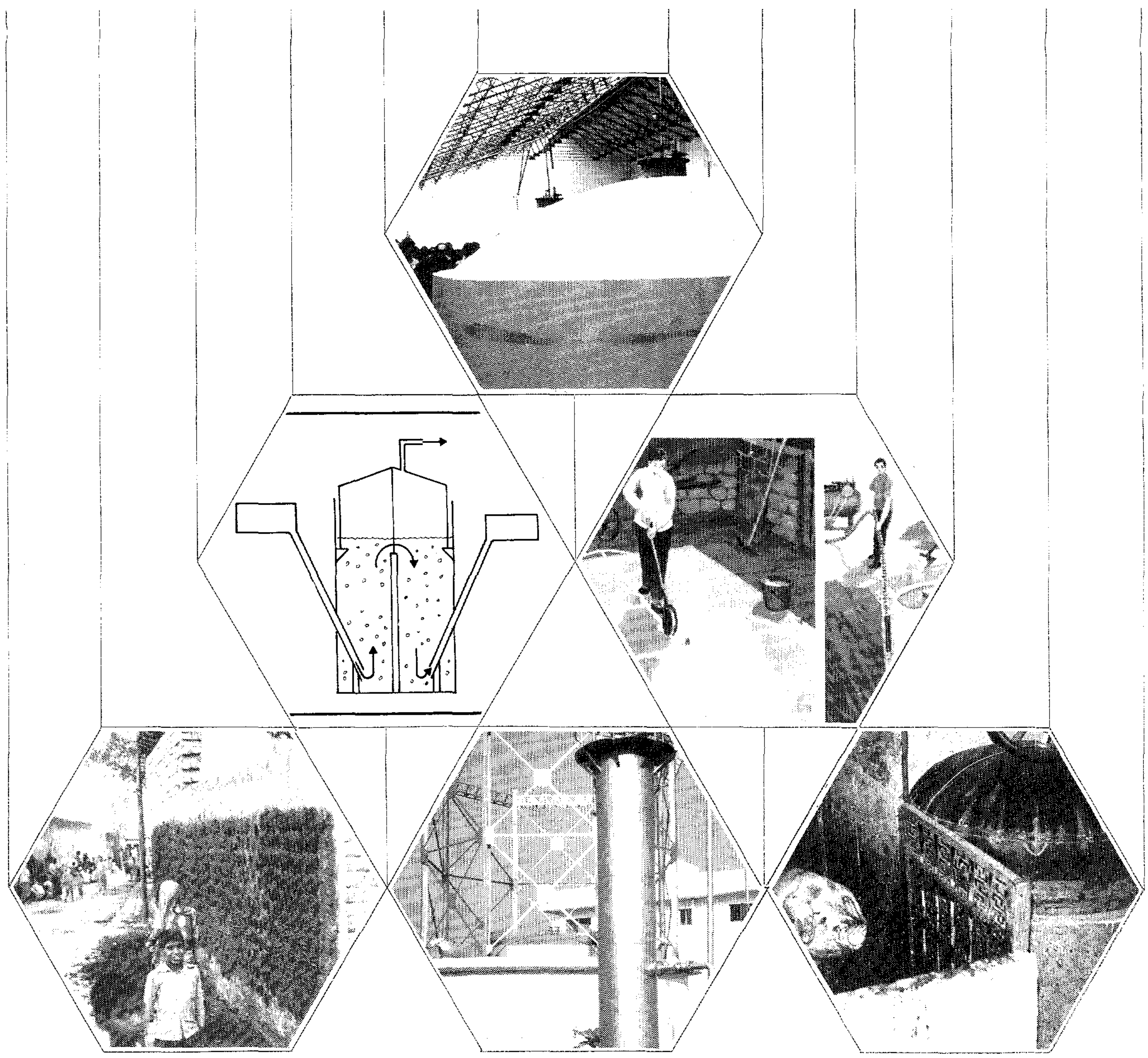
WORLD BANK TECHNICAL PAPER NUMBER 49

Integrated Resource Recovery

Anaerobic Digestion

Principles and Practices for Biogas Systems

Charles G. Gunnerson and David C. Stuckey



UNDP Project Management Report Number 5

A joint contribution by the United Nations Development Programme and the World Bank
to the International Drinking Water Supply and Sanitation Decade

1981-1990

WORLD BANK TECHNICAL PAPERS

No. 1. Increasing Agricultural Productivity

No. 2. A Model for the Development of a Self-Help Water Supply Program

No. 3. Ventilated Improved Pit Latrines: Recent Developments in Zimbabwe

No. 4. The African Trypanosomiases: Methods and Concepts of Control and Eradication in Relation to Development

