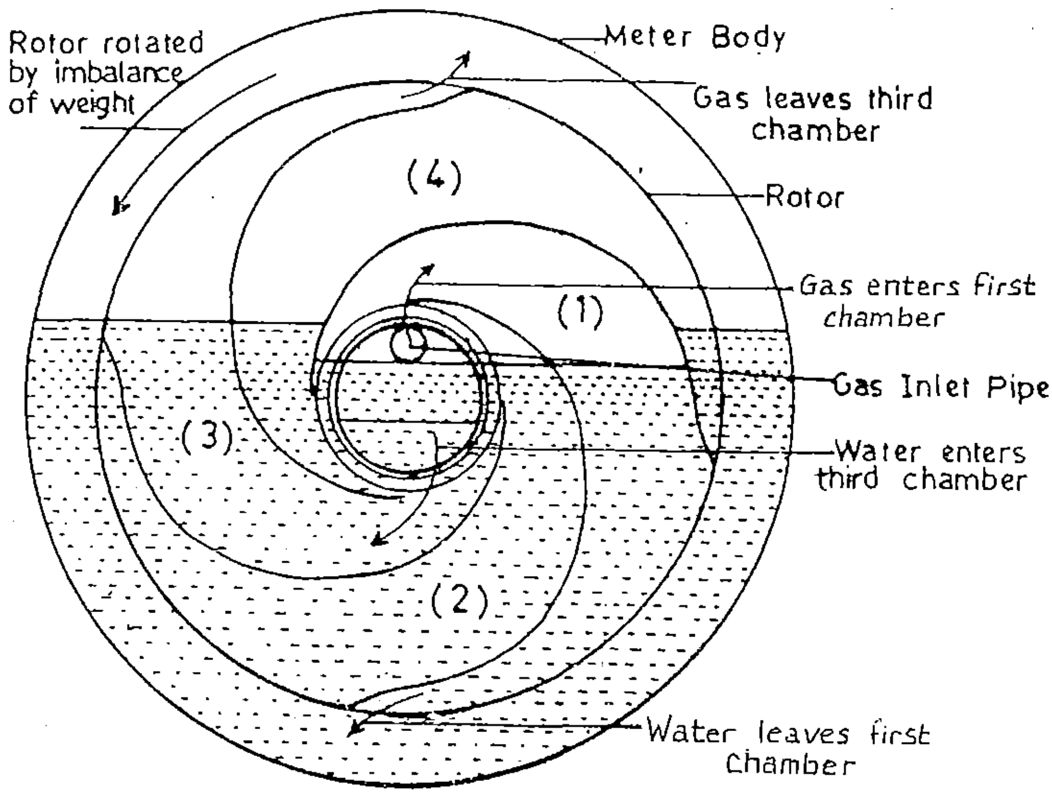


Fig. 5.5 Mechanism of a Wet Type Rotary Gas Meter

The body of the meter was originally made as a square box, but the corners tended to crack under internal gas pressure. A cylindrical body was designed, using a long (2 mm) sheet of plastic, which had been heated and wrapped around a cylindrical mould, and fitted into a circular groove cut in the side pieces (6 mm thick). The strain of the gas pressure on the flat sides of the box is taken by 5 steel bolts that run the width of the meter.

The meters were calibrated, using air from a small compressor, against an accurate commercial meter. The volume of gas passed for each rotation of the rotor proved to be smaller than calculated, so was not an integral number of litres. A slight difference in the level of water in the body can have a large effect on the calibration. The water level that ensured the rotor ran smoothly without leaks proved to be higher than exactly half-way up the rotor. A line was scribed on the side pieces to indicate the correct water level. The meter must be carefully leveled by placing wedges under the corners, until the water surface inside the transparent sides meets these lines at all points.

Some of these meters were used in field trials of dome plants and seemed to work reasonably well. They were not completely reliable, as the counter sometimes missed count. The counter arm was made longer, to increase the torque on the counter mechanism. A better type of counter was also found. These improvements are shown in Figure 5.3). This type of meter is useful for experimental work, but it is not reliable or robust enough for commercial use.

5.3 Measurement of Slurry Temperature

The slurry temperature was measured in DCS by removing a sample of slurry in a device made for the purpose (Figure 5.6). The shape of the device enabled it to be passed down the inlet or outlet pipes of a drum plant, so the temperature at the bottom of the digester pit could be measured. One experimental drum was made that had 4,114 mm OD pipes running the whole height of the drum, closed off at the top with screw caps. Using these pipes and by rotating the drum to different positions, slurry samples could be removed from almost any part of the digester pit. A mercury-in-glass thermometer was used to measure the temperature of the samples.

Later DCS was able to purchase a recording thermograph, with two bulb type temperature elements, and a dial type max-min soil thermometer. Both were fitted with one bulb that had a 5 m length of armoured capillary connecting it to the read-out unit. The temperature at any point inside a biogas plant could be measured by pushing the bulb to that point. The second bulb of the thermograph was mounted on the case so that the ambient temperature could also be measured. The chart recorder on the thermograph was driven by a clockwork motor, so it did not need an electrical supply. These instruments allowed us to measure the daily variation of temperature, both within and outside a biogas plant.

5.4 Measurement of slurry pH

A set of pH papers was used to measure the slurry pH. A strip of paper is soaked in a solution of indicator, that changes colour when placed in a liquid of a particular pH. By selecting indicators, the whole range of pH can be measured to an accuracy of about $\pm$ 0.5 pH. Such a set of pH papers are available commercially.

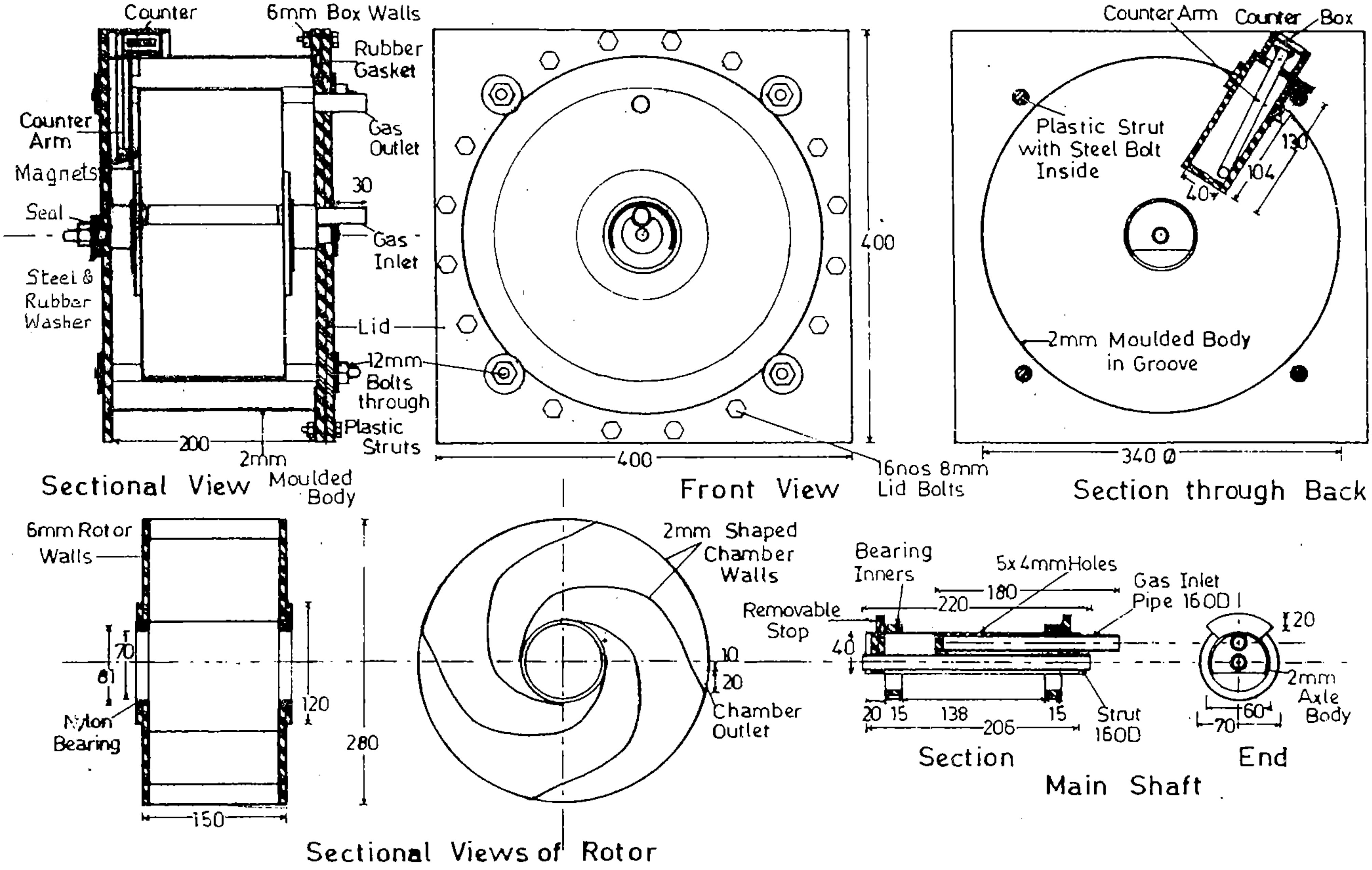


Figure 5.6 Design of Plastic Wet Type Rotary Gas Meter

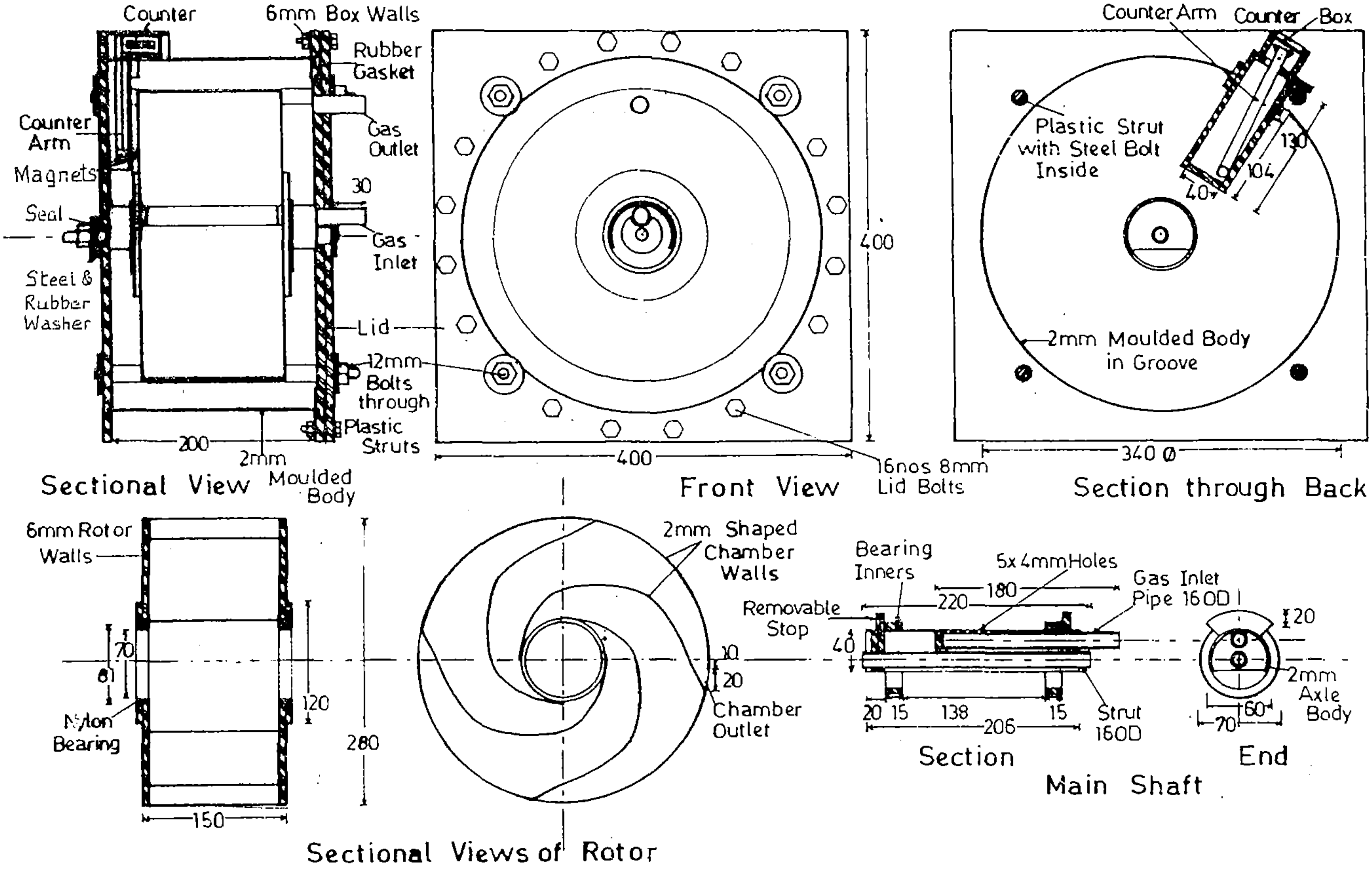


Figure 5.6 Design of Plastic Wet Type Rotary Gas Meter

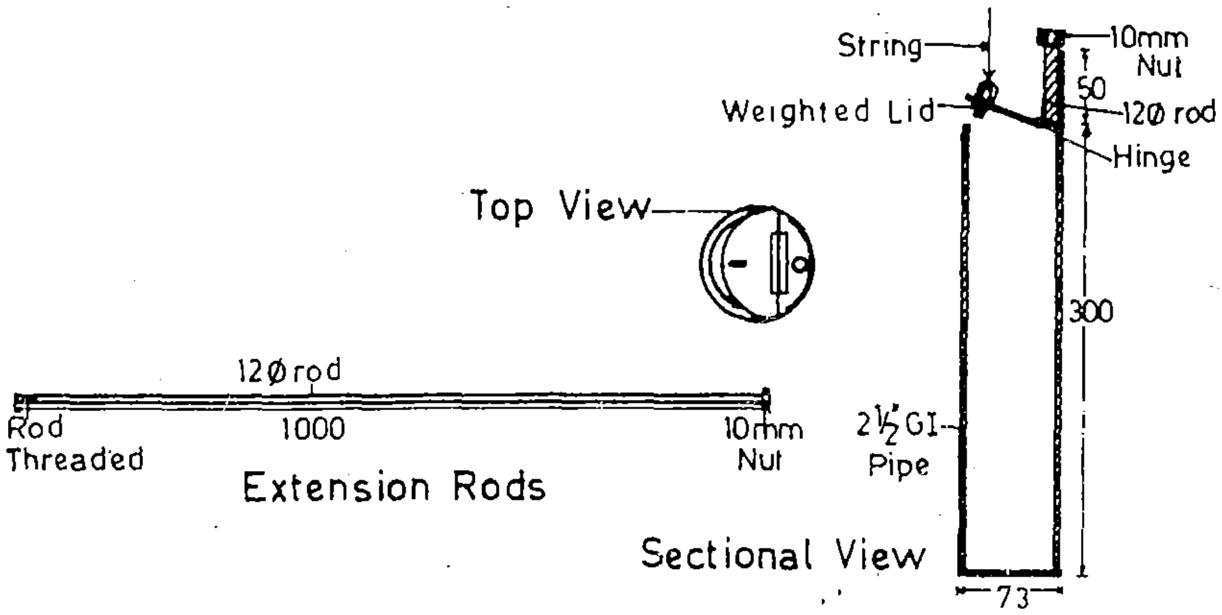


Fig. 5.6 Slurry Sampling Device

DCS was later able to purchase a pH meter, which could read to ± 0.05 pH directly from a scale. It was run on batteries, so was portable and it was fairly robust.

Volume II

Chapter 6 **ENHANCEMENT OF BIOGAS PRODUCTION IN COLD CLIMATE**

M. Lau-Wong

6.1 The Temperature Constraint

Biogas technology would have enjoyed a much wider acceptance and applicability had it not been limited by a natural constraint - temperature. As the biogas microflora is sensitive to temperature changes, a decrease in fermentation temperature induces a concomitant reduction in gas production. The onset of winter in subtropical and temperate regions often requires the use of an alternate back-up fuel when production of biogas diminishes. Below 15°C, degradation of the substrate proceeds extremely slowly, demanding a longer retention time of the substrate than at a higher temperature. In regions beset by severe winters, like Liaoning in China, biogas plants operate only during the six warmer months of the year; in winter, gas production ceases altogether (Eggeling and Stephen, 1981).

In contrast to aerobic mesophilic processes in which cooling is often necessary, anaerobic digestion generates much less heat - about 7 times less for the decomposition of glucose.

		Free energy, Δ F, kcal/mol
Anaerobic	$C_6H_{12}O_6$ ---> $3CH_4 + 3CO_2$	-102
Aerobic	$C_6H_{12}O_6$ ---> $6CO_2 + H_2O$	-688

The small amount of heat generated from biogas process readily dissipates to the surrrounding in the winter time, and gas plants should therefore be insulated or heated by external sources. Most gas plants are heated to operate at mesopholic temperatures (30 - 35°C). Although higher fermentation rates are obtained at the thermophilic range (55 - 65°C) (Hamilton Standard, 1978; Zoetemeyer, et al, 1979), a thermophilic process is not economically viable, especially for small household plants in temperate regions.

Heating the digester with the generated gas has been practised in some big operations. In one case, however, propane gas was used to supplement the biogas and as fuel for the pilot light of the boiler for reliability (Jewell, et al, 1981). From economical and practical considerations, this system is not feasible for small-size plants (3 to 10 m^3 digester volume); and alternatives that require low capital cost, maintenance and labour should be explored. In the following sections some of these methods along with experimental trials will be discussed.

6.2 Insulation

Temperature gradient of the earth

Since biogas plants are built at or under ground level, an understanding of how heat flows in the earth is essential to designing for low temperatures. From mining experience, it is well-known that temperatures increase with depth in the interior of the earth. Many deep-drill holes have been made to measure this heat flux, also known as geothermal gradient. It was found to vary between 10°C to 50°C per km on land (Carslaw and Jaeger, 1959). The temperature profile near the surface, however, is more complicated. As land near the surface is exposed to diurnal and seasonal variations of intensity of insolation (solar radiation), its temperature fluctuates accordingly and heat can flow either in or out depending on the time of the day or year. During daytime, the soil surface is warmed by insolation, while at night the absorbed heat reradiates back into space, the heat loss being more on a clear night. This diurnal fluctuation of soil temperature virtually vanishes below one metre (Russel, 1975), and thus exerts little influence on the internal temperature of a subterranean biogas plant. In contrast, seasonal variation of temperature has a more profound effect on the performance on biogas plants. In equatorial regions, seasonal fluctuation almost ceases at a soil depth of one metre, but in temperate regions, it diminishes only below 6 to 8 metres (Holmes, 1964).

Apparently, one plausible solution to the problem of heat loss in winter is to build plants at a depth where the temperature is fairly constant and agreeable to the microflora. But this may require excavation to below 10 to 15 metre which is a difficult if not impossible task. The existing plant designs also need to be modified for adaptation to the greater depth. To circumvent this, a plant can be built not far below the surface with removable insulation installed above the plant in winter. This not only avoids deep excavation but also allows quick penetration of insolation and heat when the cold season is over, simply by removing to insulating layer.

Figure 6.1 depicts a typical set of winter isotherms of the soil in Kathmandu, Nepal. As heat flux vectors are perpendicular to the isotherms, they flow upwards and finally emerge normal to the earth's surface. In the absence of heating or insulation, there is little net flow of heat horizontally across the digester to the surrounding soil. However, with insulation above the plant, the isotherms are distorted as shown in Figure 6.2. The heat flux vectors are deflected sideways from the walls of the plant before emerging at the earth surface. It is therefore crucial to insulate the plant well at the top surface rather than at the sides, although ideally, it should be done at both places. Insulation only at the surface has another advantage. If the plant is insulated at the sides, moisture entrapped in the insulating material is difficult to remove and a wet insulator automatically loses its insulating capacity. Whereas surface insulation are relatively easy to dry under the sun. Wet ground also loses more heat.