(No. 5.) Structural Changes in World Industry: A Quantitative Analysis of Recent Developments

No. 6. Laboratory Evaluation of Hand-Operated Water Pumps for Use in Developing Countries

No. 7. Notes on the Design and Operation of Waste Stabilization Ponds in Warm Climates of Developing Countries

No. 8. Institution Building for Traffic Management

(No. 9.) Meeting the Needs of the Poor for Water Supply and Waste Disposal

No. 10. Appraising Poultry Enterprises for Profitability: A Manual for Investors

No. 11. Opportunities for Biological Control of Agricultural Pests in Developing Countries

No. 12. Water Supply and Sanitation Project Preparation Handbook: Guidelines

No. 13. Water Supply and Sanitation Project Preparation Handbook: Case Studies

No. 14. Water Supply and Sanitation Project Preparation Handbook: Case Study

(No. 15.) Sheep and Goats in Developing Countries: Their Present and Potential Role

(No. 16.) Managing Elephant Depredation in Agricultural and Forestry Projects

(No. 17.) Energy Efficiency and Fuel Substitution in the Cement Industry with Emphasis on Developing Countries

No. 18. Urban Sanitation Planning Manual Based on the Jakarta Case Study

No. 19. Laboratory Testing of Handpumps for Developing Countries: Final Technical Report

No. 20. Water Quality in Hydroelectric Projects: Considerations for Planning in Tropical Forest Regions

No. 21. Industrial Restructuring: Issues and Experiences in Selected Developed Economies

No. 22. Energy Efficiency in the Steel Industry with Emphasis on Developing Countries

No. 23. The Twinning of Institutions: Its Use as a Technical Assistance Delivery System

No. 24. World Sulphur Survey

( ) Indicates number assigned after publication.

(List continues on the inside back cover)

Integrated Resource Recovery

UNDP Project Management Report Number 5

INTEGRATED RESOURCE RECOVERY SERIES
GLO/80/004
Number 5

This is the fifth in a series of reports being prepared by the Resource Recovery Project as part of a global effort to realize the goal of the United Nations International Drinking Water Supply and Sanitation Decade, which is to extend domestic and community water supply and sanitation services throughout the developing world during 1981 to 1990. The project objective is to encourage resource recovery as a means of offsetting some of the costs of community sanitation.

Volumes published to date include:

Recycling from Municipal Refuse: A State of the Art Review and Annotated Bibliography

Remanufacturing: The Experience of the United States and Implicaitons for Developing Countries

Aquaculture: A Component of Low Cost Sanitation Technology

Municipal Waste Processing in Europe: A Status Report on Selected Materials and Energy Recovery Projects

Other proposed volumes in this series include reports on:

Composting
Demand Analysis
Effluent Irrigation
Transferable Technologies
Ultimate (marine) Disposal

Cover design. Traditional and modern energy recovery systems in developing countries (clockwise from top). Community biogas system, Qin Long Commune, China. Biogas training poster showing modern construction methods, China. Household organic waste conversion system; the digester is a 1982 design, China. Nightsoil biogas holder and scrubber (foreground), Chuncheon, Republic of Korea. Cattle dung being dried for use as traditional fuel, Calcutta, India. Current KVIC design for gobar (cattle dung) biogas generator, India.

WORLD BANK TECHNICAL PAPER NUMBER 49

Anaerobic Digestion

Principles and Practices for Biogas Systems

Charles G. Gunnerson and David C. Stuckey

with major contributions by
Martin Greeley, Rolf T. Skrinde, and Roscoe F. Ward

The World Bank
Washington, D.C., U.S.A.

Manufactured in the United States of America
First printing April 1986

This is a document published informally by the World Bank. In order that the information contained in it can be presented with the least possible delay, the typescript has not been prepared in accordance with the procedures appropriate to formal printed texts, and the World Bank accepts no responsibility for errors. The publication is supplied at a token charge to defray part of the cost of manufacture and distribution.

The World Bank does not accept responsibility for the views expressed herein, which are those of the author(s) and should not be attributed to the World Bank or to its affiliated organizations. The findings, interpretations, and conclusions are the results of research supported by the Bank; they do not necessarily represent official policy of the Bank. The designations employed, the presentation of material, and any maps used in this document are solely for the convenience of the reader and do not imply the expression of any opinion whatsoever on the part of the World Bank or its affiliates concerning the legal status of any country, territory, city, area, or of its authorities, or concerning the delimitation of its boundaries or national affiliation.