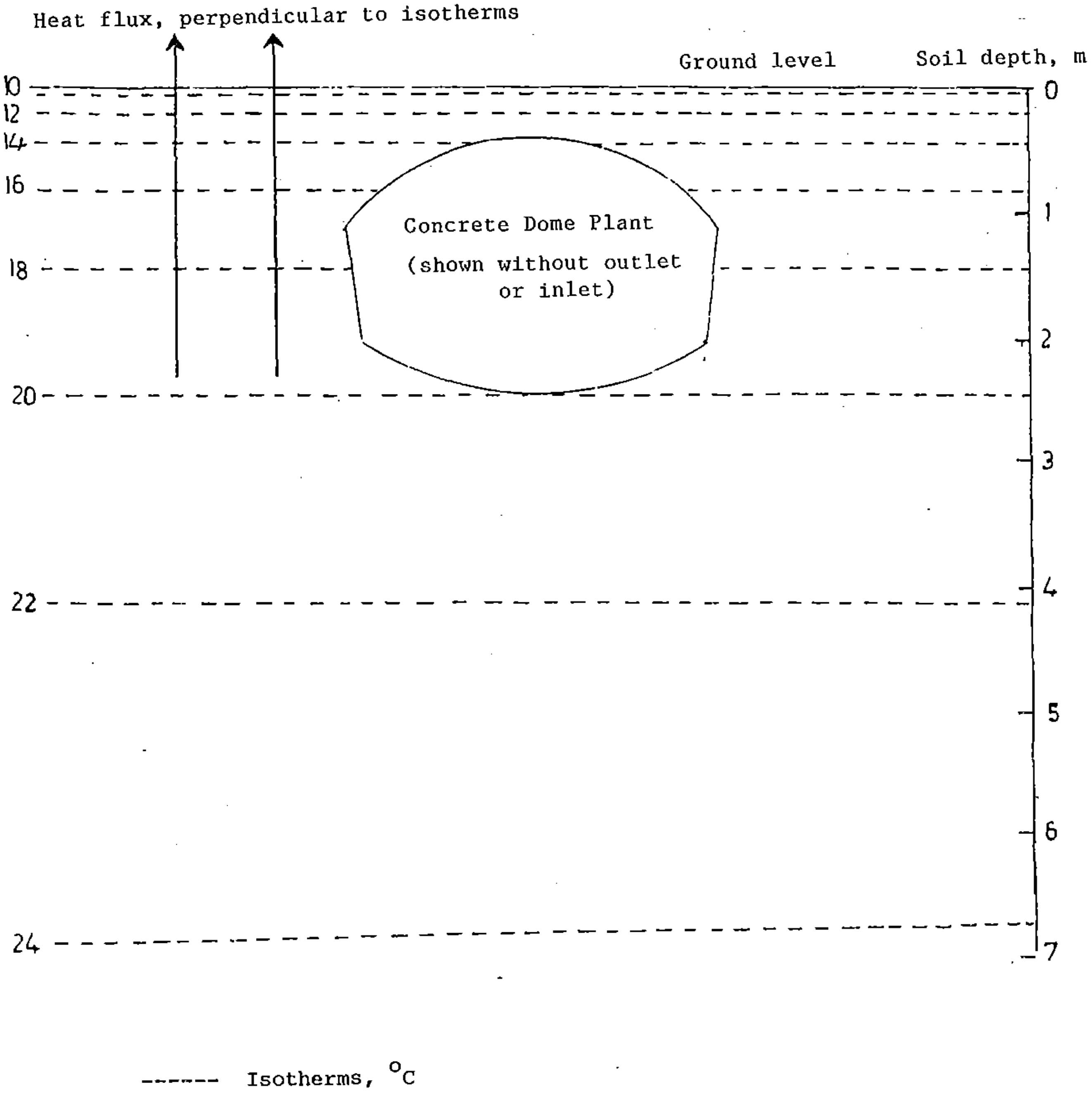
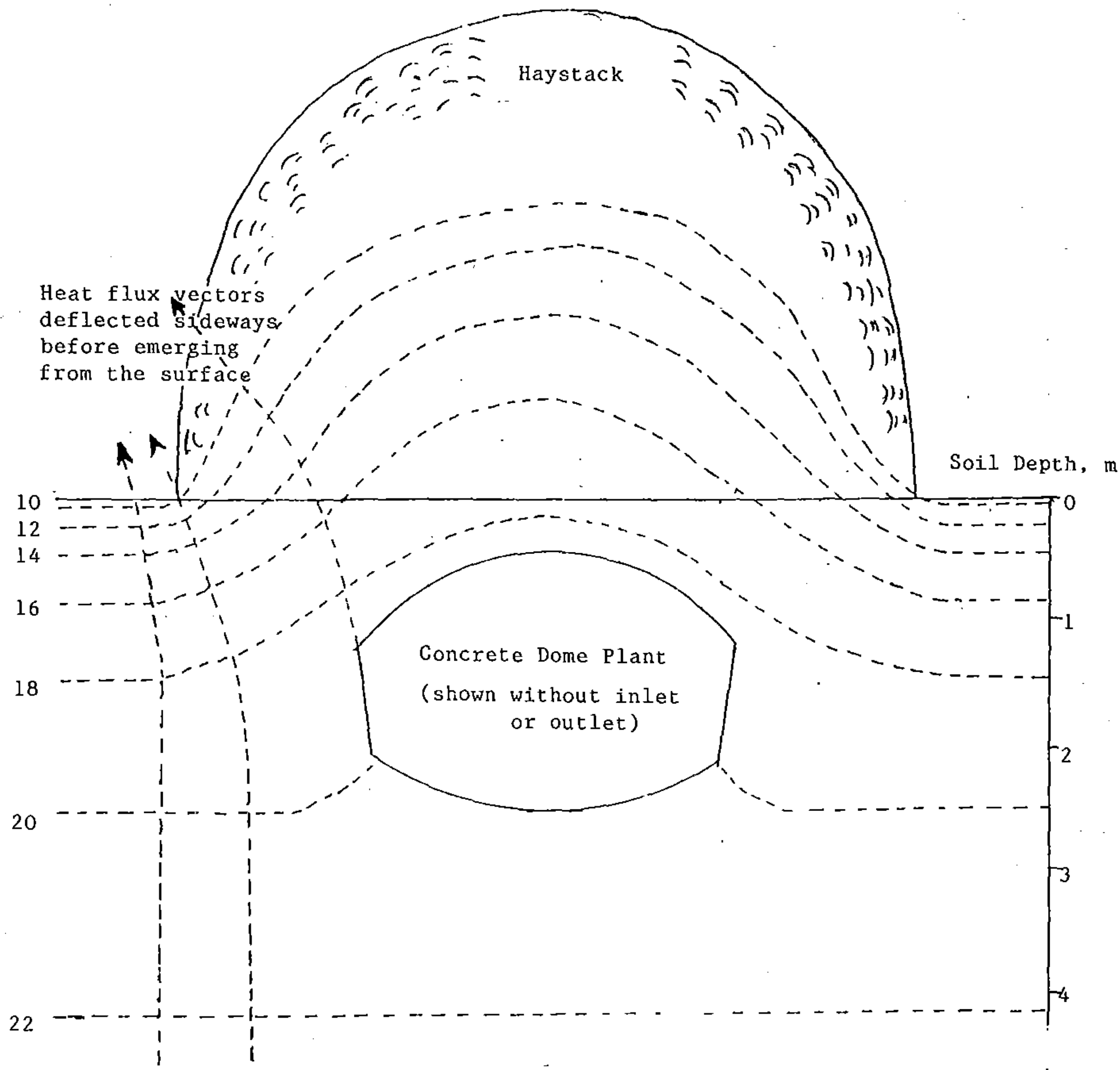


Fig. 6.1 January soil isotherms at 8:40 a.m. in Kathmandu



------- Isotherms, °C, elevated at and above gas plant,
and so does the digester temperature

Fig. 6.2 January soil isotherms distorted by haystack (Kathmandu)

Insulating with Local Materials

Plastics and fibre glass are good insulators but their prohibitive prices and unavailability in some places render them unsuitable. Local materials should therefore be explored as alternatives. Cereal straws, rick husks, saw dust and shavings are good insulating materials when dry (Table 6.1). Their thermal conductivities are 23 times lower than that of soil and comparable to that of typical insulators.

Straws and corn (maize) stovers are particularly abundant at harvest time. They can be erected in stacks above the plant with sloping sides. The slope enables rain and condensates to run off leaving the insulation dry.

Table 6.1 Thermal Conductivities of Materials
(Adapted from Weasted and Astle, 1979)

Material		Thermal Conductivity, W/M°C
Concrete		1.0
Soil (fairly dry)		1.4
Saturated soil		2.4
Saw dust (loose)		0.06
Shavings (loose)		0.06
Insulators :	Sugar cane fibre	0.05
	Insulite (Wood pulp)	0.05
	Glass wool	0.04

Plastic Cover Over Insulation

Plastic sheets like polyethylene can be used as a cover over insulating materials to reduce the amount of material required. As light penetrates the plastic, it is transformed into the longer heat waves or infrared. The heat enhances evaporation of moisture from the insulating material and ground below. Being trapped by the plastic, this moisture condenses as a film of water droplets on the undersurface of the plastic and acts as a barrier to radiation losses of the accumlated heat inside.

Vegetation

Vegetation such as grass or mulches has a blanketing effect that reduces both the diurnal and seasonal fluctuations of soil temperature. It reduces penetration of frost in winter, and like insulation, enables the soil to cool down more slowly in cold season than bare soil. Soil with a turf cover is warmer in water than bare soil. However, vegetation alone is inadequate in maintaining a reasonable operating temperature in winter.

6.3 Comparison of the Effects of Composting and Insulation

To evaluate the effectiveness of composting and insulation in increasing digester temperature in winter, experiments were conducted on three dome-type plants on private premises in Kathmandu. (Law-Wong, 1982). Kathmandu Valley is at an elevation of 1324 m. In winter, temperatures never fall below freezing but early morning frost is common and a cold damp fog envelops the Valley and rarely clears away before 10 am.

A 15 m^3 dome plant (S) was initially insulated with rice straw sandwiched between two plastic sheets at the end of September; but rotting of the straw one month later prompted its conversion into a compost pile. (Methods for Construction is given in Volume I, Chapter 10). Even at sub-zero temperatures, compost can generate significant amount of heat from aerobic decomposition of organic matters. The compost pile, 0.7 to 0.8 m high, covered an area of 5 x 5.5 m^2 on the ground above the plant. Another 15 m^3 plant (B) which had a 15 to 20 cm grass cover was used as control. A 10 m^3 dome plant (K) was insulated at the ground surface with rice straw in late November. It was 2 m high and sloping to 0.8 m at the periphery. A polyethylene sheet covered the straw and was held down loosely at the sides with bricks. A haystack of 5 m height and width was built in mid-january.

The areas of the compost and insulation were distinguished into 4 quadrants. Temperatures were measured at different locations at each quadrant daily by rotation, thus ensuring a more even sampling.

Table 6.2 showed that installations of composts, straw insulation, and haystack effectively increased diurnal fluctuations of ground surface temperature. The ground was shielded from insolation, but heat loss from the interior was also abated. Compost showed the best performance because of internal heat generation, although the large sample standard deviation indicates ununiform decomposition in this case.

Table 6.2 Influence of compost, haystack, and straw insulation on ground temperature (January 25 to March 13, 1982)

	Temperature °C					
	Minimum			Maximum		
Compost	T	S	n	T	S	n
	14.1	3.5	38	23.5	6.6	37
Haystack *1	10.4	1.5	9	13.8	2.3	9
Straw with Plastic (k)	6.6	2.5	99	24.7	5.3	99
Soil Surface *2	0.3	-	-	-	-	-
Ambient Temp : *3	3.9	-	-	19.5	-	-

Note : *1 Temperatures measured 1 to 1.5 m inside haystack near ground surface.

*2 Minimum of bare soil surface (January).

*3 Source : Kathmandu Airport Meteorological Station (HMG).

4 S and n are the sample standard deviation and number of observations respectively.

5 Diurnal fluctuation is given by the difference between Maximum and Minimum.

These temperatures were plotted in Fig. 6.3. The slurry temperatures of a steel-drum plant on one of the site was also included. Being constructed above ground, the steel-drum plant responded more quickly to temperature drop in the environment. Whereas for dome-type plants, there was a greater lag since the cooling effect takes time to penetrate below ground level; daily fluctuations of slurry temperature were less (usually with 0.5^{o}C), and the average temperature of an uninsulated dome plant was about 3^{o}C higher than that of a steel-drum type. Insulation effected a higher temperature in dome plants in mid-November than other plants which either acquired no insulation or delayed insulation. After the straw insulation was converted into compost, the generated heat continued to maintain plant S at a higher temperature.

Higher gas production per kg dried input showed that the compost method is effective (Figure 6.4). Gas production for the plant with compost (S) decreased in December since composting was done in later October, but remained faily constant thereafter. In contrast, that of the uninuslated plant (B) decreased sharply in December with some fluctuations until March when production increased in response to increasing ambient temperature. Because of the insulating effect of the compost, the onset of warmer weather in March still had no influence on plant S. The increase in gas production due to composting was shown by dotted lines in Figure 6.4. It rose from about 20% in November to a high of 80% in February, with an average increase of 54% from November to March.

6.4 Solar Heating

Location of Plant

The selection of plant site has a tremendous influence on the amount of insolation it receives. In the northern hemisphere, a south facing slope is generally warmer than a horizontal surface which in turn is warmer than a northern slope. The plant should therefore be constructed without obstructions, especially on the south side.

Solar Heating of Influent

Passive solar heating of influent at the inlet can be used as an inexpensive means of heat input into the plant. Since radiation can only penetrate a small distance in slurry, the depth of the slurry in the inlet pit should be shallow. This is achieved by building shallower in let pit of larger surface area. This also allows more exposure to insolation since the side walls are lower in height.

To prevent heat loss by force convection (or wind) and back radiation, the inlet pit should be covered by a transparent material, such as plastic or glass. Plastic is preferred since it is easier and cheaper to replace when broken. Condensation on the under surface of the cover also helps to trap heat by preventing some back radiation loss.

Experiments were performed in Butwal, Nepal, to determine -

1) the effect of plastic cover

2) the optimal retention time of slurry in the inlet pit

3) the depth of penetration of solar radiation.

Having determined the latter, the inlets could be modified by making them shallower but with a larger surface area.

On an overcast day, exposing influent in the inlet pit without plastic cover hardly increased the bulk slurry temperature. With plastic cover, only a modest increase is achieved. On a clear day when both direct and diffuse radiation are incident, the effect on influent temperature was considerable, especially when plastic cover was used.

It was evident from Figure 6.5 that irradiation had little effect on slurry below a depth of 12.5 cm while it penetrated 2.5 cm below the surface easily. Although enlarging the inlet would decrease the slurry depth and increase its bulk temperature, the larger area (8 times the original) and amount of building materials and plastic required call for a compromising alternative. A 7.5 cm slurry depth was chosen. One inlet was modified to a square of 1.69 m^2 and with its height reduced to 0.15 m, just high enough to prevent overflowing of slurry during mixing. Another inlet was made almost circular - an ellipse of axes 1.44 and 1.50 m, with the same surface area and height as the former. Both inlets were covered with polyethylene sheets when mixing of slurry was completed.

Before modification of the inlets, the side walls obstructed much of the isolation, especially in early morning and late afternoon when solar altitude is lower and irradiation weaker. At 4 pm only a small fraction was under direct sunlight. The fraction under shadow had a lower temperature than that under the sun.

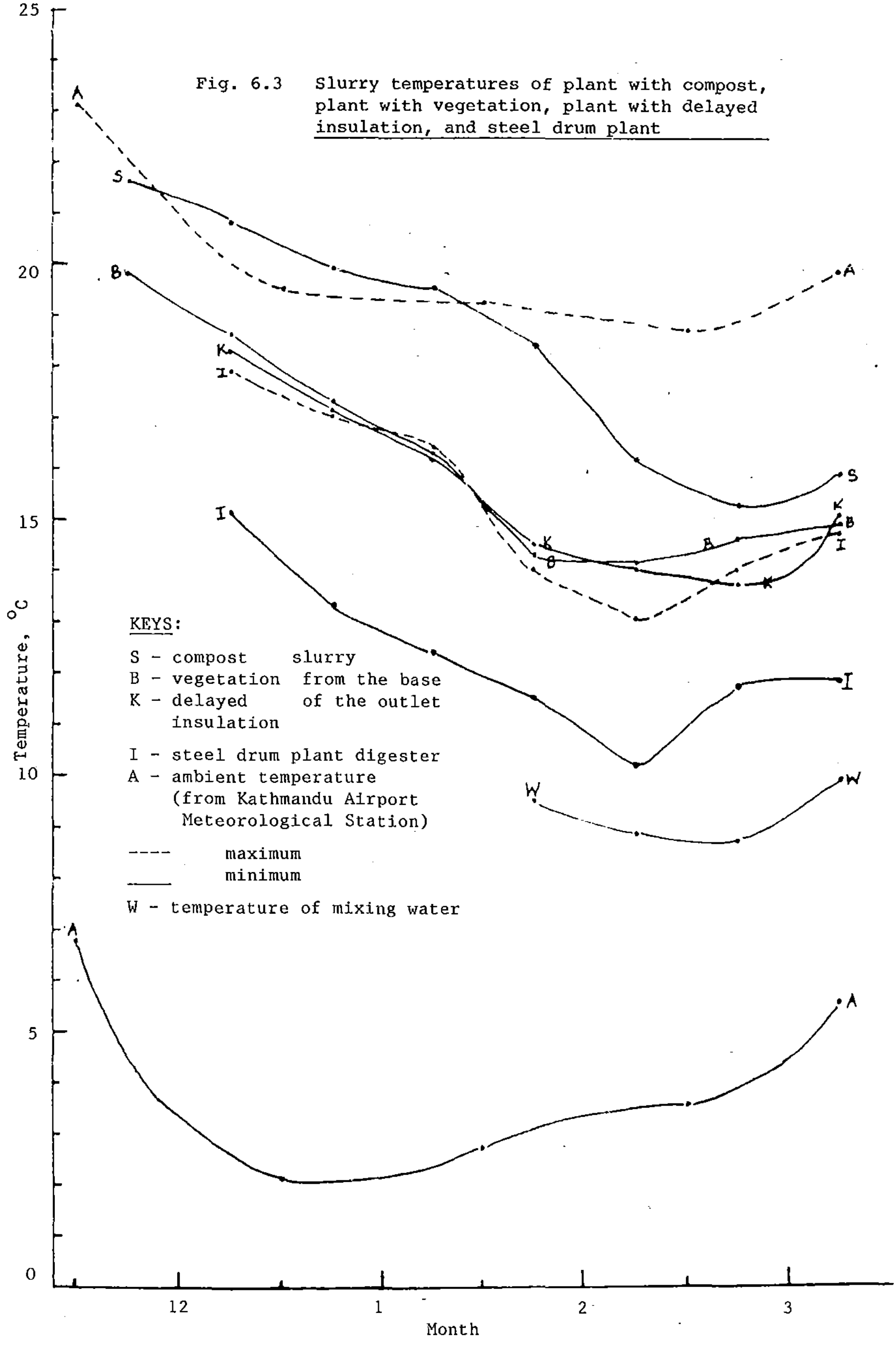


Fig. 6.3 Slurry temperatures of plant with compost, plant with vegetation, plant with delayed insulation, and steel drum plant
25
20
15
10
5
0
Temperature, °C
12
1
2
3
Month
KEYS:
S - compost slurry
B - vegetation from the base
K - delayed of the outlet
insulation
I - steel drum plant digester
A - ambient temperature
(from Kathmandu Airport
Meteorological Station)
---- maximum
—— minimum
W - temperature of mixing water
A
S
B
K
I
W