The most recent World Bank publications are described in the annual spring and fall lists; the continuing research program is described in the annual *Abstracts of Current Studies*. The latest edition of each is available free of charge from the Publications Sales Unit, Department T, The World Bank, 1818 H Street, N.W., Washington, D.C. 20433, U.S.A., or from the European Office of the Bank, 66 avenue d'Iéna, 75116 Paris, France.

Charles G. Gunnerson is an environmental engineering advisor with the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce, and David C. Stuckey is a professor at the Imperial College, London; both are consultants to the World Bank.

Library of Congress Cataloging-in-Publication Data

Gunnerson, Charles G.
Anaerobic digestion.

(World Bank technical paper ; no. 49) (UNDP project management report ; no. 5) (Integrated resource recovery series ;)
Bibliography: p.
1. Biogas--Developing countries. I. Stuckey, David. II. Title. III. Series. IV. Series: UNDP project management report ; no. 5. V. Series: Integrated resource recovery series ; .
TP359.B48G85 1986 665.7'76 86-5577
ISBN 0-8213-0752-5

ABSTRACT

This report is part of a joint global research, development and demonstration effort of the United Nations Development Programme and the World Bank. It explores the history, technology, and applications of anaerobic digestion, the biological process by which organic materials are degraded in the absence of oxygen to produce a combustible gas, methane (CH_4), and carbon dioxide (CO_2). This process occurs naturally in wet, decaying organic matter (biomass) found in swamps, bottom muds of streams, and garbage dumps. Since about 1900, it has been used in engineered systems for treatment and stabilization of municipal or industrial sludges. Starting around 1920, systems have been operated so as to capture the biogas, identical to marsh gas which contains about 55-75 percent methane, as an energy source. In addition to producing a fuel substitute, benefits of digestion include reduction or elimination of pathogens in human and animal wastes and production of a stable, generally environmentally acceptable slurry or sludge which can be used as a fertilizer and soil conditioner. The increases in population, standards of living, and energy demands, along with decreases in supplies of traditional fuels -- conditions that were exacerbated by the 1973 and subsequent oil crises -- have contributed to a current high level of interest in the science, technology, utilization, and economics of biogas.

Anaerobic digestion is approached as an integral part of a resource recovery system. This report summarizes the current and potential status and practice of anaerobic digestion in developing countries and provides an overview of the subject plus practical data for building an anaerobic digester. Relevant information includes a survey of existing systems and description of various models in current use, as well as a detailed exploration of the technical aspects of anaerobic digestion in both the text and the appendix. Emphasis is on applying new engineering concepts to low-cost technologies, on energy, and on environmental and agricultural benefits. Energy and health benefits from digestion of night soil, septage, and sludges can be achieved by properly engineered and operated biogas technologies.

This report is directed to local professionals, consultants, students, and others concerned with biogas systems.

FOREWORD

In 1981, a three-year Global Research and Development Project on Integrated Resource Recovery (Waste Recycling) was initiated as Project GLO/80/004 by the United Nations Development Programme through its Division for Global and Interregional Projects. The World Bank, via its Water Supply and Urban Development Department (WUD), agreed to act as executing agency.

The primary project goal is to achieve economic and social benefits through sustainable resource recovery activities in the developing countries by the recycling and reuse of solid and liquid wastes from municipal and commercial sources.

Increasing recognition of both the need for technical and economic efficiency in the allocation and utilization of resources and the role that appropriate recycling can play in the waste and sanitation sector has led to the inclusion of this project in the formal activities of the United Nations International Drinking Water Supply and Sanitation (IDWSS) Decade. This particular report has also received the cooperation and support of the International Reference Center for Waste Disposal (IRCWD) of the Swiss Federal Institutes of Technology (EAWAG) as part of their contribution to IDWSS.

The increases in population, standards of living, and energy demands, along with the increases in traditional fuels -- conditions that were exacerbated by the 1973 and subsequent oil crises -- have contributed to a current high level of interest in the science, technology, utilization, and economics of anaerobic digestion.

In this study, anaerobic digestion is approached as an integral part of a resource recovery system. The report summarizes the current and potential status and practice of anaerobic digestion in developing countries and provides an overview of the subject plus practical data for building an anaerobic digester. Emphasis is on applying new engineering concepts to low-cost technologies, on energy, and on environmental and agricultural benefits. Energy and health benefits from digestion of night soil, septage, and sludges can be achieved by properly engineered and operated biogas technologies.

This report is directed to local professionals, consultants, students and others concerned with biogas systems. It is one of a set of publications to be produced by the project management, four of which have already been distributed. We shall be grateful for comments on any additional sources of data for our future publications.