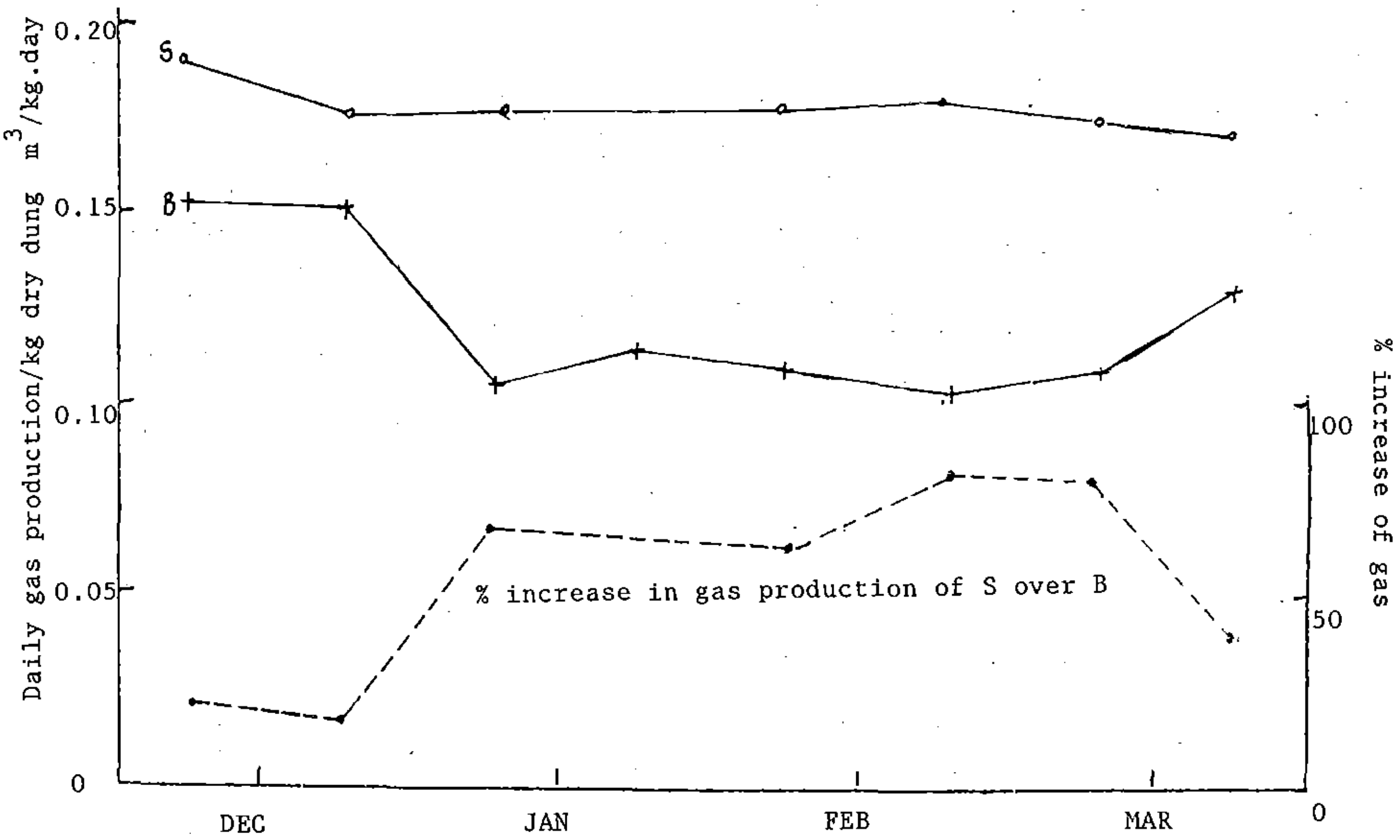


Fig. 6.4 Comparison of gas production of plant with compost (S) and plant with vegetation (B)

The influent temperatures for the modified elliptical and square inlets were depicted in Figure 6.6 and 6.7. They were a maximum between 2 and 3 pm. The average bulk temperature $\bar{T}$, at 2 pm was calculated by integrating the corresponding area on the graphs.

$$T = \int_{x=0}^{x=7.5} T.dx/7.5$$

Where T is the slurry temperature at depth x, which varies from 0 to 7.5 cm. The values of $\bar{T}$ were tabulated below, and their increases over mixing water temperature, Tw, were considerable, being 8 to 9°C on a clear day and 4 to 5°C on an overcast day.

Table 6.3 Increase of Average Bulk Temperature of Slurry (T) over that of mixing water (Tw) at 2 pm for modified inlets

Temperature °C	CLEAR DAY		OVERCAST DAY	
	Square	Elliptical	Square	Elliptical
T (Slurry)	28.3	29.7	23.4	24.7
Tw (Mixing water)	19.7	20.8	19.0	20.0
T - Tw	8.6	9.1	4.4	4.7

For testing the durability of the polyethylene sheets (0.06 mm thick), they were left in the fields even when not in use. Except for some lacerations during handling (mainly at the joints), they suffered no apparent damage from ultraviolet rays in one winter season. These sheets sustained more damage than they would normally have since the sheets had to be lifted hourly for temperature measurements. At present, one of the polyethylene sheet (2 x 2 m^2, 0.06 mm thick) cost 10 - 15 Rs., therefore, the cost for winter heating is about 50 Rs. (US $4).

Similar experiments were performed in Kathmandu with the same results. Solar heating of influent under plastic increased the influent temperature by about 9°C on a clear day and 4.5°C on a cloudy day over that of mixing water, both in the Terai (Butwal 205 m) and in Kathmandu (1324 m).

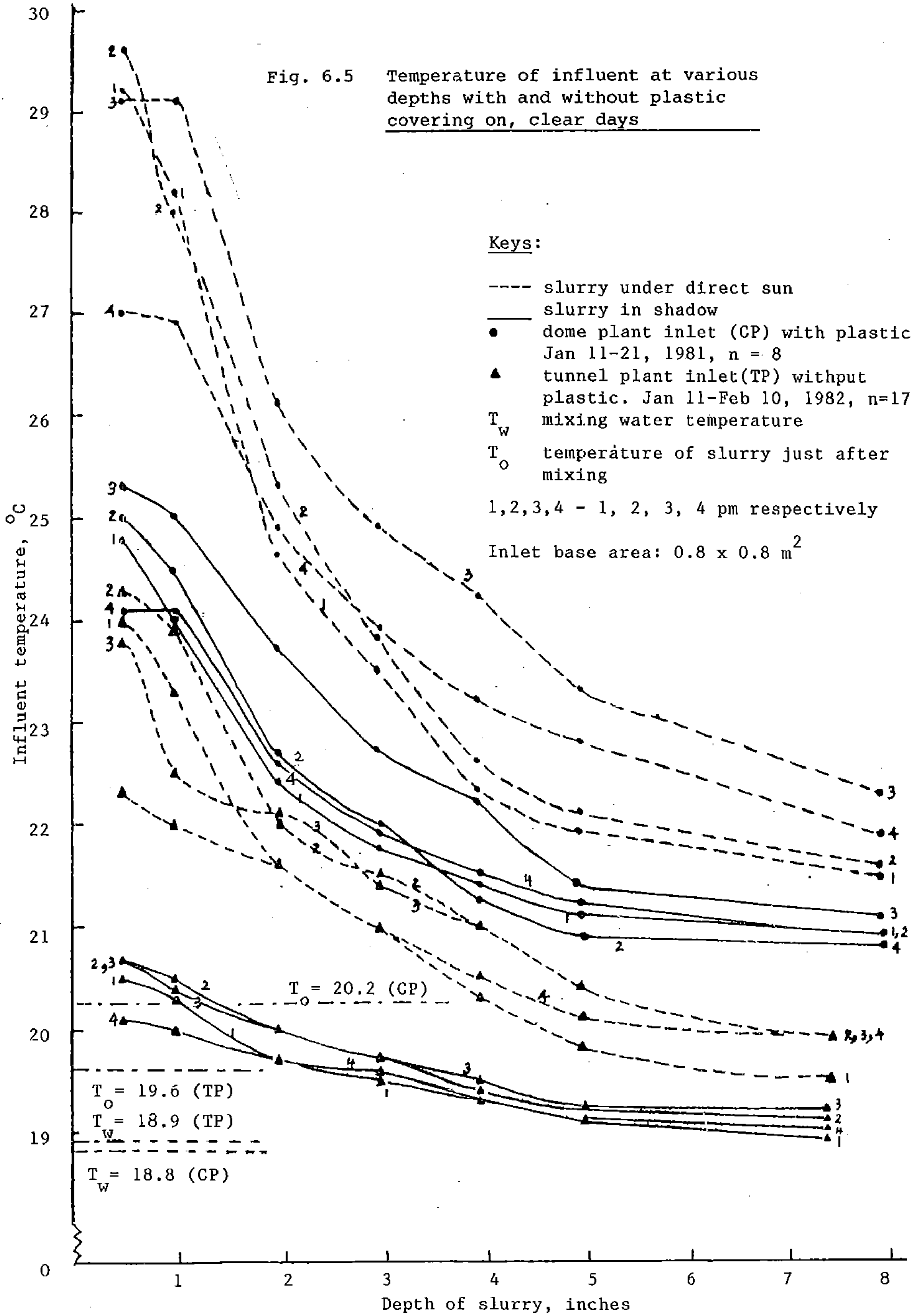


Fig. 6.5 Temperature of influent at various depths with and without plastic covering on, clear days
Keys:
---- slurry under direct sun
____ slurry in shadow
● dome plant inlet (CP) with plastic Jan 11-21, 1981, n = 8
▲ tunnel plant inlet(TP) withput plastic. Jan 11-Feb 10, 1982, n=17
T_w mixing water temperature
T_o temperature of slurry just after mixing
1,2,3,4 - 1, 2, 3, 4 pm respectively
Inlet base area: 0.8 x 0.8 m^2
T_o = 20.2 (CP)
T_o = 19.6 (TP)
T_w = 18.9 (TP)
T_w = 18.8 (CP)
Influent temperature, ^oC
Depth of slurry, inches
30
29
28
27
26
25
24
23
22
21
20
19
0
1
2
3
4
5
6
7
8

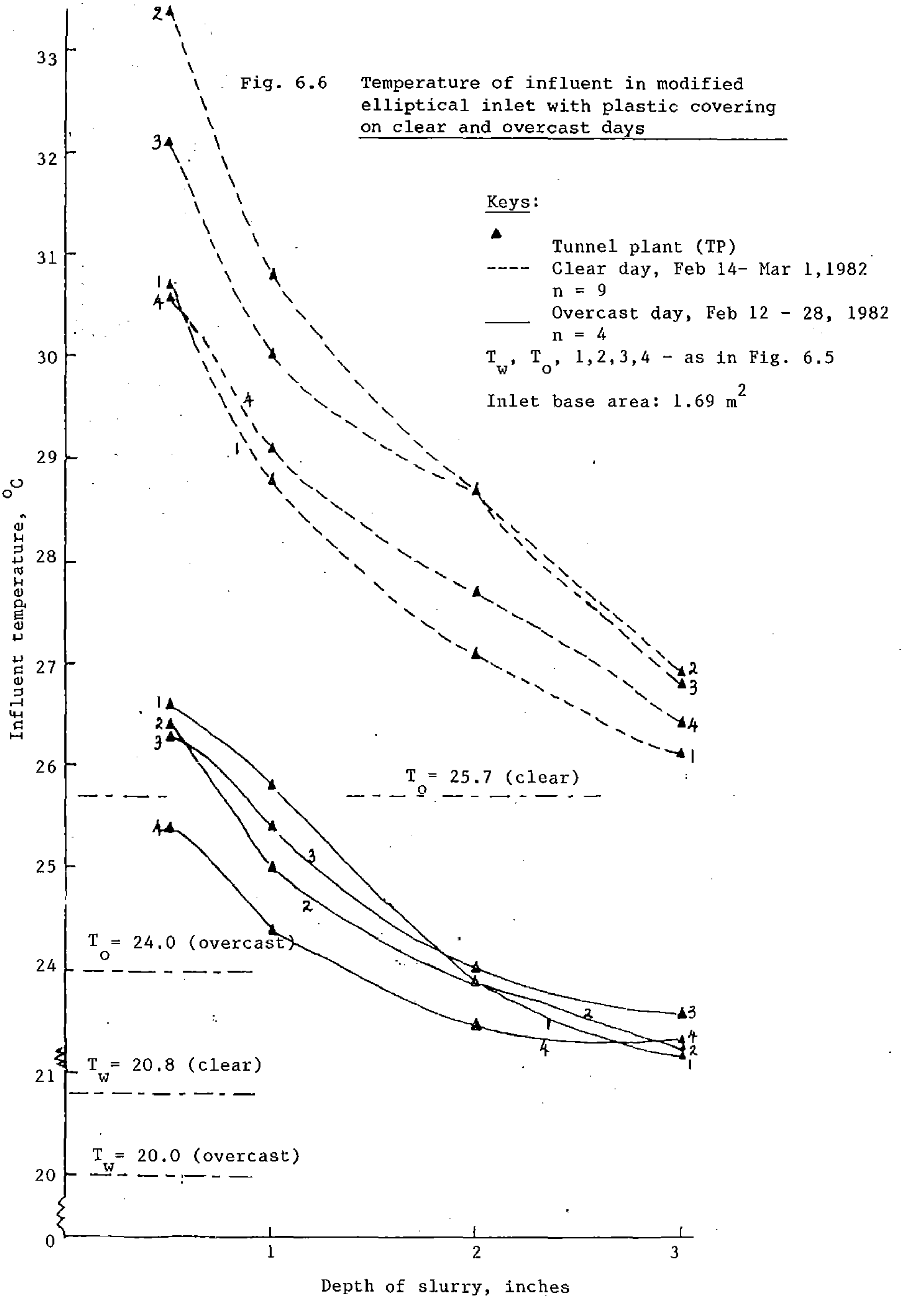
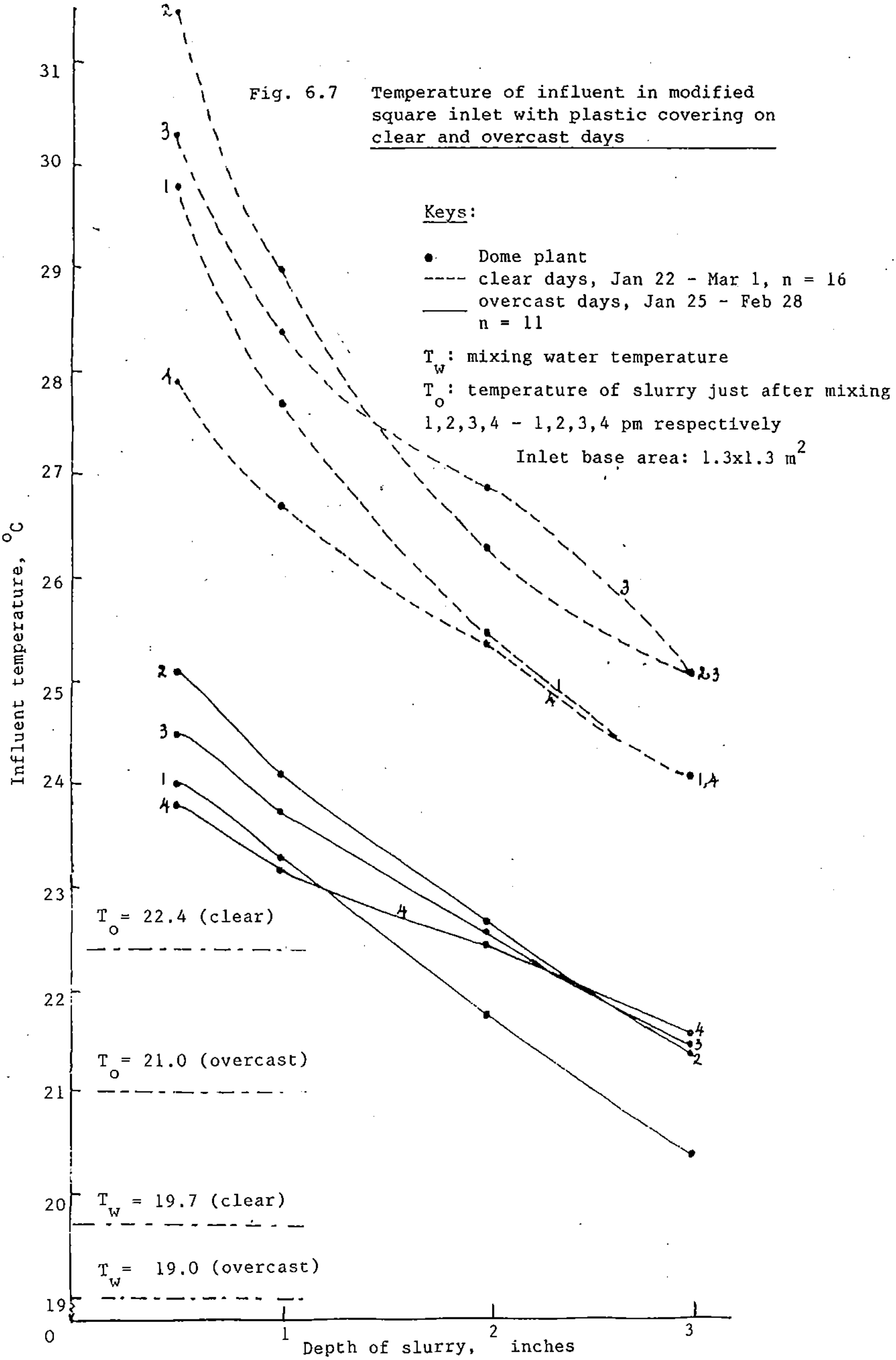


Fig. 6.6 Temperature of influent in modified elliptical inlet with plastic covering on clear and overcast days
Keys:
Tunnel plant (TP)
Clear day, Feb 14- Mar 1,1982 n = 9
Overcast day, Feb 12 - 28, 1982 n = 4
T_w, T_o, 1,2,3,4 - as in Fig. 6.5
Inlet base area: 1.69 m2
T_o = 25.7 (clear)
T_o = 24.0 (overcast)
T_w = 20.8 (clear)
T_w = 20.0 (overcast)
Influent temperature, °C
Depth of slurry, inches

Fig. 6.7 Temperature of influent in modified square inlet with plastic covering on clear and overcast days



Design for Hilly Areas

Hilly areas with south facing slopes can be exploited by building plants in the slope. A solar collector at a lower level is connected to a heat exchanger inside the plant (Figure 6.8). Heated water in the black H.D.P. pipes in the collecter panel rises and circulation is established as it is cooled at the heat exchanger inside the digester. The plant should be insulated well to preserve the heat inside. In especially cold climate the solar collector must be insulated from frost and freezing temperature by straw or other appropriate materials. Otherwise frozen water in the pipes can expand and crack the pipes.

This system can also be applied at level ground. As the solar collector is situated above the digester, a circulation pump has to be installed to drive the warm water down to the heat exchanger.

Other Passive Designs

Erecting green house over biogas plant is another possibility though not widely practised. This method is feasible only if growing plants inside green house is an acceptable practice of that area. The green house should not be made of plastic films which has a high transmittance to infrared and permit much back radiation at night. Glass is the material of choice though it is more costly. In cold climate, heat loss can be reduced by half if double glass is used instead of single (Andersson), 1977).

Additional solar radiation can be absorbed by building a thermal storage wall inside the green house (U.S.D.E., 1978). It can be made of blackened masonry material and can form the side wall of plug flow plant. As radiation hits the blackened surface. The heat in the concrete is conducted slowly inwards, facilitated by convection of digester slurry on the other side.

6.5 Utilization of Waste Heat from Engines

In Nepal, the concept of utilizing biogas to run engines for irrigation rice hulling, and flour milling is gradually gaining acceptance, especially among owners of community plants and large size plants. The engines used are mainly diesel engines converted to running on a mixture of diesel and biogas by the addition of a carburettor that mixes biogas with air. The consumption of biogas is 0.4 to 0.45 m^3 per hour. The engines can be installed with an air-cooling or water-cooling system. If water is used, the warmed water can be further heated at a heat exchanger with the engine exhaust gas. It then enters the digester through another single coil heat exchanger.

Water-Exhaust Gas Heat Exchanger

A double-pipe counter-flow exchanger was designed for the cooling water-exhaust gas system (Figure 6.9). It is easy to fabricate and costs about 400 Rs. NC (US$33) for materials and labour. Exhaust gas enters the central G.I. pipe before emerging from the exhaust at the other end. Water from the engine enters the shell at the cooler end and flow in opposite direction to the exhaust gas. This type of flow, called counter current or counter flow, results in higher heat transfer than parallel flow design. In case of fouling (depositing of scale in pipes), the efficiency of heat transfer diminishes and the exchanger should be dismantled and cleaned thoroughly.

If the amount of cooling water flowing through the engine is more than required for the heat exchanger, the flow can be restricted by two valves at the water inlet end. In this way, different flow rates were adjusted when the exchanger was tested on a 8 H.P. engine, and the corresponding steady state temperatures were recorded. The inlet water temperature at the exchanger was 28.5^{o}C. The outlet water temperature was plotted against the water flow rate (Figure 6.10).