S. Arlosoroff, Chief
Applied Technology Unit (WUD)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE AND ACKNOWLEDGMENTS

The purpose of this report is to provide information to officials in the developing countries about those anaerobic digestion facilities throughout the world that provide energy and health benefits from digestion of crop wastes and animal offal, night soil, septage, and sludges. A brief history of the subject; a primer on the fundamentals of anaerobic digestion, landfills, and digester designs; a discussion of the various outputs and their uses, alone or in integrated resource recovery sytems; an overview of the economics involved; and a survey of existing biogas programs are included within the text. Appendix I provides more detailed technological information for the engineer, and Appendix II comprises a glossary of terms. A detailed Bibliography supplies additional sources of information.

The generous help and collaboration of a number of people during the preparation of this report are gratefully acknowledged. The support of Mr. Roland Schertenleib, Director, International Reference Center for Waste Disposal (IRCWD), Swiss Federal Institutes of Technology (EAWAG), in Duebendorf, Switzerland, is especially acknowledged.

Thanks are also due to six short-term consultants who collected information in the various regions of the world: in Latin America, Dr. Alvara Umana of the University of Costa Rica, and Guillermo Duarte Monroy; in Northern Africa, Dr. M. M. El-Halwagi of the National Research Centre in Cairo, Egypt; in Southern Africa, Dr. P. A. M. Misiko of Egerton College, Njoro, Kenya; in Southeast Asia, Prof. Oei Ban Liang of the Bandung Institute of Technology, Bandung, Indonesia; and in China, Chan U Sam of Macau.

In addition, Mick Howes of the Institute of Development Studies of the University of Sussex provided considerable input on the social/ institutional aspects of biogas; Andrew Barnett of the International Development Research Centre, Ottawa, was of great help in reviewing and commenting on the chapters on the economics and diffusion of biogas; Mr. C. P. Halvadakis of Biosferiki in Athens made significant comments in his review, especially on methane production from sanitary landfills; and Prof. G. Lettinga and his colleagues of the Agriculture University in Wageningen, Netherlands, presented a thorough review of the report as a whole.

Ms. Elissa Bellassai was invaluable in helping plot and design numerous graphs and in formatting the bulk of the finished paper. The production process was ably assisted by Ms. Deirdre Murphy and Mrs. Margaret Carnes.

CHAPTER ONE

INTRODUCTION AND OVERVIEW

In recent years the conversion of biomass materials to methane for use as an energy source has excited interest throughout the world. This conversion is accomplished by anaerobic digestion, the biological process by which organic materials or feedstocks are degraded in the absence of oxygen to produce a combustible gas, methane (CH_4), and carbon dioxide (CO_2). The energy product is often called "biogas." In India the common name is "gobar gas" after the Hindi word for cattle dung, which is the predominant organic feed for their anaerobic digesters. Another term which is occasionally used in Europe is "bihugas," which is an abbreviation for "biological humus and gas." For the sake of convenience the term "biogas" will be used throughout this review since it is the term most commonly used in the literature when referring to the product of anaerobic digestion in developing countries.

Other benefits of digestion include reduction or elimination of pathogens, depending upon temperature, and production of a stable, generally environmentally acceptable slurry or sludge which can be used as a fertilizer and soil conditioner.

HISTORICAL BACKGROUND

One of the earliest to mention the mysterious appearance of flickering lights and flames emerging from below the surface of the earth was Plinius (van Brakel, 1980). The explanation for this phenomenon was that it was the product of the local dragon, and it is highly probable that these occurrences gave rise to the myth of dragons. The Romans called these mysterious dancing flames "ignis fatuus"--foolish fire, for many people who were fascinated by them were lured into trackless swamps. In English the term "will-o-wisp" is derived from these ephemeral flames.

In 1630 Van Helmont recorded the emanation of an inflammable gas from decaying organic matter. In 1667 Shirley described this gas more precisely, and is sometimes considered to be its discoverer. However, Volta is generally recognized as putting methane digestion on a scientific footing. From a number of observations he concluded in 1776 that:

a. the amount of gas that evolves is a function of the amount of decaying vegetation in the sediments from which the gas emerges; and

b. certain proportions of the gas so obtained form an explosive mixture with air.

In 1804 Dalton established the chemical composition of methane, and in 1806 Henry confirmed that town gas was very similar to Volta's "marsh gas." In 1808 Davy established that methane was produced from decomposing cattle manure, which may be the first time readily available organic wastes were recognized as a source of energy.

It was not until toward the end of the 19th century that methanogenesis was found to be connected to microbial activity. In 1868 Bechamp, a student of Pasteur, named the "organism" responsible for methane production from ethanol. This organism was apparently a mixed population since Bechamp was able to show that depending on the substrate different fermentation products were formed. Popoff, in 1875, was the first to systematically investigate the formation of methane using different complex substrates, and he found that with cellulose the end products were methane, carbon dioxide and some hydrogen, while with acetate no methane was produced. However, in 1876 Herter, a collaborator of Hoppe-Seyler, reported that acetate in sewage sludge was converted stoichiometrically to equal amounts of methane and carbon dioxide (Zehnder 1978, 1982).

In 1884 Gayon, another student of Pasteur, fermented manure at 35°C, obtaining 100 liters of methane per cubic meter of manure. It was concluded that the fermentation could be a source of gas for heating and lighting, and the "Compagnie des Omnibus" in Paris requested that Gayon design an installation in which the manure of their many horses could be digested to methane to be used for street lighting. Gayon declined, however, saying that his work was only preliminary (van Brakel, 1980). As early as 1896 gas from sewage was used for lighting streets in Exeter, England, and gas from human wastes in the Matinga Leper Asylum in Bombay, India was used to provide lighting in 1897.

In 1906 Sohngen was able to enrich for two distinct acetate utilizing bacteria, and he found that formate, and hydrogen plus carbon dioxide could act as precursors for methane. This remained the major breakthrough in the microbiology of methane bacteria for thirty years.

On the applied side, Buswell began studies of anaerobic digestion in the late 1920s and developed a solid base of information on such issues as the fate of nitrogen in anaerobic digestion, the stoichiometry of reaction, the production of energy from farm wastes and the use of the process for industrial wastes (Buswell and Neave, 1930; Buswell and Hatfield, 1936).

Barker's studies contributed significantly to our knowledge of methane bacteria, and his enrichment cultures enabled him to perform many of the common biochemical studies (Barker, 1956). Schnellen was the first worker to isolate two methane bacteria in 1947, *Methanosarcina barkeri* and *Methanobacterium formicium*. Much of this work is still relevant today, and those who are developing biogas as an energy source would gain much from review of this earlier work.

PRESENT INTEREST IN BIOGAS

The technology of anaerobic digestion has not yet realized its full potential for energy production. In industrialized countries biogas programs are often hindered by operational difficulties, a lack of basic understanding of the fundamentals involved, and little engineering innovation. In some developing countries, on the other hand, development of biogas programs has lacked urgency because of readily available and inexpensive noncommercial fuels such as firewood.

Biogas technology is also potentially useful in the recycle of nutrients back to the soil. Burning of noncommercial fuel sources such as dung and agricultural residues leads to a severe ecological imbalance since the nutrients (nitrogen, phosphorus and micronutrients) are essentially lost from the ecosystem. Biogas production from organic materials not only produces energy, but preserves the nutrients, which can be recycled back to the land in the form of a slurry. The organic content also acts as a soil conditioner by contributing humus. Fertilizing and conditioning of soil can be achieved by simply using other fuel sources and recycling the waste back to the land without burning it. However, while data are sparse, Chinese workers report that digested biomass increases agricultural productivity by as much as 30% over farmyard manure on an equivalent basis (van Buren, 1979). This is due in part to the biochemical processes occurring during digestion which cause the nitrogen in the digested slurry to be more accessible for plant utilization, and to the fact that less nitrogen is lost during digestion than in storage or composting. This aspect of biogas technology may, in fact, be more important than the gas produced (Gosling, 1980).

In the area of public health and pollution control, biogas technology can solve another major problem, that of disposal of sanitary wastes. Digestion of these wastes can reduce the parasite and pathogenic bacterial counts by over 90% (Feacham et al., 1983; McGarry and Stainforth, 1978; van Buren, 1979), breaking the vicious circle of reinfection via drinking water, which in many rural areas is untreated. Industrial waste treatment using anaerobic digestion is also possible.

To summarize, biogas technology is receiving increased attention due to its potential to alleviate the following problems:

a. dependence on imported commercial fuels;

b. deforestation and resulting erosion leading to loss in agricultural productivity;

c. shortage of inexpensive fertilizers to increase food production;

d. disposal of sanitary wastes which could cause severe public health problems; and

e. disposal of industrial wastes which cause water pollution.

OBJECTIVES OF THE REVIEW

Many planners and engineers have expressed an interest in a cohesive discussion of anaerobic digestion and biogas technology.

Application of the fundamentals to design and operation of digesters to enhance their technical and economic viability has been complicated by the complexity of interdisciplinary skills required for optimum selection of size and style for intended goals.