A pump for circulating water through the heat exchanger is necessary when the engine is used for hulling and milling, but not when pumping water. Heated water from the exchanger enters the plant via H.D.E. pipes which in turn is connected to a single coil inside the digester (Figure 6.11). The whole assembly costs about 900 Rs. (US$70). To prevent heat loss, the exchanger and pipe fittings should be insulated - wrapping in dry jute bags worked well.

The overall heat transfer coefficient for the coil and digester slurry was estimated to be 170 w/m^{o}C with fouling (Perry and Chilton, 1973), and the length of coil required is 11 m (Lau-Wong, 1982).

If ambient temperature is 20^{o}C, the plant can be maintained at 23 to 24^{o}C by heat generated from the engine if run 6 hours daily. But this requries 12 m^{3} gas for a 5 H.P. engine and a digester operating temperature of 28 to 30^{o}C. It is therefore essential to apply insulation or solar heating of influent as an extra source of heat.

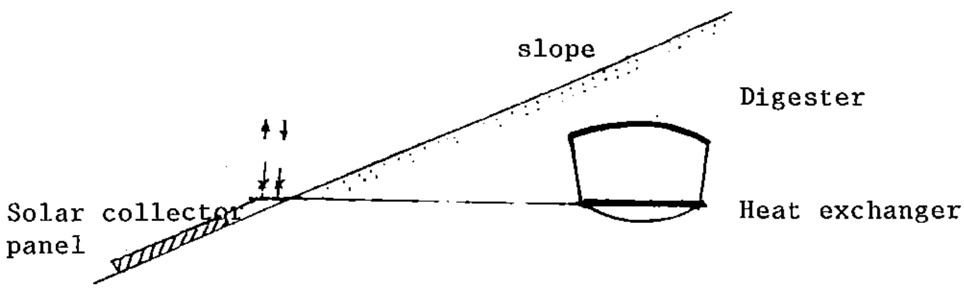


Fig. 6.8 Solar heating of plant built in south-facing slope

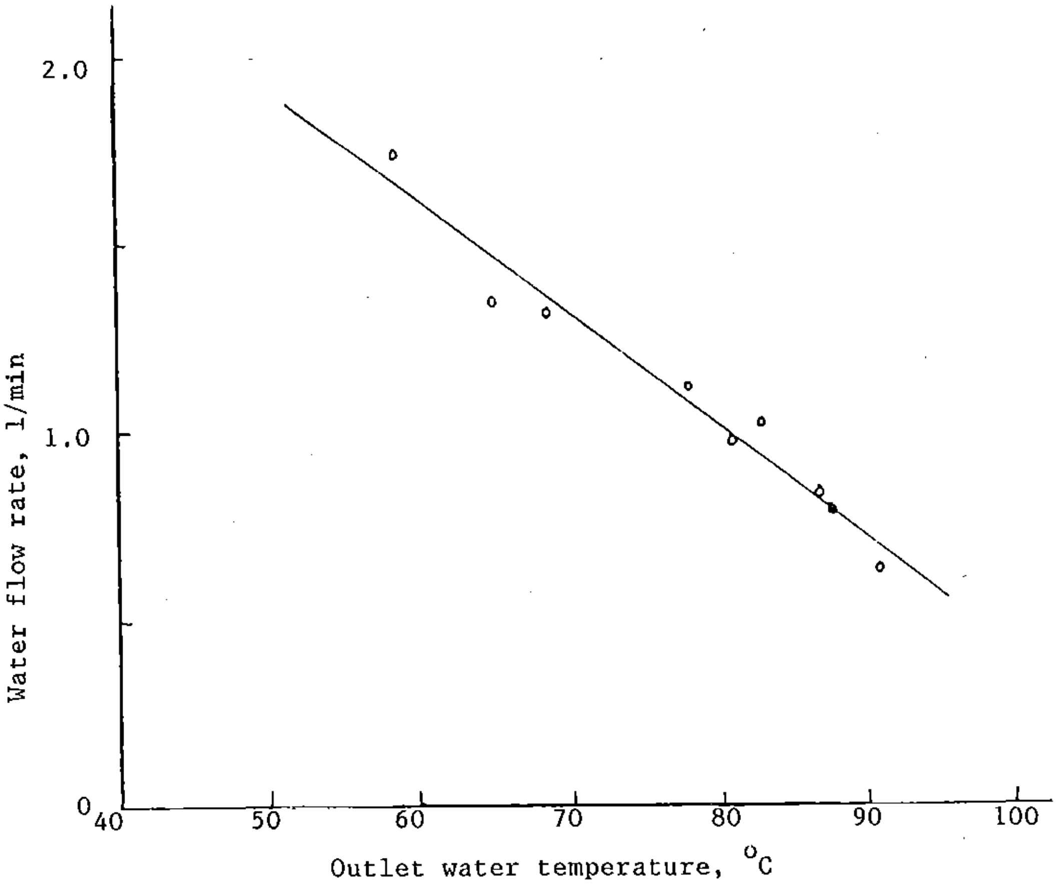


Fig. 6.10 Heat Exchanger, temperature of outlet water vs. water flow-rate

Fig . 6.9 Heat exchanger

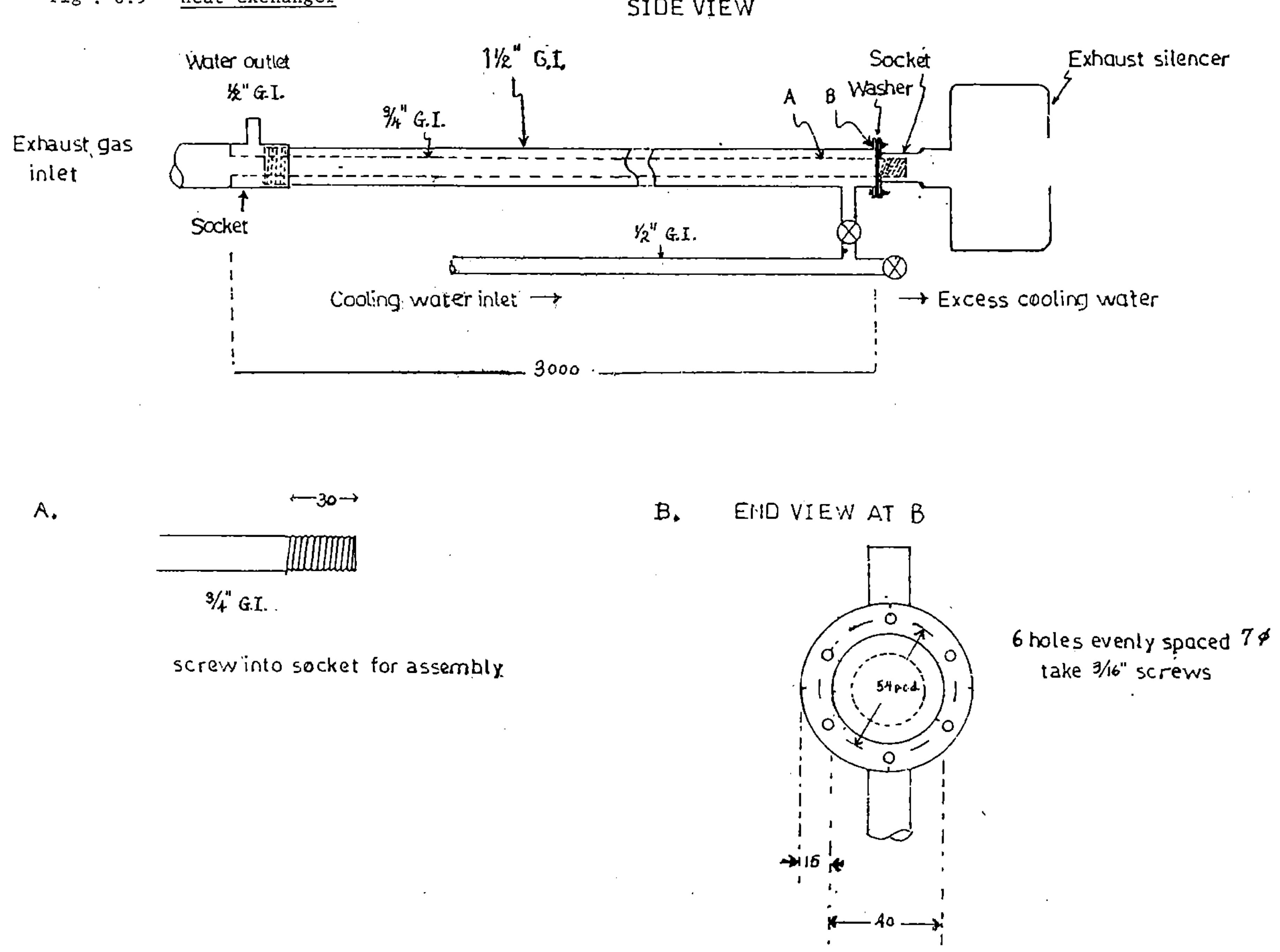
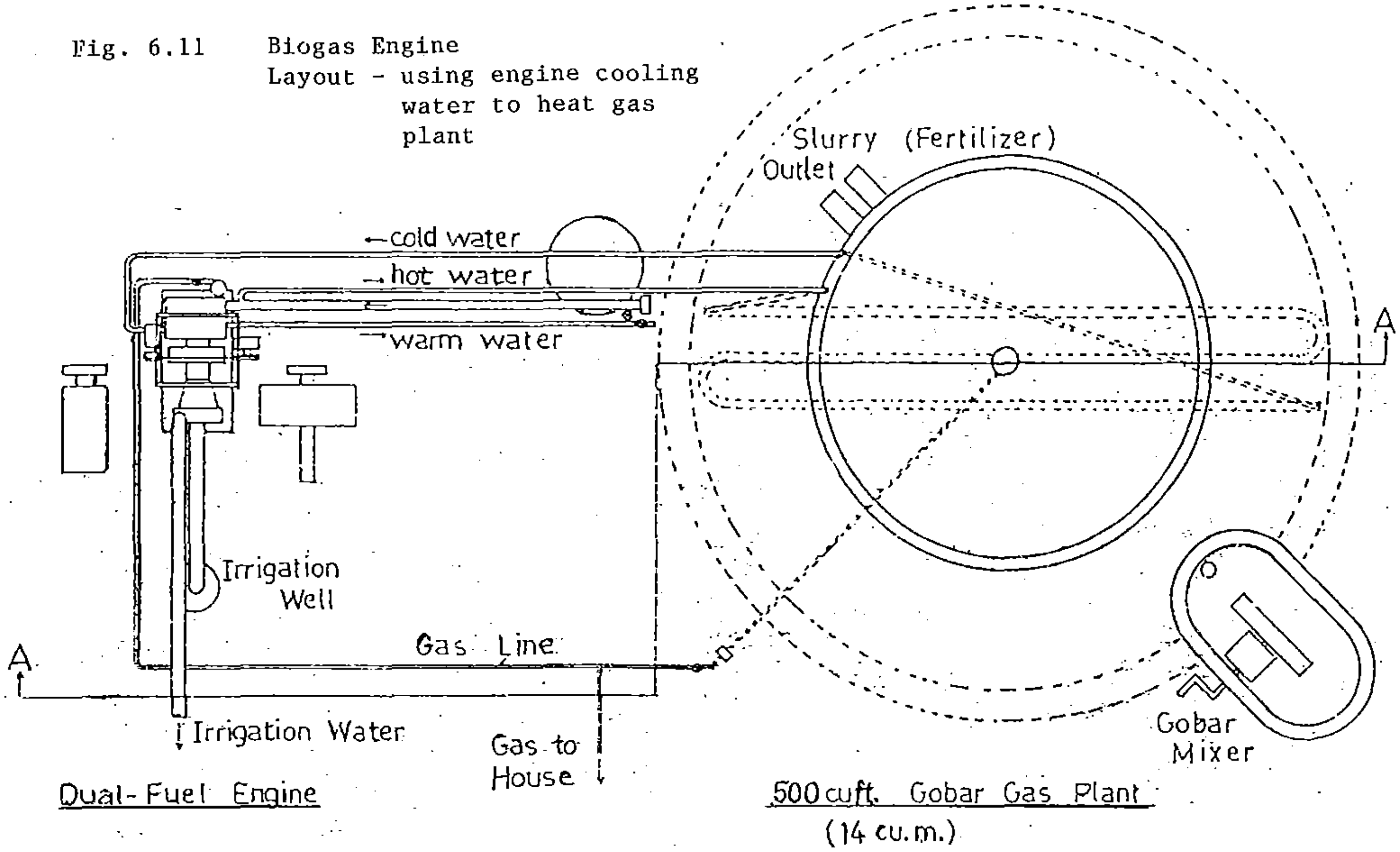
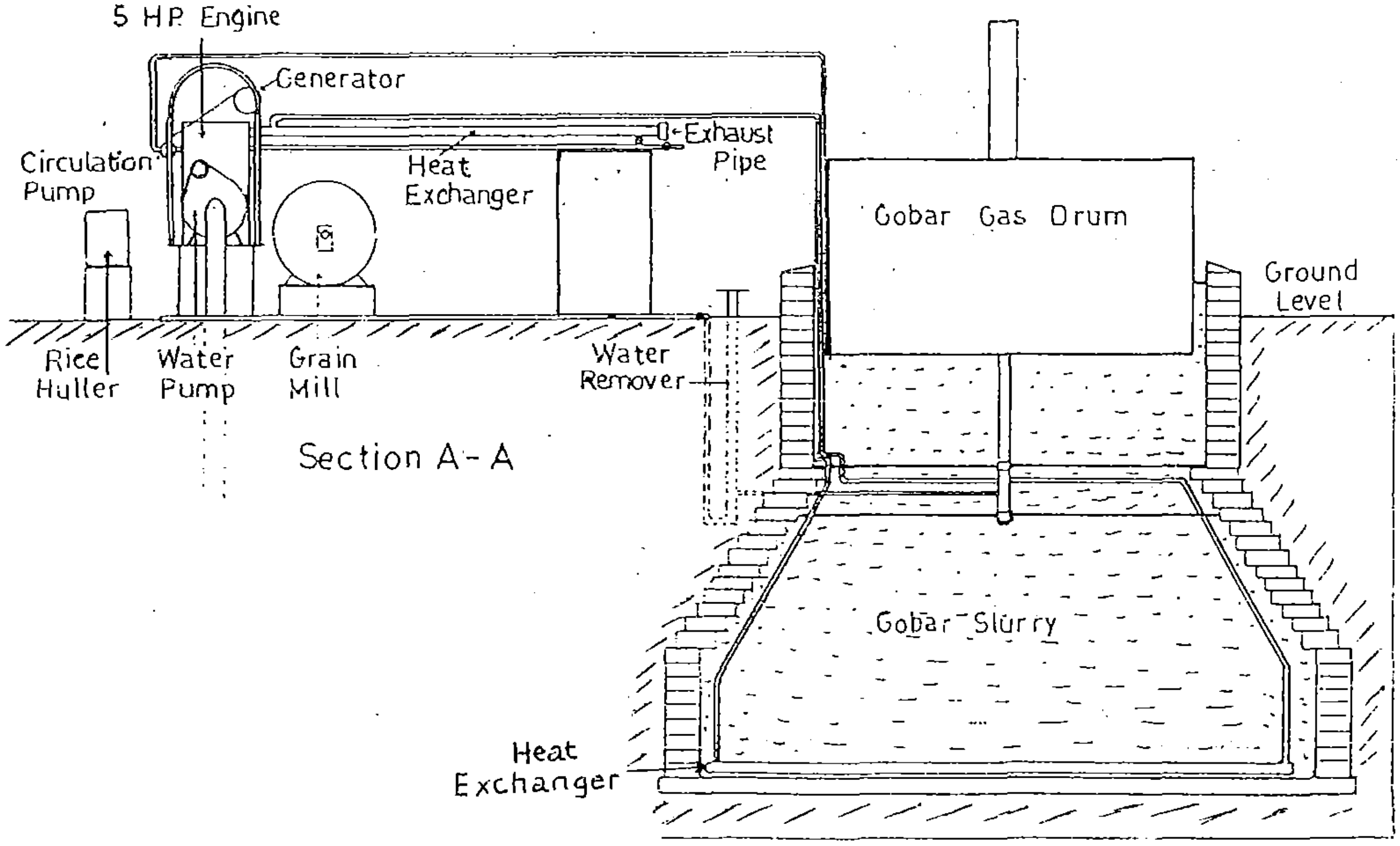


Fig. 6.11 Biogas Engine
Layout - using engine cooling water to heat gas plant



Site Plan (Scale 1:50)



Section A-A

Appendix

6.6 Heat Loss Calculations -

Heat loss from steel drum plant (34 m^3 digester volume)

All lengths are in meters ;

d_c = 0.23

d_m = 0.0025

l_1 = 0.70

l_2 = 0.35

l_3 = 1.15

l_4 = 1.22

l_5 = 1.05

r_1 = 1.40

r_2 = 1.68

r_3 = 2.34

Let q_i (i = 1 to 5) be the heat loss from various sections of the plants.

T_A = air temperature

T_S = digester operating temperature

U_i = overall heat transfer coefficient at different sections

x = depth of soil

Heat transfer coefficient :	W/m^2 C
Gas to steel drum, h_{GM}	10
Steel drum to air, h_{MA}	20
Slurry to concrete, h_{SC}	581.5
Concrete to air, h_{GA}	23.3
Soil to air, h_{SA}	5.8

Thermal Conductivity	W/ m C
Concrete, k_C	1.3
Steel, k_M	100
Soil, k_S	1.4

Assumptions :-

1. The metal drum is half-way above the slurry and the remaining half has no effect no heat transfer.
2. Insolation and radiation losses from the plant are negligible.
3. Heat flux in the soil traverse vertically upwards.

Heat loss from section i is given by the equation :

$$q_i = U_i A_i \ (T_S - T_A)$$

Section 1 :

$1/U_i = d_{M/k_M} + 1/h_{GM} + 1/h_{MA}$

Substituting the corresponding values, $U_1 = 6.67\ W/m^{2\,o}C$

A_1 = Area of the exposed top and side of the drum = 12.32 m^2

$q_1 = U_1 A_1 \ (T_S - T_A) = 82.17 \ (T_S - T_A)$ J/S

Section 2 :

$1/U_2 = 1/h_{SC} + 1_C/k_C + 1/h_{CA}$

Log mean value, $\overline{d_C}$, can be used instead of d_C

$\overline{d_C} = r_i \text{ in } (r_o/r_i)$ where r_o = outside radius
r_i = inside radius

$U_2 = 4.80\ Wm^2C$

$A_2 = 3.44\ m^2$

$q_2 = 16.49\ (T_S - T_A)$ J/S

Section 3 ;

$1/U_3 = 1/h_{SC} + \overline{d_C}/k_C + x/k_S$

$U_3 = 1/(0.1786 + 0.7143x)$

$q_3 = \int U_3 \ (T_S - T_A) dA$

$= \int_0^{1_3} U_3 \ (T_S - T_A))\ 2 \ \ r_2 \ dx$

$= 25.46\ (T_S - T_A)$ J/S

Section 4 :

$U_4 = U_3$

$d_A = m_1 \ (r_2 + m_2 \ x) \ dx$

where $m_1 = 2\pi\sqrt{l_4^2 + (r_3 - r_2)^2}/l_4 = 7.15$

$m_2 = (r_3 - r_2)/l_4 = 0.54$

$$q_4 = \int_0^{l_4} U_4 \ (T_S - T_A) \ m_1 \ (r_2 + m_2 s) \ dx$$

$$= 33.94 \ (T_S - T_A) \ J/S$$

Section 5 :

$U_5 = U_3$

$$q_5 = \int_0^{l_5} U_5 \ (T_S - T_A) \ 2\pi r_3 dx$$

$$= 33.98 \ (T_S - T_A) \ J/S$$

q_6 = heat required for heating daily influent of 500 kg.
= 500 x 4184 x $(T_S - T_A)$ J/day = 24.22 $(T_S - T_A)$ J/S

assuming specific heat of slurry to be 4182 J/Kg C

Total heat loss = $Q = \sum_{i=1}^{6} q_i = 216.26 \ (T_S - T_A)$ J/S

Q is the upper bound for heat loss since the path of heat flux in the soil was taken vertically instead of being deflected sideways as shown in Fig. 2.2.2. This makes x smaller and subsequently U_i and q_i larger.