This paper attempts to present a concise review of the engineering, chemistry, microbiology and socio-cultural aspects of biogas programs, especially as they may be applied to developing countries. References cited can provide more indepth studies of given areas of interest, and the appendix provides specific formulae describing the process of anaerobic digestion, for the technically minded. The chapter on biogas products and their uses (Chapter 5) gives an idea of the potential applications of biogas technology.

This report is intended to assist engineers/researchers and government officials/funding agencies to make informed decisions on promotion of anaerobic digestion for an alternate source of energy, soil conservation and enrichment, pollution reduction, and other benefits such as pathogen reduction in human wastes or feed enhancement for fish and animals.

OVERVIEW

Technical Status

Three basic designs of biogas plants--fixed dome (Chinese), floating cover (Indian), and bag (membrane)--have been used in a number of countries for many years. The designs reflect modest optimization for reduced capital costs and increased volumetric gas yields (volumes of gas per volume of digester per day), although more can be done in this area. Application of other, recent, designs such as the upflow anaerobic sludge blanket digester, anaerobic filter, and anaerobic baffled reactor should also be explored. These show promise in treating a wide variety of feedstocks at low capital investment with high volumetric gas yields. Performance can also be increased by selective use of heating, pretreating and mixing.

Lack of technical expertise can be a significant deterrent to widespread acceptance of biogas programs. Many digesters fall into disuse within months because of such problems as gas leaks or faulty construction of gas holders. Some designs are not "user friendly." Plants that are extremely labor intensive, for instance requiring manual handling of feedstock and/or digested slurry, are soon abandoned. Cost is also a major factor. Process design should eliminate unnecessary and expensive equipment in favor of simple, low maintenance systems or cost effective major capital items. Fixed wall digesters, for example, should be sized for high loading rates and low retention times. Alternatively, inexpensive pits can be optimized by taking advantage of longer retention times for negligible cost, allowing lower temperatures, less mixing and less concern with daily maintenance and control.

Careful consideration of plant goals must precede design. Not all end uses are consistent with the same size or type of digester.

Initial feedstock should be as fresh as possible if the goal is high gas yield, as large portions of volatile solids are consumed aerobically over time. Pathogen destruction requires higher temperatures and longer retention times, as do many industrial or toxic wastes. Proper handling for nitrogen conservation enhances slurry use as a soil conditioner.

Integrated resource recovery systems can improve the financial viability of biogas plants, and help combine several goals into effective programs. The private sector should be encouraged to incorporate biogas technology into commercial and industrial applications.

Economic Viability

There are two ways of looking at economic viability of biogas programs and intergrated resource recovery. A strictly financial approach involves analyses of monetary benefits such as sale or reuse of products (methane, carbon dioxide and slurry) and the costs of constructing and maintaining facilities. The societal costs of inputs and outputs, including such intangibles as improvements in public health, reduced deforestation and reduced reliance on imported fossil fuels, are added to the equation in a social cost benefit analysis (SCBA). There is no agreed upon methodology for quantifying these social benefits, so rigorous economic comparisons between biogas and other renewable as well as conventional energy sources are difficult.

In assessing the economic viability of biogas programs, it is useful to distinguish between four main areas of application: individual household units, community plants, large scale commercial animal rearing operations, and municipal/industrial projects. In each of these cases, the financial feasibility of individual facilities depends largely on whether outputs in the forms of gas (for cooking, lighting, power) and slurry (for use as fertilizer/soil conditioner, fishpond or animal feed) can substitute for costly fuels, fertilizers or feeds which were previously purchased. For example, a plant has a good chance of being economically viable when the farmers or communities previously paid substantial percentages of their incomes for cooking fuels (e.g., kerosene, coal) and/or fertilizers (e.g., urea). The economics may also be attractive in farming and industry where there is considerable cost involved in disposing of manure or effluent. In these cases the outputs can be sold or used to reduce energy costs, repaying the original capital investment. If outputs/products do not generate income or reduce cash outflow, then the financial viability of a biogas plant decreases; for example, when cooking fuels such as wood or dung can be collected at no financial cost, or where the cost of commercial fuel is so low that the market for biogas is limited.

If the broader SCBA criteria are used to evaluate anaerobic digestion, then determination of viability requires knowledge of real resource or opportunity costs of inputs and outputs. When such outputs as improved public health, greater rural self-sufficiency, reduced deforestation, and reduced dependence on imported fossil fuels can be incorporated, SCBA analysis usually results in more positive conclusions than strictly financial analysis.

Biogas Programs in Developing Countries

Technical, social and economic factors, government support, institutional arrangements, and the general level of commercial activity in the construction of biogas plants and related equipment are highly interrelated. All influence the development of biogas programs. Focusing attention on any one aspect will not bring about successful results.

A large variation exists in the number of digesters installed in developing countries throughout the world, depending on the extent of government interest and support. Three countries--China, India and the Republic of Korea--have installed large numbers of units, ranging from some seven million plants in China to approximately 30,000 in Korea. Other countries have fewer than 1,000--usually less than 200. Most countries rely on two basic designs, the floating cover and the fixed dome digester.

The relative poverty of most rural and urban people in developing countries and their concomitant lack of capital is an especially powerful economic consideration. Socially, program growth will be slow if facilities require a relatively large number of people to cooperate and alter their behaviors simultaneously. Commercial and private sector interest in anaerobic digestion is steadily increasing in conjunction with government tax policies, subsidies which alter prices of competing fossil fuels and fertilizers, and pollution control laws which all affect biogas program growth.

Institutional program infrastructure and government policies are the primary administrative and driving forces behind biogas implementation. With the exception of China, and possibly Brazil and India, the infrastructure to disseminate information on biogas to technical personnel, policy makers and potential users is somewhat fragmented. Both qualitative and quantitative assessments of ongoing activities are needed to improve technology and adapt its use to each specific country. Generally program coordination is relatively tenuous between indigenous research and development projects and implementing agencies. Biogas programs which have expanded rapidly have had strong government support, including subsidized capital costs and tax incentives.

CONCLUSIONS

Anaerobic digestion provides some exciting possibilities and solutions to such global concerns as energy production; safely handling human, animal, municipal and industrial wastes; controlling environmental pollution; and expanding food supplies. Technical data available on biogas plants relate primarily to only two digester designs, the floating cover and fixed dome. Promising new techniques such as bag, dry fermentation, plug flow, filter, and anaerobic baffled reactors should be explored to establish a firmer technical data base on which to make decisions regarding the viability of biogas technology. A broader economic data base is also needed in order to draw conclusions about the feasibility of anaerobic digestion programs--independently and in conjunction with integrated resource recovery plans--under other conditions of design, feedstock, social and environmental considerations, and target areas of application.

Ongoing research, experimental and functional programs throughout the world are rapidly adding to our knowledge of anaerobic digestion, and should provide increasingly efficient and useful designs to improve the quality of life everywhere.

CHAPTER TWO

FUNDAMENTALS OF ANAEROBIC DIGESTION

The published literature on anaerobic digestion is replete with information on the microbiology and biochemistry, environmental factors, biodegradability, kinetics, and health aspects of the anaerobic digestion process. A knowledge of these fundamentals is useful in the design and operation of efficient digesters, and in understanding how upset conditions can occur and how to alleviate them. Below is a general discussion of key concerns. For a more in-depth review, please refer to Appendix I.

MICROBIOLOGY AND BIOCHEMISTRY

The degradation of organic matter to produce methane relies on the complex interaction of three different groups of bacteria. The first group consists of a mixture of fermentative bacteria, sometimes called acid formers, which hydrolyze the complex organics to simple compounds such as short chain fatty acids and alcohols. The second group, also acetogenic, produces acetate and hydrogen. The third group, known as methanogens, convert the intermediate products to methane and carbon dioxide. Stable digester operation requires that these bacterial groups be in dynamic yet harmonious equilibrium. Changes in environmental conditions such as temperature variations or shock loadings of substrate can affect this equilibrium and result in the buildup of intermediates such as long chain fatty acids and hydrogen, which inhibit the overall process. If such upsets are not corrected, digester performance will decrease and failure may ultimately occur.

THE EFFECTS OF ENVIRONMENTAL FACTORS ON ANAEROBIC DIGESTION

Environmental factors which influence biological reactions, such as pH, temperature, nutrients and toxicant concentrations, are amenable to external control in the anaerobic digestion process.

pH

Acetate and fatty acids produced during digestion tend to lower the pH of digester liquor. However, the ion bicarbonate equilibria of the carbon dioxide in the digester exert substantial resistance to pH change. This resistance, known as buffer capacity or buffer intensity, is quantified by the amount of strong acid (or base) added to the solution in order to bring about a change in pH. Thus the presence of bicarbonate helps prevent adverse effects on microorganisms (methanogens) which would result from low pH caused by excessive production of fatty acids during digestion. The higher the concentration of bicarbonate in the solution, the greater the buffering capacity and the resistance to changes in pH.