<u>Calculation for the length of single-tube heat exchanger coil in digester</u>

The dimensions of the tube are
Outer diameter : 0.035 m
Inside diameter : 0.031 m

Let W_w = water flow rate

L = length of coil

c_p = heat capacity for after = 4184 J/kg C

U = overall heat transfer coefficient

r_o = outer radius

Considering an infinitesimal section dx of the tube :
On the water side, $dQ = w_w \, c_p \, dT_w$

For heat transfer, $dQ = - U \, 2\pi \, r_O \, (T_W - T_S) \, dx$

$$U \, 2 \; r_o \, (T_W - T_S) \, dx = w_w \, c_p \, dT_w$$

Integrating :

$$\ln \left[(T_{wi} - T_s)/(T_{wo} - T_s) \right] = U \, . \, 2\pi \, r_o L / w_w \, c_p$$

where t_{wi} and T_{wo} are the inlet and outlet temperature of water in the coil respectively.

If $\dot{w}_w = 1.2$ l/min $= 0.02$ kg/s, $T_i = 70^oC$ from Fig. 3.3.2

Heat transferred from the water to the slurry,

$$Q_t = w_w \, c_p \, (T_{wi} - T_{wo}) = 83.68 \, (70 - T_{wo})$$

From Appendix 5.1 :

If $T_A = 20^oC$, heat loss $Q = 216.26 \, (T_S - 20)$ J/S

For $Q = Q_t$ and $T_{wo} > T_s$, T_s was found to be 24^oC and T_{wo} to be 28.6^oC.

Using these values in equation (1) and $U_o = 170 \; W/m^2 \; C$,

$$\mathrm{Ln} \; \frac{(70 - 24)}{28.6 - 24} = 170\pi \times 0.035 \times L/0.02 \times 4184$$

giving a value of L = 10.3 m

Chapter 7 **SHAPE AND STRUCTURE OF BIOGAS PLANTS** D. Fulford

The shape of a biogas plant, as well as the way in which it is built, determines its strength and whether it is able to stand up to the stresses placed upon it. In general, the circle is the shape in which stresses are most evenly distributed, so biogas plants are usually designed to be cylindrical or partly spherical in shape.

When a biogas plant is being designed and drawn up, the internal volumes of these shapes and the quantities of materials required to build them need to be calculated. The stresses on the different parts of the digester need to be assessed to ensure the design is strong enough. The equations given below should enable these calculations to be made for most designs of biogas plant.

7.1 Steel Drum Biogas Plant - Size and Shape

The simples shape of biogas plant is that of the straight steel drum digester pit (Figure 7.1). It is a vertical cylinder with internal diameters : D_1, and external diameter : D_2 and height : H.

The internal volume (V_i) is then :

$$V_i = \frac{\pi}{4}.D_1^2.H.$$

The volume of the brickwork (V_b) is given by :

$$V_b = \frac{\pi}{4}.(D_2^2.t_f + (D_2^2 - D_1^2).H),$$

where t_f is the thickness of the floor.

If the thickness of the walls is : t_w, the total area of the brickwork in the walls (A_b) is :

$$A_b = \pi . (D_1 + t_w).H .$$ V_b is then given by :

$$V_b = A_b.t_w + \frac{\pi}{4} . (D_1 + 2.t_w)^2 . t_f.$$

Table 7.1 gives the number of bricks and volume of mortar to be used for different brick walls, in terms of both brickwork volume and surface area.

The taper type of steel drum biogas plant has a slightly more complex shape (see Figure 7.2). It has two cyclindrical sections (ID : D_1 and D_3, OD : D_2 and D_4, heights : H_1 and H_3), connected by a truncated of height : H_2. The

The internal volume (V_i) is then :

$$V_i = \frac{\pi}{4} .(D_1^2.H_1 + D_3^2.H_3 + (D_1^2 + D_3^2 + D_1D_3).\frac{H}{3}2).$$

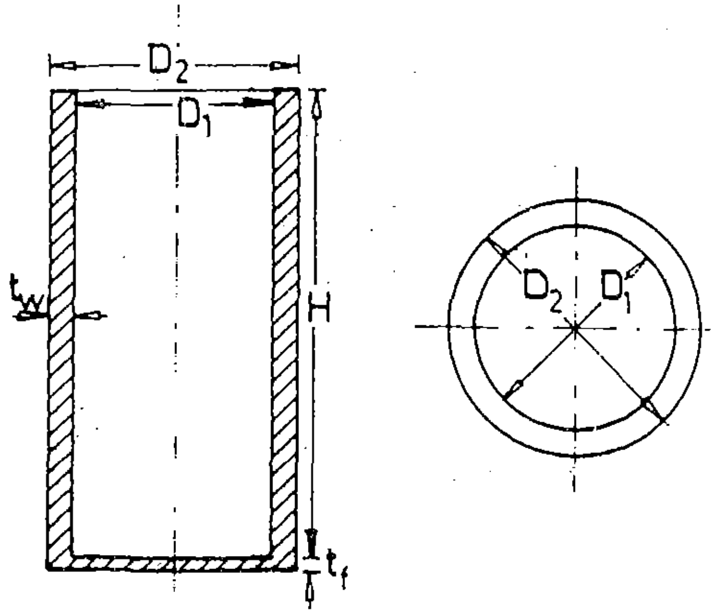


Fig. 7.1 The Shape of a Straight Type Steel Drum Biogas Plant

Type of Wall (mm)	$1\ m^2$ Area Contains		$1\ m^3$ Volume Contains	
	Bricks	Mortar (l)	Bricks	Mortar (l)
Side Laid (70)	35	7	500	100
1/2 Brick (120)	60	18	500	150
1 Brick (240)	120	46	500	195
1 1/2 Brick (360)	180	83	500	230
2 Brick (480)	240	110	500	230
Mass Brick	-	-	500	230

Table 7.1 Quantities of Bricks and Mortar in Brick Walls

The volume of the brickwork (V_b) is :

$$V_b = \frac{\pi}{4} \cdot (D_4^2 . t_f + (D_2^2 - D_1^2).H_1 + (D_4^2 - D_3^2).H_3 +$$

$$(D_2^2 - D_1^2 + D_4^2 - D_3^2 + D_4 D_2 - D_3 D_1).\frac{H}{3}2) .$$

If the thickness of the walls is : t, the area of brickwork in the walls (A_b) is :

$$A_b = \pi \cdot [(D_1 + t).H_1 + (D_3 + t).H_3 + (D_1 + D_3 + 2t).\frac{H}{2}2]$$

$$V_b = A_b.t + \frac{\pi}{4} \cdot (D_3 + 2t)^2.t_f .$$

Example 7.1

The volumes of the SD200 straight and taper plants can be found from their dimensions (see Volume I, Chapter 2).

SD200 Straight Plant (Volume I, Figure 2.4, Table 2.2)

D_1 (E) = 2000; D_2 (H) = 2480; H (A) = 4630

$$V_i = \frac{\pi}{4} \times 2.0^2 \times 4{,}63 = 14.54\ m^3. \qquad (\ = 3.14159)$$

$$V_b = \frac{\pi}{4} \times (2.48^2 \times 0.12 + (2.48^2 - 2.0^2) \times 4.63) = 8.40\ m^3$$

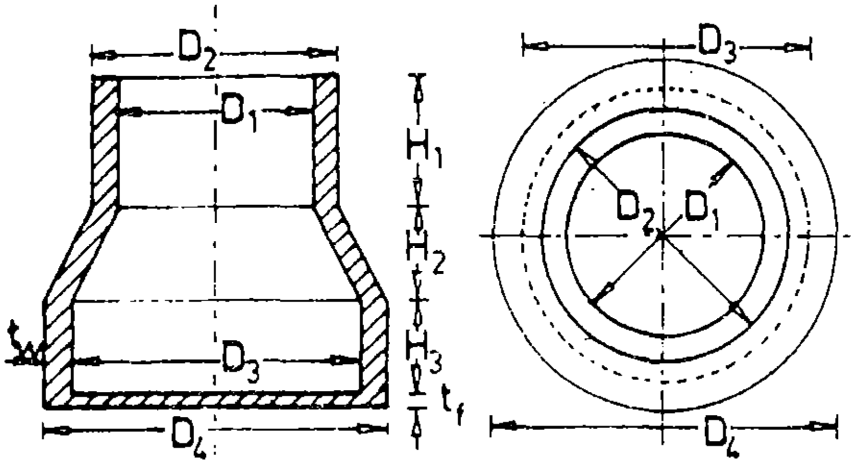


Fig. 7.2 The Shape of a Taper Type Steel Drum Biogas Plant

Motor Mix (1 lit)	Cement (kg)	Sand (lit)	Water (l)
1:1	1.00	0.70	0.25
1:2	0.68	0.94	0.20
1:3	0.51	1.05	0.20
1:4	0.40	1.10	0.20
1:6	0.28	1.17	0.20
1:8	0.22	1.22	0.20

Table 7.2 Quantities of Cement, Sand and Water in 1 Litre of Mortar (CAI)

$A_b = \pi \times (2.0 + 0.24) \times 4.63 = 32.58\ m^2$, so :

$V_b = 32.58 \times 0.24 + \frac{\pi}{4} \times 2.48^2 \times 0.12 = 8.40\ m^3$.

SD200 Taper Plant (Volume I, Figure 2.3, Table 2.3)

D_1 (E) = 2000; D_2 = 2480; D_3 (G) = 2900; D_4 (H) = 3360;

H_1 (B) = 1270; H_2 (C) = 910; H_3 (D) = 910; t = 240.

$$V_i = \frac{\pi}{4} \times [2.0^2 \times 1.27 + 2.9^2 \times 0.91 + (2.0^2 + 2.9^2 + 2.0 \times 2.9) \times 0.91/3]$$

$$= 14.34\ m^3.$$

$$V_b = \frac{\pi}{4} \times [3.26^2 \times 0.12 + (2.48^2 - 2.0^2) \times 1.27 + (3.36^2 - 2.9^2) \times 0.91$$

$$+ (2.48^2 - 2.0^2 + 3.36^2 - 2.9^2 + 3.36 \times 2.48 - 2.9 \times 2.0) \times 0.91/3]$$

$$= 7.07\ m^3.$$

$$A_b = \pi \times [2.24 \times 1.27 + 3.14 \times 0.91 + (2.0 + 2.9 + 0.48) \times 0.91/2]$$

$$= 25.60\ m^2.$$

$$V_b = 25.60 \times 0.24 + \frac{\pi}{4} \times 3.14^2 \times 0.12$$

$$= 7.07\ m^3.$$

The volume of bricks and mortar required for the input put, pipe supports and slurry outlet must be added to the above figures to obtain the total material quantities that are required to build this digester pit.

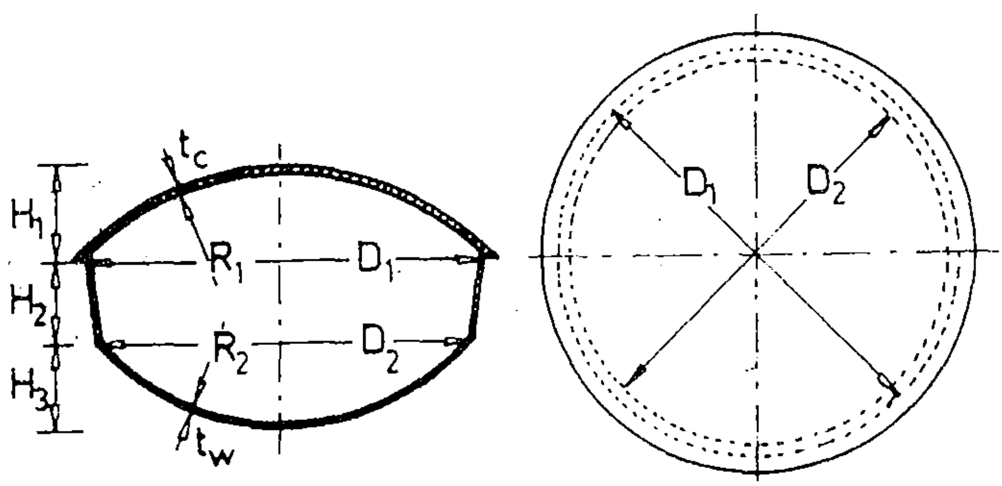


Fig. 7.3 The Shape of a Concrete Dome Biogas Plant

Concrete Mix (1 lit)	Cement (kg)	Sand (lit)	Aggreg. (l)	Water (l)
1:1:2	0.55	0.38	0.36	0.18
1:2:2	0.43	0.59	0.59	0.18
1:2:3	0.36	0.49	0.74	0.18
1:2:4	0.31	0.42	0.85	0.17
1:3:3	0.31	0.54	0.64	0.17
1:3:6	0.22	0.45	0.90	0.17
1:4:8	0.17	0.46	0.92	0.16

Table 7.3 Quantities of Cement, Sand, Aggregate and Water in 1 Litre of Concrete (CAI)

7.2 Concrete Dome Biogas Plant - Size and Shape

The digester pit of the concrete dome biogas plant (Volume I, Chapter 3) consists of two spherical segments connected by a truncated cone (Figure 7.3). The top spherical segments, the "Dome", is the gas storage volume, so it is useful to deal with this seperately.

There are several parameters belonging to a circular or spherical segment that are related to each other (Figure 7.4) : the radius of the arc (r), the width of the segment (d), the height of the segment (n) and the enclosed angle (2θ) :-

$$d = 2.r.\sin(\theta); \quad n = r.[1 - \cos(\theta)];$$

$$r^2 = (r - h)^2 + \left(\frac{d}{2}\right)^2$$

$$\text{or} \quad r = \frac{1}{2}.(n + \frac{d^2}{4H}) \quad \text{and} \quad h = R - \sqrt{r^2 - \frac{d^2}{4}}.$$

If two of these parameters are known, the other two can be found. The internal volume of the gas dome (G_i) of radius : R_1 and internal height ($H_1 - t_c$) is :

$$G_i = \frac{\pi}{3} . (H_1 - t_c)^2.[3.R_1 - (H_1 - t_c)]$$

H_1 is the external height and t_c is thickness of the concrete.

The volume of concrete in the spherical part of the dome is the external volume less the internal volume :

$$G_c = \frac{\pi}{3}.(H_1^2.(3.(R_1 + t_c) - H_1) - (H_1 - t_c)^2.(3.R_1 - (H_1 - t_c))).$$

If the thickness of the concrete (t_c) is much less than than the radius of the dome (R_1), then the above equation can be simplified :

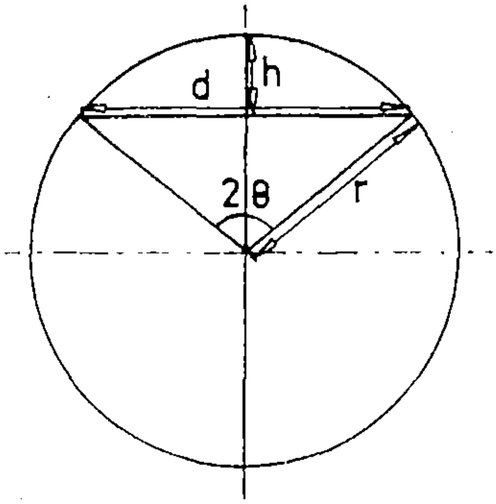


Fig. 7.4 Parameters Belonging to a Spherical Segment

$$G_o = 2.\pi.\ H_1.(R_1 + t_c).t_c$$

These calculations do not allow for the extra thickening of the dome in the region of the collar. The volume of the concrete in the collar (G_e) can be found by taking the area (A_e) of the extra thickness in one half of the cross section (the shaded area in Figure 7.5) and the radius of the centre of gravity (G) of this area (R_e) :-

$$G_e = 2.\pi.R_e.A_e$$

For the DCS designs of dome plant, an approximation may be made by doubling the volume of concrete in the spherical part of the shell, to allow for this thickening.

The internal volume of the lower spherical segment can be found using the formula, with the appropriate internal radius ($R_2 - t_w$) and height ($H_3 - t_w$, where t_w is the thickness of the cement plaster). The internal volume of the digester pit (V_i), without the gas storage dome is this volume, plus the volume of the truncated cone (IDs : $D_1 - t_w$ and $D_2 - t_w$ and height : H_2) :

$$V_i = \frac{\pi}{3}.((H_3 - t_w)^2.(3(R_2 - t_w) - (H_3 - t_w) + ((D_1 - t_w)^2 + (D_2 - t_w)^2 + (D_1 - t_w)(D_2 - t_w)).\frac{H}{4}2).$$

Since the plaster layer over the inside of the digester pit is fairly thin, (30 mm), the volume of plaster (V_p) can be found by calculating the surface area of the digester pit (A_i) and multiplying by t_w :-

$$A_i = \pi.(2.R_2.H_3 + \frac{(D_1 + D_2)}{2} \; H_2^2 + \sqrt{\left(\frac{D_1 - D_2}{4}\right)^2}) \quad \text{and :}$$

$$V_p = A_i.t_w.$$

The volume of plaster used to seal the dome (V_g) is :

$$V_g = 2. \; .R_1.(H_1 - t_c).t_g,$$

where t_g is the thickness of the plaster layer.

The total volume of the biogas plant (V_t) is then :

$$V_t = V_i + G_i.$$

The Working Volume of the plant is defined as :

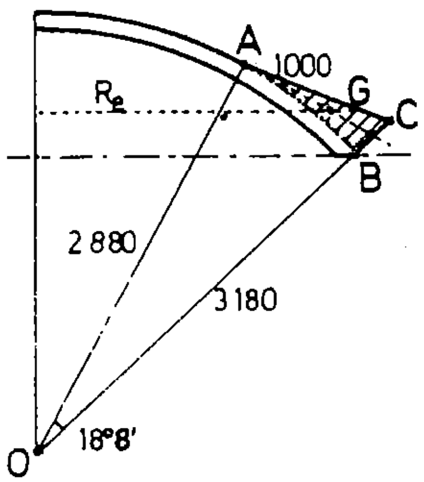


Fig. 7.5 Volume of Concrete in Collar of Dome

$$V_w = V_i + \frac{G_i}{2}$$

as the gas storage dome is not always full of slurry. In practice, the working volume depends on the cycle of gas production and usage. If more gas is stored for longer in the gas storage dome, the working volume is reduced.

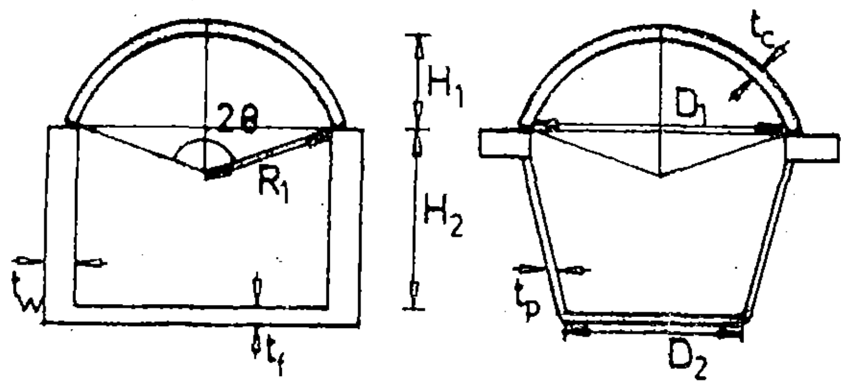


Fig. 7.6 The shape of a Tunnel Biogas Plant

(i.e. 0.12 m^3 of 1:2 plaster with 2% paint + 0.04 m^3 cement with 4% paint).

The volume of cement in the collar can be found more accurately by calculating the area of shape : ABC in Figure 7.5 :

$$\text{Area of Triangle : } A\dot{O}C = \sqrt{S.(S - OA).(S - OC).(S - AC)}$$

$$= \sqrt{3.53 \times 0.65 \times 0.35 \times 2.53}$$

$$= 1/425 \ m^2,$$

where $S = \frac{1}{2} . (OA + OC + AC)$, the half-perimeter.

The angle : $A\hat{O}C$ is given by : Area $= \frac{1}{2}$. OA x OC x $\sin(A\hat{O}C)$, so:

$$A\hat{O}C = \sin^{-1} \left(\frac{2 \times 1.425}{2.88 \times 3.18} \right) = 18^{\circ}8'.$$

$$\text{Area of Segment AOB} = \frac{1}{2} \times OA^2 \times AOC \text{ (rads)} = \frac{1}{2} \times 2.88^2 \times \frac{18^{\circ}8'}{180^{\circ}} \times \pi$$

$$= 1.312 \ m^2$$

Area of ABC = 1.425 - 1.312 = 0.113 m^2.

The centre of gravity (G) lies 2/3 of the distance between the top of shape, point : A and the mid-point of the base, line : BC. The radius of this point from the vertical axis of the spherical segement, line : OP is : 1.945 m, so :

$G_e = 2 \times 1.945 \times 0.113 = 1.381\ m^3.$

The total volume of concrete in the roof of the plant is then :

$G_t = 1.332 + 1.381 = 2.713\ m^3.$

7.3 Tunnel Biogas Plant - Size and Shape

The gas storage volume of a tunnel biogas plant is a segment of a cylinder lying horizontally (Figure 7.6). The internal volume of this tunnel is found by multiplying the cross-sectional area (A_g) by the length (L).

$$A_g = \frac{1}{2}.R_1^2.(2\theta - \sin 2\theta),$$

where : 2θ is the angle, in radians, subtended by the circular arc, radius : R_1, at its centre

$$G_i = A_g.L.$$

The concrete in one roof piece (g_c), which covers one half of the width of the tunnel and is of length : l is :

$$g_c = \frac{1}{2}.((R_1 + t_c)^2 - R_1^2).\theta.l\ .$$

The extra thickness at the edges can be allowed for, by adding 12% onto this figure. The total volume of concrete in the roof (G_c) is :-

$$G_c = 1.12 \times 2 \times g_c \times \frac{L}{l}.$$

There are two types of digester pit, or trench (Volume I, Chapter 4), lined with either brick masonry or cement plaster. The internal volume of the brick-lined trench (V_i) is :

$$V_i = D_2.H_2.L,$$

where : D_2 and H_2 are the widths and height of the trench.

The volume of the brick walls (V_b) is :

$$V_b = (2.H_2.t_w + (D_2 + 2.t_w).t_f).\ L\ ,$$

where : t_w and t_f are the thickness of the walls and floor.

If the outlet pit and the end walls are included :

$$V_b = (2.H_2.t_w + (D_2 + 2.t_w).t_f).B + (H_1 + H_2 + t_f).(D_2 + 2.t_w).2t_w$$

where : B is the total length of the brick trough.

The internal volume of the cement lined trench (V_i), which has a trapezoidal section, is :

$$V_i = \frac{1}{2}.(H_2 - t_p).(D_1 + D_2).L \;;$$

and the volume of the cement plaster :

$$V_p = (D_2 + 2.t_p + 2.\sqrt{\frac{(D_1 + D_2)^2}{4} + (H_2 + t_p)^2}).\ L.t_p.$$

If the outlet pit and the plaster on the end walls are included :

$$V_p = (D_2 + 2.t_p + 2.\sqrt{\frac{(D_1 + D_2)^2}{4} + (H_2 + t_p)^2})B.t_p +$$

$$2:\frac{1}{2}.\ (H_1 + H_2).(D_1 + D_2).t_p.$$

<u>Example 7.3</u>

The volume of the TP10 biogas plant can be found from its dimensions (Volume I, Figure 4.1 and 4.2, Table 4.2):

$R_1 = 600$; $D_1 = 1130$; $H_1 = 400$; $L(A) = 9000$; $t_c = 40$;

$B = 9600$.

For the brick lined trench : $t_w = 120$; $D_2 = D_1$; $H_2 = 800$; $t_f = 70$.

For the plaster lined trench ; $t_p = 30$; $D_2 = 800$; $H_2 = 800$.

From the geometry of a circular segment (see above and Figure 7.4):

$$\theta = \cos^{-1}(1 - \frac{H_1}{R_1}) = \cos^{-1}(1 - \frac{0.4}{0.6}) = 70^o31' = 1.231 \text{ rads.}$$

$$= 2.970 \text{ m}^3.$$

$$G_i = \frac{1}{2} \times 0.6^2 \times (2 \times 1.231 - \sin 2.462) \times 9.0$$

$$g_c = \frac{1}{2} \times (0.64^2 - 0.6^2) \times 1.231 \times 0.5$$

$= 0.0153 \text{ m}^3$ or 0.0171 m^3, if allowance is made for the ends.

$$G_c = 0.0171 \times 2 \times \frac{9.0}{0.5}$$

$$= 0.616\ m^3.$$

For the brick lined trench :

$$V_i = 1.13 \times 0.8 \times 9.0$$

$$= 8.136\ m^3,$$

and the total volume of brickwork in the trench is :

$$V_b = (2 \times 0.8 \times 0.12 + 1.37 \times 0.07) \times 9.6 + 2 \times 1.27 \times 1.37 \times 0.12$$

$$= 3.181\ m^3.$$

Extra bricks are used to hold the tunnel covers in place, as well as for the inlet pit and reservoir. Extra concrete is used for both the curved and flat covers for the reservoir.

For the cement plaster lined trench :

$$V_i = \frac{1}{2} \times 0.8 \times (1.13 + 0.8) \times 9.0$$

$$= 6.948\ m^3.$$

and the total volume of cement plaster is :

$$V_p = (0.86 + 2 \times \sqrt{\frac{3.725}{4} + 0.689}) \times 9.6 \times 0.03 + 1.2 \times 1.93 \times 0.03$$

$$= 1.050\ m^3.$$

Again, allowance must also be made for the bricks used in this design, as well as the extra concrete for the reservoir covers.

The total internal volume for the two types of tunnel plant are :

$V_t = 8.136 + 2.970 = 11.106\ m^3$ for the brick lined trench, and

$V_t = 6.948 + 2.970 = 9.918\ m^3$ for the plaster lined trench.

The working volume is defined as :

$V_w = 8.136 + 2.970/2 = 9.621\ m^3$ for the brick lined trench, and

$V_w = 6.948 + 2.970/2 = 8.433\ m^3$ for the plaster lined trench.

7.4 Inlet Pits and Reservoirs

Most of the inlet pits and slurry reservoirs used in these designs of biogas plant are of rectangular shape, so the internal volume (V_r) is :

$$V_r = S_1.S_2.G_1,$$

where : S_1 and S_2 are the length and breadth of the pit and G_1 is the depth of slurry in the pit.

The volume of brickwork in the walls (V_b) around a rectangular pit is :

$$V_b = 2.(S_1 + S_2 + 2.t_w).G_2.t_w,$$

where t_w is the thickness of the walls and G_2 the height.

Most other shapes in a biogas plant can be broken into rectangular or triangular areas, to allow these volumes to be calculated.

7.5 Stresses on a Biogas Plant

The lining of a digester pit is not designed to take much stress; its main function is to act as a barrier to stop the slurry leaking from the pit. For brick lined digesters, careful backfilling of the spaces between the brick walls and the uncut earth ensures that the hydraulic pressures from the mass of slurry in the pit are absorbed by the mass of earth around the walls. A brick wall can withstand very little tension stress. The main stress on this brick wall, then, is the weight of the rest of the wall above.

The plaster lining used in the dome and in one type of tunnel plant, is also only a barrier and cannot take any stress. It must be applied to smooth, undisturbed earth, which must resist the pressure on the cement.

The part of a biogas plant that does have to withstand stress is the concrete roof of a dome type plant and the arched roof of a tunnel plant. These must be designed so that all the stress comes in compression, which concrete, and also brick masonry, can withstand.

If the thickness of a circular concrete shell is small compared with the radius of the circle, and the shell is uniformly loaded, the strains within the concrete can be ignored, and the shell treated as if it were a membrane. As the roof of a dome or tunnel plant is almost 1 metre underground, the layer of earth above it should spread any live load above it (e.g. a buffalo standing on top) uniformly over the whole area of the roof. The analysis below is not valid for point or non-uniform loads.

7.6 Stress Analysis for an Arch

Taking a section of circular arch (7.7), subtending an angle : 2o at the centre, the membrane theory can be applied if the thickness (t) is much less than the radius (R) of the arc, so that higher terms of $t(t^3)$ can be ignored.

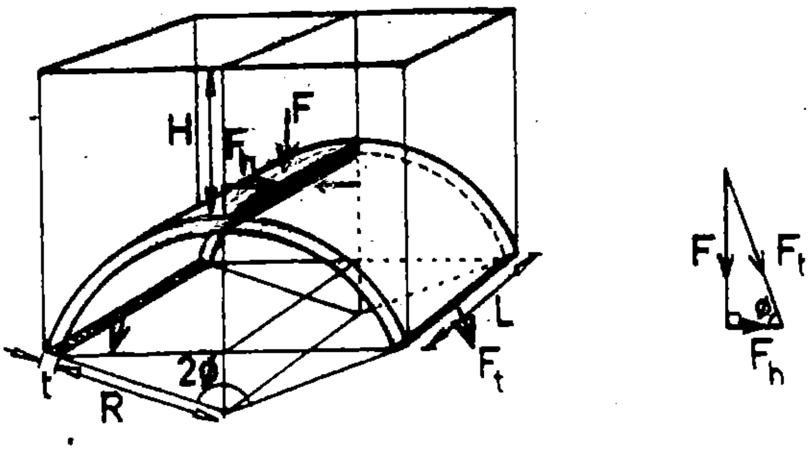


Fig. 7.7 Forces Acting on a Cylindrical Arch.

The stresses on a length : L of this arch are caused by the weight of the arch itself (M_s), the weight of the earth on top of it (M_w) and any live load on top of the (M_1). The mass of earth of depth : H above the centre of the arch is :

$$M_w = (2.(H + (R + t).(1 - \cos\phi)).(R + t).\sin\phi -$$

$$= \frac{1}{2}.(R + t)^2.(2\phi - \sin 2\phi)).\rho_e.L$$

$$= (2.(H + R + t).\sin\phi - \frac{1}{2}.(R + t).(\sin 2\phi + 2\phi)).$$

$$\rho_e.L.(R + t),$$

being a rectangular solid less the volume enclosed by the outside of the arch.

The mass of concrete in the arch is :

$$M_s = \rho_c.(R + t).\phi.t.L \quad .$$

The total mass on top of the arch (M) is then :

$$M = M_w + M_s + M_1.$$

The force ($F = M.g$) due to this mass, can be resolved into horizontal (F_h) and tangential (F_t) components at each edge of the section :

$$F_h = \frac{F}{\tan \phi} \quad ; \qquad F_t = \frac{F}{\sin \phi} \quad .$$

The horizontal force (F_h) effectively acts as a force "pushing" the two halves of the arch together and is resisted by a strain in the top of the arch (f_h) :

$$f_h = \frac{F_h}{L.t}$$

The tangential force (F_t) acts outwards from the edges of the section, over the area of the concrete at the edges, producing a strain (f_t) in each edge :

$$f_t = \frac{F_t}{2.L.t}$$

Taking all these equations together :

$$f_h = \frac{((2.\rho_e.(H + R + t)\sin\phi - \tfrac{1}{2}\rho_e(R + t)(\sin 2\phi + 2\phi) + \phi.t.\rho_c)}{L.t.\tan\phi}$$

$$\underline{\times\ (R + t).L + M_1).g}$$

$$f_t = \frac{((2.\rho_e.(H + R + t)\sin\phi - \tfrac{1}{2}\rho_e(R + t)(\sin 2\phi + 2\phi) + \phi.t.\rho_c)}{2.L.t.\sin\phi}$$

$$\underline{\times\ (R + t).L + M_1).g}$$

These strains are essentially independant of length (taking the live load as per unit length), so the tunnel plant can be built to any length, without causing any structural problems.

Example 7.4

The stresses on the arched roof of a tunnel plant can be found from its dimensions (see Example 7.3 above) :

$R(R_1) = 600$; $t = 40$; $H = 900$; $\phi = 70^{\circ}31' = 1.231$ rads.

The density of earth (ρ_e) is : 1.8×10^{-6} kg/mm^3;

the density of concrete (ρ_c) is : 2.2×10^{-6} kg/mm^3;

The acceleration due to gravity (g) is : 9.81 m/sec^2.

Ignoring the live load, the force downwards on 1 metre section of tunnel is :

$$F = [(2 \times 1540 \times \sin 1.231 - 1/2 \times 640 \times (\sin 2.462 + 2.462)] \times 1.8 \times$$

$$10^{-6} + 1.231 \times 40 \times 2.2 \times 10^{-6}) \times 640 \times 1000 \times 9.81$$

= 22,317 N/metre length.

$$\text{So : } f_h = \frac{22,317}{1000 \times 40 \times \tan 1.231} = 0.197 \text{ N/mm}^2 \text{ or MPascals, and:}$$

$$f_t = \frac{22,317}{2 \times 1000 \times 40 \times \sin 1.231} = 0.296 \text{ N/mm}^2 \text{ or MPa.}$$

If the values of the horizontal and tangential strains are checked over the range of angles from 0 to 70^o, it is found that the horizontal strain reaches a maximum of 0.516 N/mm^2, at small angles. The tangential strain is maximum at the above point, where = $70^o31'$. The value for both strains is always positive, over this range of angles, indicating that the strains are always compressive.

Placing a live load of 700 kg, spread over 2 m of length (simulating a large buffalo standing on top) :

$$F = 22,317 + \frac{700}{2} \times 9.81 = 25,751 \text{ N/metre length and :}$$

$$f_h = 0.228 \text{ N/mm}^2 \text{ and : } f_t = 0.342 \text{ N/mm}^2$$

Even putting a 1.5 tonne tractor on top, straddling 2.5 m of plant :

$$F = 28,203 \text{ N/m; } f_h = 0.249 \text{ N/mm}^2; \quad f_t = 0.374 \text{ N/mm}^2.$$

Since the compressive strength of concrete should be at least 10 N/mm^2, (CAI) the concrete roof pieces of a tunnel plant are easily strong enough to withstand this level of uniform loading. In practice, the roof pieces are far more likely to be broken while being transported or put in place, by sudden non-uniform loads, such as being dropped on one corner.

7.7 Stress Analysis for a Dome

A section of spherical shell (Figure 7.9) which subtends an angle : 2o at the centre, can be analysed by the membrane theory if the thickness of the shell (t) is much less than the radius (R) of the sphere.

The mass of earth (M_w) of depth : H at the centre, on top of the dome segment, is found by taking a cylinder, of depth : $H + H_1$ and subtracting the volume enclosed by the outside of the sphere :

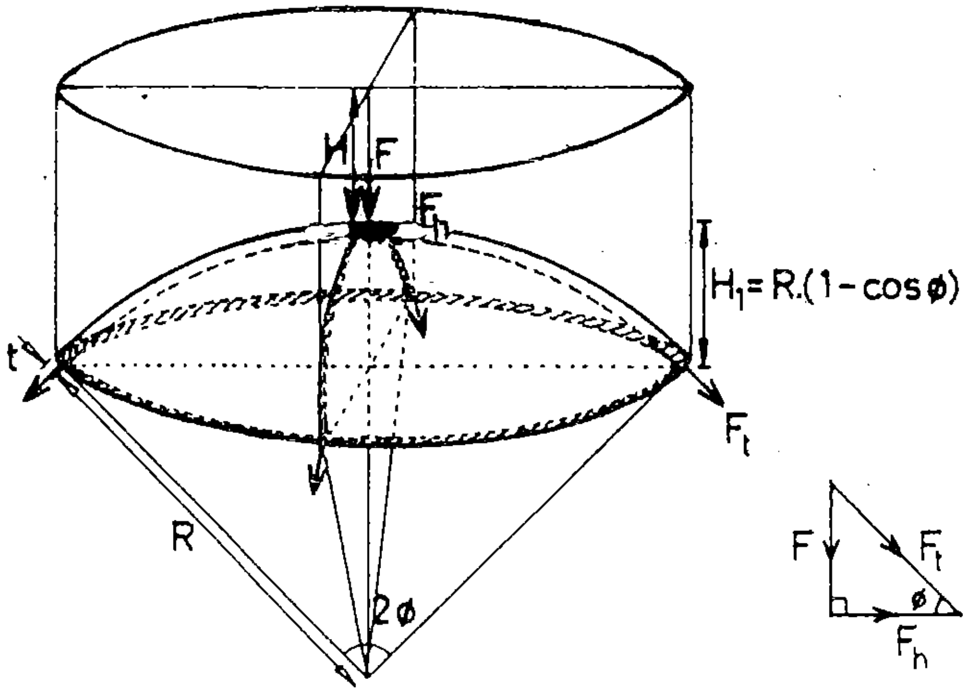


Fig. 7.8 Forces Acting on a Dome Segment

$$M_w = \rho_e.\Pi.((R + T)^2.\sin^2\phi.(H + R + t)(1 - \cos\phi)$$

$$- (R + t)^3((1 - \cos\phi)^2 - 1/3.(1 - \cos\phi)^3))$$

$$= \rho_e.\Pi.(R + t)^2.((H + R + t).\sin^2\phi$$

$$- (R + t).(2/3 - \cos\phi\ (1 - \sin^2\phi) + 1/3.\cos^3\phi))$$

$$= \rho_e.\Pi.(R + t)^2.((H + R + t).\sin^2\phi$$

$$+ 2/3.(R + t).(\cos^3\phi - 1))$$

The mass of the shell itself (M_s) is :

$$M_s = 2/3.\rho_c.\Pi.((R + t)^3 - R^3).(1 - \cos\phi) \quad (V = 2/3.\ .R^2.H_1)$$

$$= 2.\rho_c.R.t.(R + t).(1 - \cos\phi) \quad \text{(ignoring terms in } t^3)$$

The force on the spherical shell is then :

$F = (M_w + M_s + M_l).g$ and the horizontal and vertical components are :

$F_h = \frac{F}{\tan \phi}$ and : $F_t = \frac{F}{\sin \phi}$.

The horizontal force acts over an arch of the shell, of area :

$A_h = 2.t.(R + t).\phi$, so :

$f_h = \frac{F_h}{2.t.(R + t).\phi}$.

The tangential force acts over the area (A_t) at the edge of the dome :

$A_t = 2.\pi.(R + t).t.\sin\phi$,

so : $f_t = \frac{F_t}{2.\pi.t.(R + t).\sin \phi}$

Taking all these equations together :

$$f_h = \frac{\pi.(\rho_e.\frac{1}{2}.(R + t).((H + R + t).\sin^2\phi + \frac{1}{3}.(R + t)(\cos^3\phi - 1)) + \rho_c.R.t(1 - \cos\phi)).g}{t.\phi.\tan\phi}$$

$$f_t = \frac{(\rho_e.\frac{1}{2}.(R + t)((H + R + t)\sin^2\phi + \frac{1}{3}.(R + t)(\cos^3\phi - 1)) + \rho_c.R.t.(1 - \cos\phi)}{t.\sin^2\phi}$$

Example 7.5

The stresses on the dome of a CP20 biogas plant can be found from its dimensions (see Example 7.2 above) :

$R\ (R_1) = 2800;\quad H = 800;\quad t = 80\ ;\quad D_1 = 4000;$

$$\phi = \sin^{-1}(\frac{D_1}{2R_1}) = \sin^{-1}(\frac{4.0}{2 \times 2.8}) = 45^{\circ}35' = 0.796 \text{ rads.}$$

Ignoring live loads, the force downwards on the whole of the dome is :

$$F = 2.\pi.x\ 9.81 \times 2880 \times ((\frac{2880}{2} \times 3860 \times (\sin 0.796)^2 + \frac{1}{3} \times 2880^2 \times ((\cos 0.796)^3 - 1)) \times 1.8 \times 10^{-6} + 2800 \times 80 \times (1 - \cos 0.796) \times 2.2 \times 10^{-6})$$

$$= 352{,}174 \text{ N.}$$

$$f_h = \frac{352{,}174}{2 \times 80 \times 2880 \times 0.796 \times \tan 0.796} = 0.940 \text{ N/mm}^2 \text{ or MPa.}$$

$$f_t = \frac{352{,}174}{2\pi \times 2880 \times 80 \times (\sin 0.796)^2} = 0.476 \text{ N/mm}^2 \text{or MPa.}$$

If the values of the horizontal and tangential strains are checked over the range of angles from 0^o to 45^o, it is found that the horizontal strain is maximum at 20^o, being : 1.070 N/mm^2. The tangential strain is maximum at the above position, i.e. $45^o35'$. Both strains are always positive, over the above range of angles, so the strain is always compressive.

Putting a 1.5 tonne tractor on top of the dome :

F = 352,174 + 1,500 x 9,81 = 366,889 N and :

f_h = 0.979 N/mm^2 and : f_t = 0.511 N/mm^2.

Again, since the compressive strength of concrete should be at least 10 N/mm^2, the dome of a CP20 biogas plant is easily strong enough to take even a tractor standing on top of it, as long as the load is uniformly spread over the dome by the layer of earth above it.

The tangential component of the weight of the dome is taken by the soil on which it rests. The weight of the dome is higher than calculated above, as the edge is thickened, giving :

F = 357,593 N.

However, the area on which the dome rests (A_t) is then:

$$A_t = 2.\pi \times 2990 \times (300 + 100 \times \sin 0.796) \times \sin 0.796$$

$$= 4{,}986{,}545 \text{ mm}^2$$

$$f_t = \frac{357{,}593}{4{,}986{,}545 \times \sin 0.796} = 0.100 \text{ N/mm}^2$$

A medium quality soil has a bearing capacity of 0.12 N/mm^2 (Khanna), so would be strong enough to support the dome. A poorer soil, such as soft clay or sand, may not be able to support this load, so the dome might settle into the ground, or even crack due to non-uniform loads.

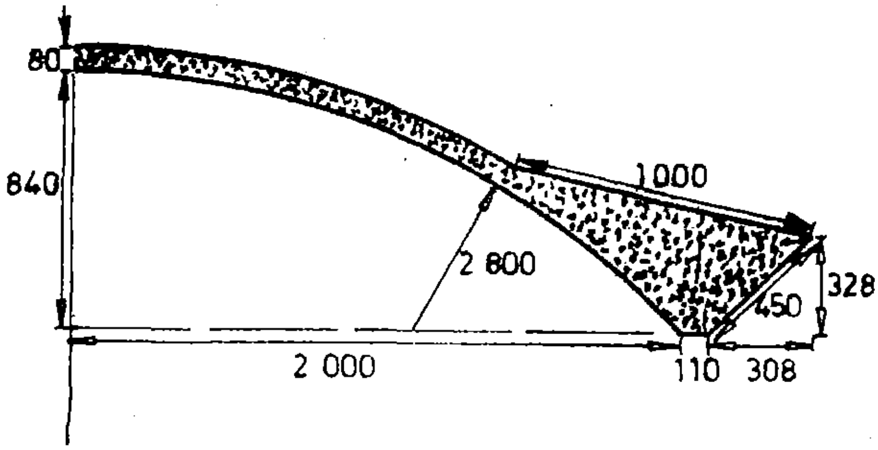


Fig. 7.9 Alternative Design of Collar for Use with Poor Soils

The use of brick pillars is one way to support the dome (see Volume I, Chapter 3); the area under the base of the pillars should be at least 6 sq. m. A better way would be to redesign the collar of the dome for use with poor soils. If the thickness of the edge of the dome is made to be 450 mm (Figure 7.9), the compression of the soil is reduced to 0.067 N/mm^2, which is within the bearing capacity of even a poor soil (Khanna). The volume of this collar is 2.116 m^3, giving a total volume for the whole top of 3.448 m^3.

Chapter 8 **DEVELOPMENT OF COMMUNITY BIOGAS IN NEPAL** D. Fulford

The concept of community biogas technology is based on three basic assumptions, which make up the "community biogas equation". If these assumptions are yalid, they offer a way in which the restraints of biogas technology, particularly the relative high captial cost, can be overcome. This would allow poorer sections of the community to benefit from this technology.

The assumptions are :-

Scale : if a large scale biogas plant is built, the effective cost per cu. m. of biogas produced is lower. A community of people can share their supplies of feedstocks and other inputs.

Economic : a larger biogas plant produces more biogas, which may be used for purposes that generate income. If a biogas plant can earn enough cash so that the origional investment (as a loan) can be recovered in a short enough time, lack of money is not a restraint.

Socioloical : if a biogas plant is placed in the social context of a primary group, it will evoke the same set of reactions as in the context of one owner/user. A primary group is characterised as having 'face to face' relationships, sharing close physical proximity and having a common identity (Cooley), so they should have a common set of responsibilities as well.

These assumptions need to be tested in a real environment. This was done by looking at previous attempts to set up community biogas plants in Nepal, as well as setting up our own project.

8.1 A Survey of Previous Attempts

There was one programme in Nepal in 1979, sponsored by His Majesty's Government of Nepal and United States AID, that planned to build 4 community biogas plants, one in each of the Development Regions of that time. Three community plants were completed (Karki). The plants drew on a wide range of possible uses of biogas technology in a number of different social settings (Bulmer).

Plant number : 1 was sited in a settled village environment, with cow dung as the feedstock, and the biogas used for cooking and lighting by 5 Hindu households.

Plant number : 2 was sited in a resettlement camp for 26 Buddhist families, to provide lighting for the work of carpet making. Both cow dung and human excreta were used as feedstocks.

Plant number : 3 was sited in an urban setting to provide gas for cooking for 10 low-caste Hindu households. The main purpose of the plant was to take human excreta from latrines, that were to serve as hygenic measure for about 300 low-caste women.

One year after these plants had been completed, none were working as planned :-

Plant number : 1 was only being used by 3 of the 5 families. Only one family really took interest in the plant, although they complained that the biogas appliances and the plant itself were in need of repair. They did not know who to approach about maintenance.

Plant number : 2 was being used by 5 of the 26 families. Gas was insufficient for all the lights; probably because of pipe leakages. The latrines were still being used.

Plant number : 3 had been abandoned. There were several problems of a technical, social and administrative nature that proved too complex to solve. The biogas produced would not burn; the latrine attendant (a man) was not being paid (from the sale of biogas); the initial popularity of the latrines faded as the system became overloaded and began to smell.

The main causes of failure in these projects were identified as being in the approach used by the implementing organisations to the communities. Many problems related to the social organisation of these communities only came to light after the biogas plants were built. Data must be collected about the community in which a biogas project is to be built, before any technical work is started.

Priority was given to the building of the biogas plant, although the real needs and priorities of the people may have been entirely different. The real needs of a community must be assessed objectively, and if biogas technology cannot offer an answer to those needs, then a plant should not be built there.

People in these communities could not work together as well as they thought they could. Methods should be devised to assess people's ability to work together as a community, before they are committed to such a relatively expensive project as a biogas plant.

These biogas plants were built for the communities, paid for by the aid agency. The people expected the aid agency to repair the plants when they went wrong and had little commitment to ensure they were kept working. If people make a financial commitment, themselves, to a project, they are far more likely to keep it going.

While the biogas plants were in some way related to income earning, such as giving lighting for carpet making, the uses for the biogas did not earn an income directly. If biogas is used directly to earn money, then people have a high incentive to continue to use it.

The implementing organisation left the projects, once the biogas plants were built. The responsibility for such a community project does not end there; careful follow-up, training and maintenance are required to ensure such a project continues working.

8.2 Another Approach

Three independent institutions were involved in the second community biogas programme in Nepal, each taking on a particular responsibility.

The Small Farmers' Development Programme works under the Agricultural Development Bank of Nepal, with the guidence of the Freedom from Hunger Campaign of the Food and Agricultural Organisation (RAFE). They help to organise poor farmers into groups that are then able to borrow money for development projects. The Nepal SFDP also provides expert help for some of these projects, such as pumped irrigation and improved livestock breeding. The ADB/N provides loans for such projects at 11% interest over 7 years. They also had a fund from United Nations Development Programme to pay 50% subsidies for the setting up of community biogas plants.

The Gobar Gas tatha Krishi Yantra Bikash (Pvt) Ltd was set up to build biogas plants in Nepal (see Volume I, Chapter 13). They offer training in biogas technology for farmers and give a 7 year guarantee for any plant they build. They have a network of sales and service depots in many parts of Nepal, and make yearly follow-up visits to customers, as part of the guarantee, to do minor maintenance.

Development and Consulting Services has been continuing a research and development programme on biogas (see Chapter 2). They were able to offer expert technical help, as well as feasibility analysis of the programme.

Year	No. Households	Village	District	Machines		
				Huller	Grinder	Pump
1981	4	Tiklegard	Rupendehi	1	1	
1982	22	Chokatey	Gorkha	1	1	
1982	4	Bhutaha	Nawal Parasi	1	1	
1982	5	Laxmipur	Dang	1	1	
1982	10	Pokodyia	Dhanusa	1	1	
1983	4	Birendra-nagar	Chitwan	1	1	
1983	12	Madhi	Chitwan	1	1	
1983	5	Dulari	Itahari	1	1	
1983	37	Madhubasa	Dhanusa	1	1	1

Table 8.1 Community Biogas Plants Built by Gobar Gas Company

The Small Farmers' Development Programme had gained valuable experience with working with small groups of farmers (4 to 20 households), so the first "community" biogas plant was built for such a group. Four families, who lived near to each other, agreed to purchase an SD500 biogas plant by taking out a cooperative loan from ADB/N (which requires less security than an individual loan). SFDP were also able to find a 50% subsidy for the biogas plant. Initially the biogas was to be used for only cooking and lighting, but concerns about finding enough money to pay back the loan encouraged the four families to test the use of an engine driving a rice huller (see Case Study 8.1, following).

Since this first "group" biogas plant was built, others have followed (see Table 8.1), about 7 in all. About 7 more have been ordered and are being built. The growth of interest in group ownership of biogas plants has coincided with a growth in interest in the use of biogas to run engines to drive grain mills. At least 6 individually owned SD 500 biogas plants have also been purchased in the same period (4 years), to run engines, and more have been ordered.

The "group" type of community biogas plant should be distinguished from the "village" biogas plant, in which larger numbers of people are involved. Only one village biogas system has been set up, at the time of writing, to drive an irrigation pump (see Case Study 8.2, following).

The difference between a group biogas plant and a village one is not always clear. The plant at Chokatey (see Table 8.1) is counted as a group plant, even though 22 families are involved. A group is a collection of people who have come together to form a cooperative, so they can take part in a development project, usually with the help of the SFDP in Nepal. A group of 22 families is near the maximum size. The village of Chokatey were helped by the Resource Conservation and Utilization Project of USAID. A group is self-selecting : people only join it if they wish, and people can leave it at any time, as long as they have fulfilled their commitments to the group.

A village biogas plant includes everyone in a natural community, who normally live and work closely together. A village grouping tends to include a larger number of families (over 20) and may include people who are less inclined to cooperative ventures, or who have little interest in the project (Roy). Since tensions and divisions are far more likely in a village, than in a group, a village biogas project is much more difficult to start.

Case Study 8.1 : Group Ownership of a Biogas Plant

Village	:	Kusongodai	Kusongodai lies 5 km South-West of
Panchayat	:	Tiklegard	Balawadi, which is on the Butwal-
Ward No.	:	7	Bhairahawa road.
District	:	Rupendehi	
Zone	:	Lumbini	Plant used for cooking/lighting/milling.

In 1980, the Small Farmers' Development Programme manager (the Group Organiser/Action Research Fellow) suggested to SFD Group Number 36 that they set up a community biogas plant. They were having problems with obtaining fuel in the local area and had seen an individually owned biogas plant nearby and were interested by it. The SFDP GO/ARF asked DCS to make a survey of the village (Bulmer).

5 of the houses in the village of Kusongodai were very close together, so the piping of biogas to these houses would be easy. 2 other houses were fairly close. All the people living in the village (10 families) were Brahmins and related to one another. They traditionally work together in their farming activities and had been involved in the Small Farmers' Development Group. In 1980, they were spending about Rs. 1,500 per household on wood and kerosene for cooking and lighting. These prices were increasing, and would have doubled by 1990. 4 of these families had approximately equal landholdings and livestock.

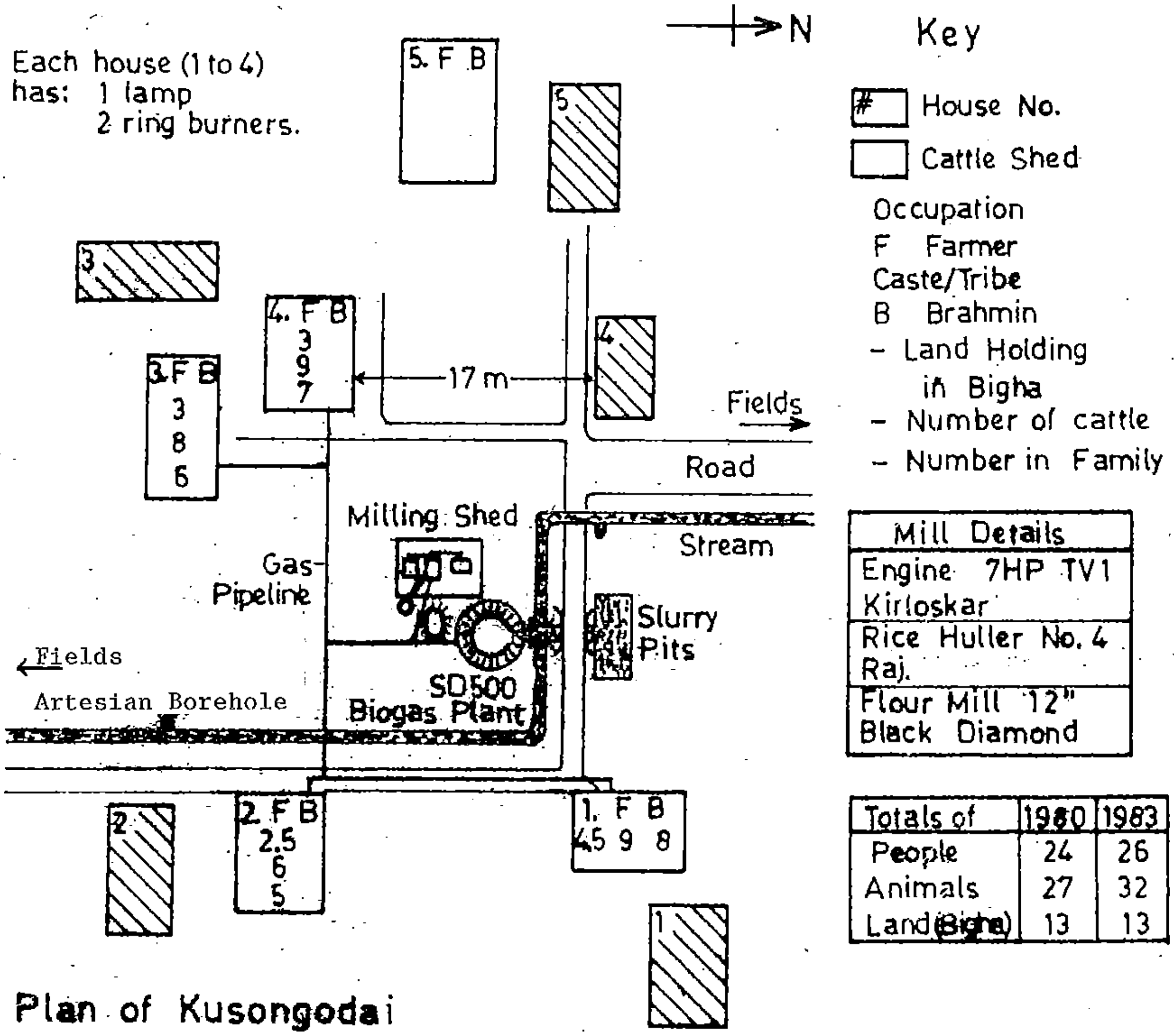


Fig. 8.1 Small Farmers' Development Group No. 36, Tiklegard

Factors against the success of a group plant were the total number of cattle (27), which was too low for feeding an SD500 biogas plant; and the opposition of one family head (no. 5), who was a respected elderly priest, who had influence in the village.

The biogas plant was built in April 1981, for four families of SFDG No. 36, providing 2 ring burners and 1 biogas lamp for each of the 4 houses (see Figure 8.1). In February 1982, the Gobar Gas Company persuaded these families to install a 5 HP Kirloskar dual-fuel engine and a rice-huller for a 6-month trial period. In August 1982, the engine was taken back by the Gobar Gas Company, and the villagers bought a 7 HP dual-fuel engine and a flour grinder with a loan from ADB/N, through the SFDP. They later purchased the rice huller from DCS.

8.3 Allocation of Responsibilities

The villagers have carefully organised themselves to ensure that the biogas system works well. Each house brings 3 buckets of cattle dung to feed the biogas plant each morning, and a person from the house helps to mix the slurry. The four house heads have agreed to open the main gas valve at fixed times, so the gas can be used for cooking : 5.00 to 5.50 am for early morning tea; 6.00 to 8.30 am for the main meal; 1.30 to 2.00 pm for afternoon tea; 6.30 to 9.00 pm for the evening meal and for running the gas lamps. The 4 households take it in turn to be responsible for the oversight of the main gas valve for 10 days at a time.

The mill is used for as long as there is demand for its services. In the winter months, when there is less gas, the houses have to use wood to cook the evening meal. Outside customers tend to come to the village to have their rice hulled or grain ground towards late morning. If the gas has all been used, they will run the engine on diesel alone.

The effluent slurry is collected in pits at the edge of the village. Each household has its own storage pit and takes slurry from the central pit whenever they need it. They must count the number of buckets of slurry that they take and make sure that each house has the same amount.

The mill is operated by two people : the driver, who is hired from outside the village and a cashier, who is one of the people from the 4 households. The driver arrives for work at 7.00 am and is given an hour off for his mid-day and evening meals. He is paid Rs. 300 a month, however much work he does. In the slack seasons (e.g. the monsoon) he may only work for 3 hours a day. In the harvest months, he may have to work for 18 hours/day; sometimes all night long. He often collects diesel (20 litres a time) using a bicycle for the 7 km journey. He also does any maintenance and repair work required on the mill.

The cashier issues slips of paper to the people waiting to have their grain processed in the mill. The slips have numbers on, to save arguments about who came first, and they also show how much grain is being milled and how much must be paid, in money or in grain. Duplicates of these slips are retained by the cashier for accounting purposes. The job of cashier is taken by each household in turn.

The cashier writes a record of the daily income in a register in house no. 4, in the presence of the head of the house. He then takes the grain and money to house no. 2, where it is again recorded and put away for safe-keeping. The head of house no. 2 also keeps a monthly register to record repayments to the bank for the loan. He also sells grain from the stock earned from milling to people who come to buy it. Another person from another house must be present, when grain is sold.

The work of maintaining the engine, mill and biogas plant is done by the driver, with the help of the young men of the village. Many visits have been made to the site by the Gobar Gas Company technical staff and the villagers are satisfied with this service.

8.4 Effectiveness of a Group Biogas System

The villagers are very satisfied with the dual role of their biogas plant, providing fuel for cooking and lighting, as well as running a small mill that provides them with an income. They are pleased that the money earned by the mill is enough to finance the cost of the loan repayments, so they do not have to find that money elsewhere. The close cooperation between the 4 households is motivated by the benefits that they see coming from effective operation of their biogas system.

It has not been possible to give exact details of their monthly income from the plant. These people are farmers who are naturally cautions towards outsiders, especially people who might tell the tax authorities about their earnings. Despite the apparent organisation of accounting and record keeping, the books are not clearly arranged and the calculations are difficult to understand. (see Volume I, Chapter 11 for an estimate of monthly income and expenditure).

The villagers seem to have been able to compete with other grain mills in their area, about 5 diesel mills within an hours walk of the village. Their price, especially for rice hulling, has been lower and local people prefer to come to a small mill, which is happy to process small quantities, than go to a larger place, where they may have to wait. However, with the extension of an electricity supply to the area, 3 electric mills have been set up, which charge lower prices still, so this further competition may have an effect on the profitability of the Kusongodai system.

Case Study 8.2 Village Ownership of a Biogas Plant

Village	:	Madhubasa	Madhubasa lies 6 km North-East of
Panchayat	:	Pushbalpur	Dalkebar, which is on the East-West
Ward No.	:	9	Highway, at the junction with the road
District	:	Dhanusha	to Janakpur.
Zone	:	Janakpur	Plant used for Irrigation/lighting/cooking.

Madhubasa village people had set up their own cooperative society called "Sano Kalpana Sagha Sanstha", A society with a Little Vision. A local school master wrote a small booklet on it (Adhikari), so the village was chosen as a place for a Small Farmers" Development Group in 1979. SFDP suggested the village as a site for a community biogas project and DCS did a survey in December 1980.

The village lies at the base of the foothills of the Himalayan range of mountains, so has hills and forests to the North, with the flat North Indian plain to the South. There are 37 families, with a total population of 187 (in 1983). All the families are of one tribal group, the Magars, and all are farmers. The village is at the meeting point of two rivers. These rivers are usually dry, but they are subject to flash flooding in the monsoon season, when water runs off the hills to the North. These floods are getting much worse in recent years, as deforestation and the removal of soil cover means that run-off is increased and less water is absorbed into the hill sides.

The "Society with a Little Vision" was begun in 1964 on the initiative of the people themselves. All villagers are members of this society and 11 persons are office holders. There are regular meetings at which minutes are recorded. The minutes become law in the village, once they have been fully discussed and everyone has signed their name, or made their mark, after the minute (Bulmer).

Madhubasa is not a typical village, although the Magar tribe are noted for their community spirit. The strong, but open, leadership in Madhubasa and the willingness of the people to join in community ventures, put it in a class of its own.

8.5 The Approach

The survey by DCS concentrated upon the real needs of the villagers. At first, they had little interest in biogas technology : they had not seen a biogas plant, or even heard of the idea; they did not have a problem with cooking fuel, being so close to the forest. They had two main concerns; the yearly monsoon flash floods were eroding the land on which they were growing their crops; they wanted to irrigate the remaining land, so they could grow more crops on it.

After deciding to work in the village, DCS defined several principles on which we would work : the identity of the village had to be respected; the Society with a Little Vision was unique and all the 37 households in it had to benefit from any development work done in the village. The first priority was to solve the problem of land erosion. After that , a community irrigation scheme could be planned : first by digging wells, then by installing a lift irrigation pump, that could be driven by biogas.

The land erosion problem was reduced by building gabion barriers into the path of the flash floods in the dry river beds. About 5.5 ha of river bed was reclaimed for agriculture, in this way (Bulmer). Several exploratory wells were dug, as local people thought that the Jalad river flowed underground during most of the year. Two permenant wells, 80 m apart were eventually constructed, with an underground plastic pipe connecting them. The Japanese funded Janakpur Agricultural Development Project gave much help for this work, including expert technical advice and the use of digging machinery.

The work of construction of the gabion barriers was done mainly by the villagers themselves, once they had received training in the making of the netting boxes from wire. Stone was brought to the site by a tractor and trailer, loaned by J.A.D.P. This gave us ample opportunity to observe the people at work and to test their cooperataive spirit.

Planning for the community biogas irrigation scheme was also done. An economic feasibility study was done (Fulford) in 1981, updated in 1983. The possible profits from growing a wheat crop in the dry season appeared to be enough to cover the loan repayments for the system. A Biogas Committee was set up in the village; the members eventually being the office holders in the Society with a Little Vision. No women were on this committee, although we advised that there should be.

In May 1982, 6 members of the committee went on a "Biogas Tour", visiting the Gobar Gas Company office in Butwal, the group biogas plant in Kusongodai (see Case Study 8.1) and the biogas irrigation scheme in Parwanipur (see Volume I, Chapter 8). The villagers wrote their own report on this visit (Madhubasa). In October of the same year, two of the young men of the village were sent off for a course in engine operation and maintenance at JADP. The village were loaned a diesel engine, so they could become used to its use. Tests were also done to see how much water could be taken from the wells at different times of the year.

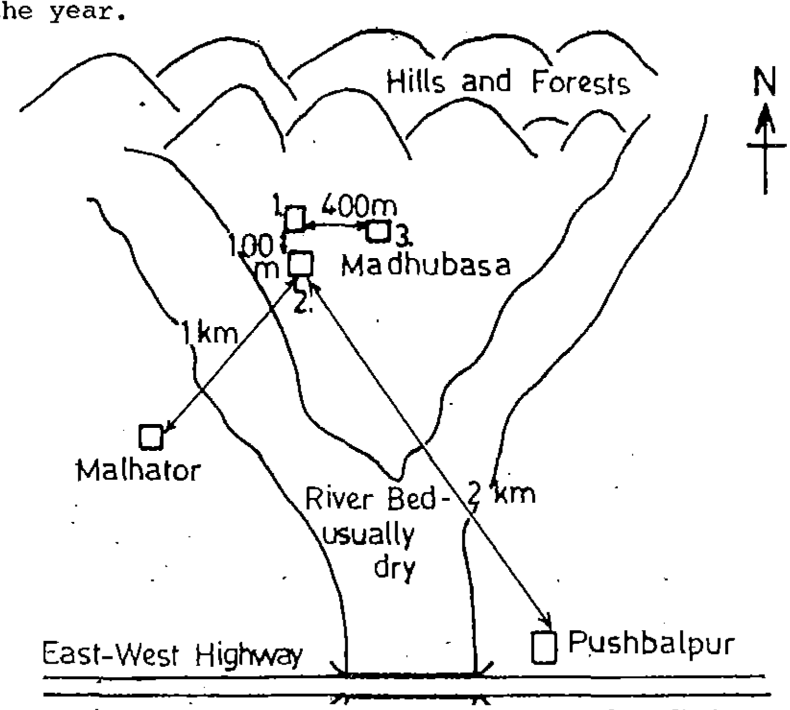


Fig 8.2 A Map of the Area around Madhubasa

8.6 Decisions to be Made

While the biogas plant was originally seen as an answer to one of the villagers' felt needs, that of irrigating their land, consideration was given to alternative uses of the biogas. Irrigation is a seasonal activity, so the pump would be used for only 150 days of the year. The villagers wanted gas lamps in the village, so they could hold society meetings by gas light. Another lamp was placed in a prominent position, so that people from other villages could see it. Two gas ring burners were also placed in the community house, for use in making tea for the meetings and for guests in the village.

Another suggestion was that the engine should be used to run a grain mill, as they had seen the one at Kusongodai. Some people even thought the biogas plant should be sited at Pushbalpur, near the road, where such a mill would have more customers. This idea was unanimously rejected at the next meeting, because the women of the village protested to their husbands that they would not benefit from such an idea.

The original scheme for using biogas to run an irrigation scheme has been kept, although the whole system could be expanded to include a mill, in the future. An addition to the original idea, was the use of the pump-set to pump water up to a drinking water storage tank on a hill near the village. The Local Development Department of HMG/N had offered to pay for water pipe and a storage tank for the village.

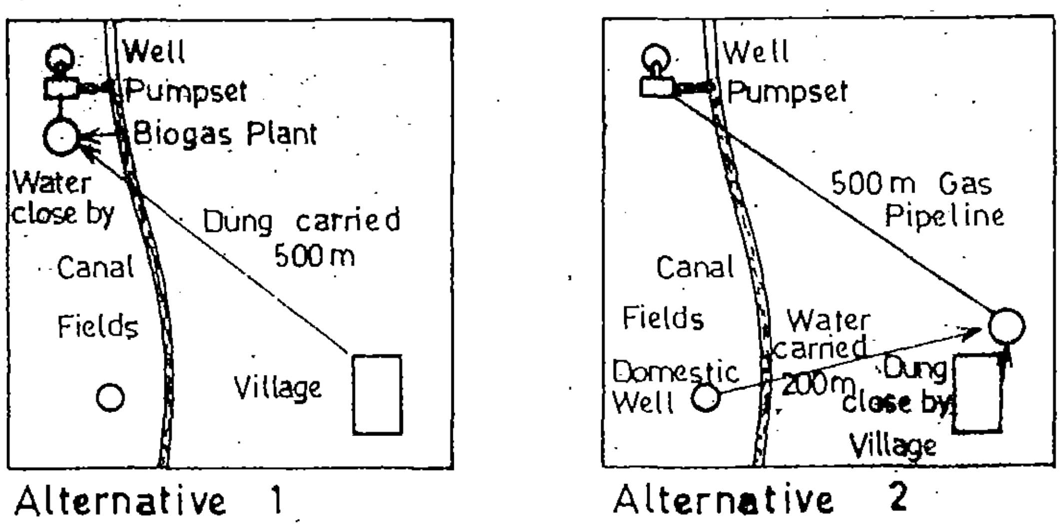


Fig. 8.3 Alternative Sites for the Biogas Plant

8.7 Siting of the Biogas Plant

From a technical point of view, we recommended that the biogas plant be sited near the engine by the well. The biogas would need to be piped only a short way, and the effluent slurry could be put directly into the irrigation water. Water for mixing the slurry would be available from the well, nearby. (Figure 8.3). The only disadvantage would be that cattle dung would have to be carried from the village : 300 or 400 kg for 500 m each day. The villagers disagreed : carrying dung would take too long each day, and they were not prepared to keep the cattle away from the village. They were concerned about the security of the biogas plant, being afraid as much of possible attacks from evil spirits as of possible human interference.

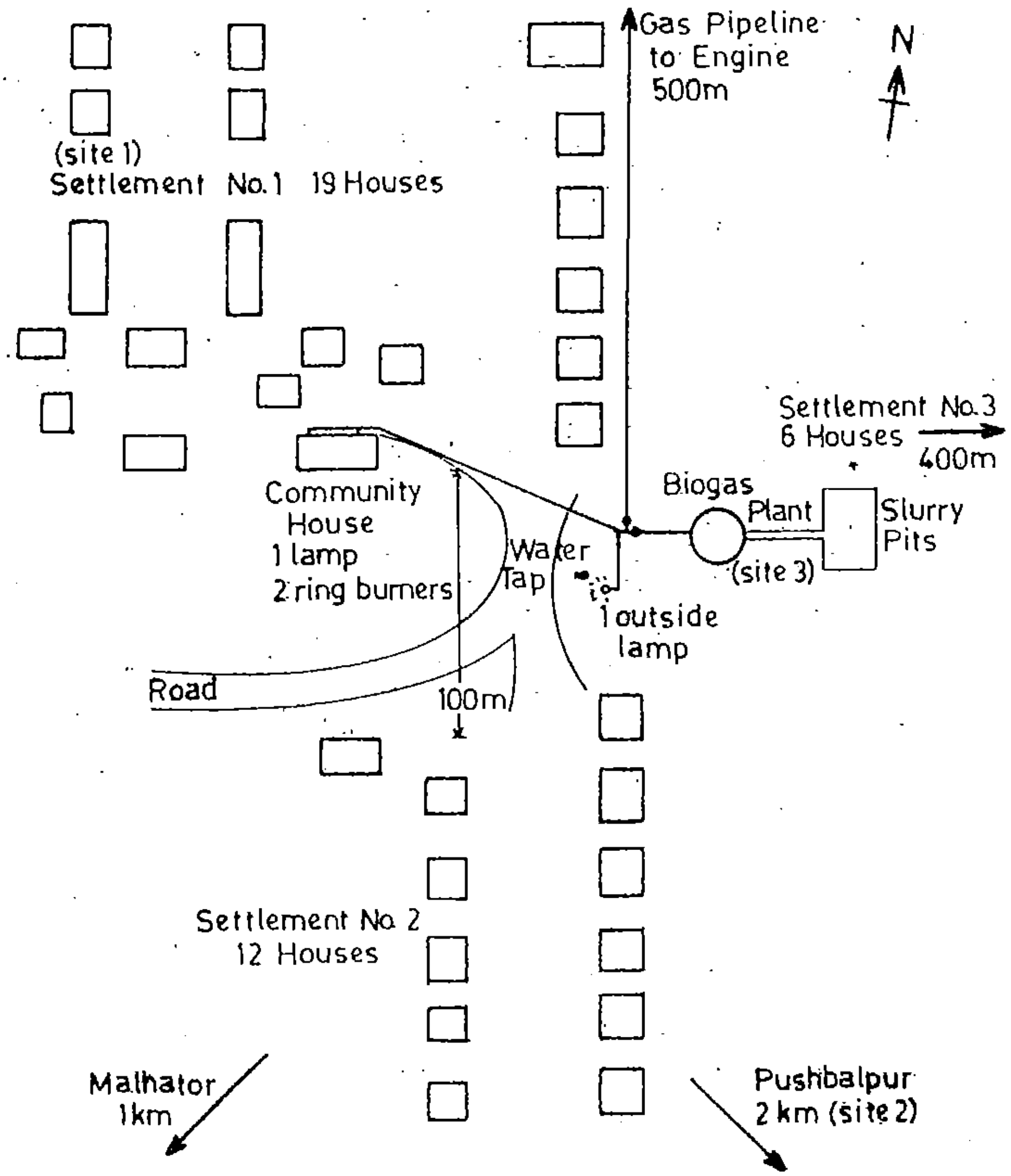


Fig. 8.4 Layout of the Settlements in Madhubasa Village

The biogas plant was sited in the village. The idea of carrying the gas to the pump each day in a plastic balloon was also rejected. Such a bag, which would have to be at least 7 cu. m. in volume, would be difficult to carry and would quickly fail. The idea of a 500 m pipeline to carry the biogas was adopted. If the pipe is of the correct size (see Volume I, Chapter 6), the biogas should reach the engine without much loss in pressure. Such a pipeline proved fairly expensive, and there are concerns about a plastic pipe being chewed by rats.

The question of where the plant should be sited in the village arose. Most of the available land belonged to the leader of the community and his brother, so they wanted to put it near their houses (site no. 1 in Figure 8.4). The other villagers wanted the plant to be in the centre of the two main settlements of the village (site 3), (site no. 2 at Pushbalpur had already been rejected). The two brothers agreed to give the land between the two settlements for the biogas scheme. The water tap would also be on the same land. The biogas plant is now the first thing that visitors coming up the road to the village see, as they enter the village, so it acts as a status symbol.

The 6 households in Settlement No. 3, which is 400 m East of the biogas plant have agreed to take part in the scheme. They will contribute cattle dung, as they will also benefit from the irrigation pumping.

8.8 Financial Arrangements

The group biogas plant at Kusongodai had set the precedent of giving a 50% subsidy for community biogas projects, so this was followed for the Madhubasa scheme. The rest of the capital cost had to be paid from a loan from ADB/N, via the SFDP. Not all members of the Society with a Little Vision were members of an SFDG; 28 people were members of Group NO. 37, while another 7 formed part of Group No. 67, with 6 people living in Malhator village, about 1 km away (Figure 8.5).

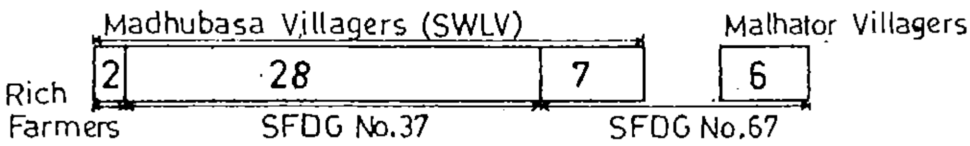


Fig. 8.5 Different Groups in Madhubasa Village

The solution was for the members of SFDG No. 37 to take out the loan in their name, while the other two groups, the richer farmers and the members of SFDG 67, are to pay their contributions to the others. The loan is for 7 years at 11% interest. The subsidy was paid from the USAID grant.

8.9 Irrigation of Land

The wells and pump-set are sited by an existing irrigation canal, that takes water from the Jalad river during the monsoon, when it flows above ground. The main profit from the scheme will come from a winter wheat crop grown on the area of land served by this small canal. However, only 22 households have land in this area; another 10 people have land in another place, while 5 households have no land at all. Since all the 37 households in the Society with a Little Vision were supposed to belong to the scheme and benefit from it, they had to somehow all be included.

Several ideas were put forward, but discussions went on for about a year before the matter was resolved. One idea was the definition of "Gas Rights", whereby the people using the engine would pay a fee to those who contributed dung and labour, but did not have land in the irrigated area. A similar system of "Water Rights" was used in other places in Nepal with community gravity irrigation schemes (Martin). This idea seemed to be too complicated for the village. Another idea was to buy a piece of land that was owned by someone from outside the village, but was in the irrigated area. The owner was keen to sell, but there was no obvious source of money with which to purchase it.

The real challenge to the 22 people who had land came from the idea that they should be willing to share it. The idea was not at all popular with the 11 committee members, 10 of whom had land in the irrigated area. The turning point came when the committee members were asked to imagine that they had changed roles, the ones that had land had to imagine that they did not. After an hour of very heated discussion, they all agreed to lease a portion of their land on the "Bathya: system, in which the farmer and the land owner share the crop on a 50 - 50 basis. The people in the village had come to recognise that living in community meant that things, even land, had to be shared.

The real test of this agreement, which was written in the minutes and to which everyone in the village has put their signature or mark, is when they start getting an income from the wheat harvest.

8.10 Effectiveness of a Village Biogas System

At the time of writing, the system has not been effectively tested. People are putting their cattle dung into the biogas plant, on a rota system. The engine has been used to pump water to the drinking water tank and for irrigation. The engine runs well on biogas, and sufficient gas comes down the 500 m pipeline. Each component works well, but the real test comes when the system is used to irrigate a winter wheat crop which is the harvested and sold.

An evaluation of this project is yet to be done.

8.11 The effectiveness of the Original Assumptions

While a large size biogas plant does give some economy of scale, it is insufficient to reduce the price per cu. m. of biogas to that which a poor farmer can afford. The real price reduction to the farmers in these projects came from a subsidy : a political rather that an economic or technical solution.

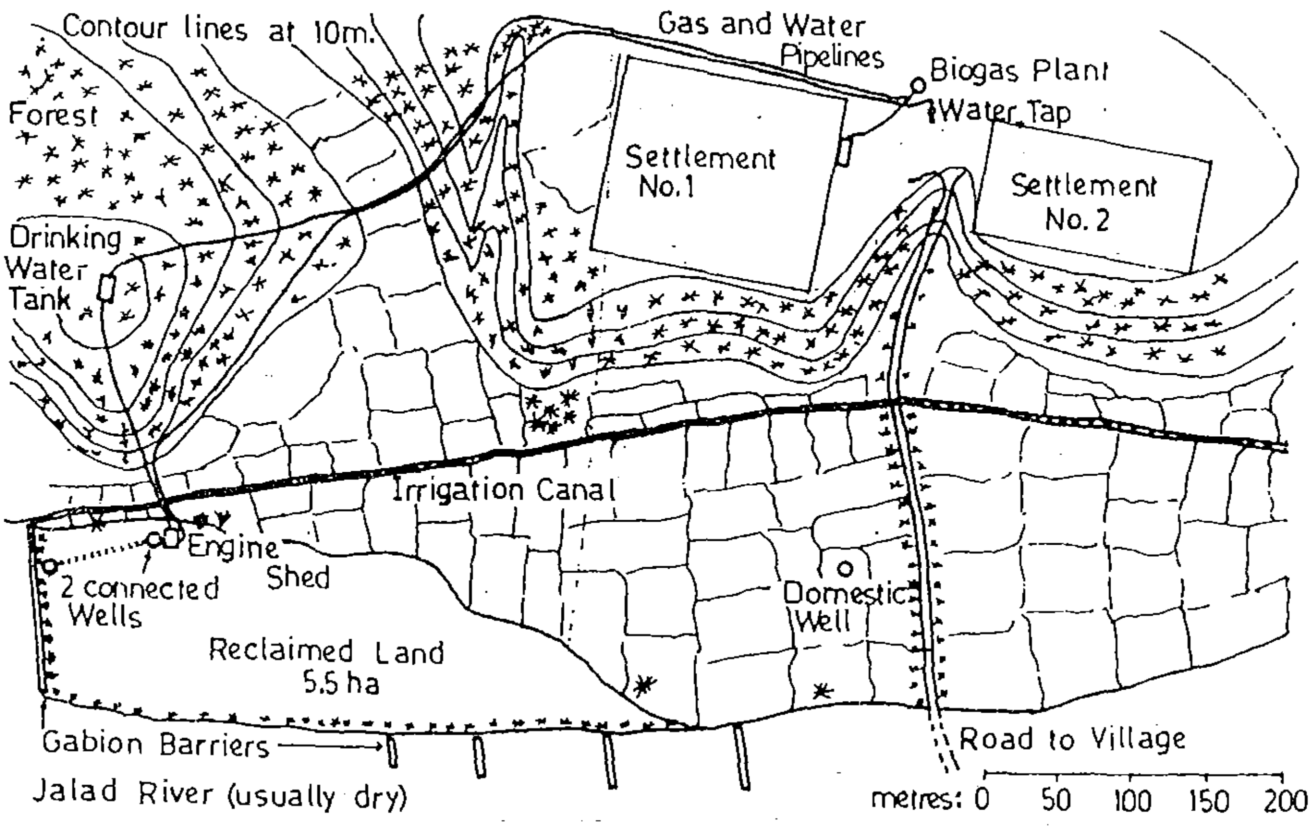


Fig. 8.6 The Layout of the Finished Biogas System in Madhubasa

The real value of a community, a group or a village, biogas plant comes when it is used to run an engine which can be used for activities that earn an income for the villagers. This concept introduces a vitally important new dimension into the whole concept of community biogas.

People's commitment to a cooperative project depends on the benefit that they receive from it. If the project is earning a cash income in which all the members of the community can share, then people's commitment is likely to be far higher than if the biogas is used for domestic purposes alone. Thus the second assumption strongly reinforces the third, which is the weakest one of the three.