Most microorganisms grow best under neutral pH conditions, since other pH values may adversely affect metabolism by altering the chemical equilibrium of enzymatic reactions, or by actually destroying the enzymes. The methanogenic group of organisms is the most pH sensitive. Low pH could cause the chain of biological reactions in digestion to cease.

There are two main operational strategies for correcting an unbalanced, low pH condition in a digester. The first approach is to stop the feed and allow the methanogenic population time to reduce the fatty acid concentration and thus raise the pH to an acceptable level of at least 6.8. Stopping the feed also slows the activity of the fermentative bacteria and thus reduces acid production. Once the pH returns to normal, feeding can be recommenced at reduced levels and then increased gradually so as to avoid further drops in pH.

A second method involves addition of chemicals to raise the pH and provide additional buffer capacity. Reducing the feed rate in conjunction with chemical addition may be necessary in some cases. An advantage of chemical addition is that the pH can be stabilized immediately and the unbalanced populations allowed to correct themselves more quickly. Calcium hydroxide (lime) is often used. Sodium carbonate (soda ash), while more expensive, can prevent calcium carbonate precipitation. Ammonia is also useful, but must be used with care to avoid toxicity.

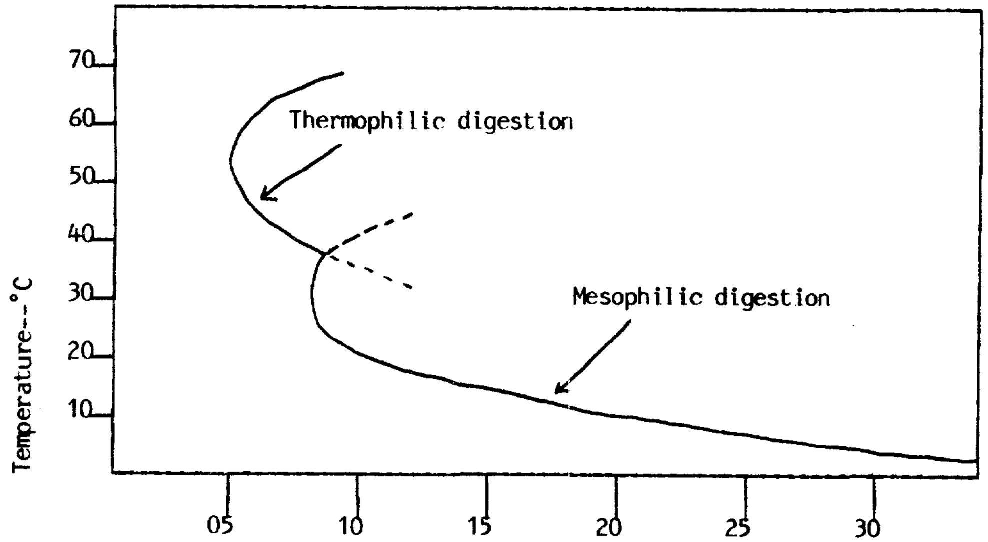
Temperature

The metabolic and growth rates of chemical and biochemical reactions tend to increase with temperature, within the temperature tolerances of the microorganisms. Too high a temperature, however, will cause the metabolic rate to decline due to degradation (denaturing) of enzymes which are critical to the life of the cell. Microorganisms exhibit optimum growth and metabolic rates within a well defined range of temperatures which is specific to each species, particularly the upper limit which depends on the thermostability of the protein molecules synthesized by each particular type of organism.

Methanogenic bacteria are more sensitive to changes in temperature than other organisms present in digesters. This is due to the faster growth rate of the other groups, such as the fermenters which can achieve substantial catabolism even at low temperatures (Schmid and Lipper, 1969). All bacterial populations in digesters are fairly resilient to short term temperature upsets up to about two hours, and return rapidly to normal gas production rates when the temperature is restored. However, numerous or prolonged temperature drops can result in unbalanced populations and lead to the low pH problems discussed in the previous section. Temperature variations as small as 2°C can have adverse affects on mesophilic (~35°C) digestion or 0.5°C with thermophilic (~55°C) digestion.

Two distinct temperature regions for digestion of sewage sludge have been noted. Optimum digestion occurs at about 35°C (mesophilic range) and 55°C (thermophilic range), with decreased activity at around 45°C (see Figure 2.1). This response to temperature may be due to effects on methanogenic bacteria, since these appear to exhibit similar optimal

Figure 2.1. Relative Digestion Time of Plain-Sedimentation Sludge Digested at Temperatures of 10°C to 70°C. Digestion time refers to time required at 25°C.



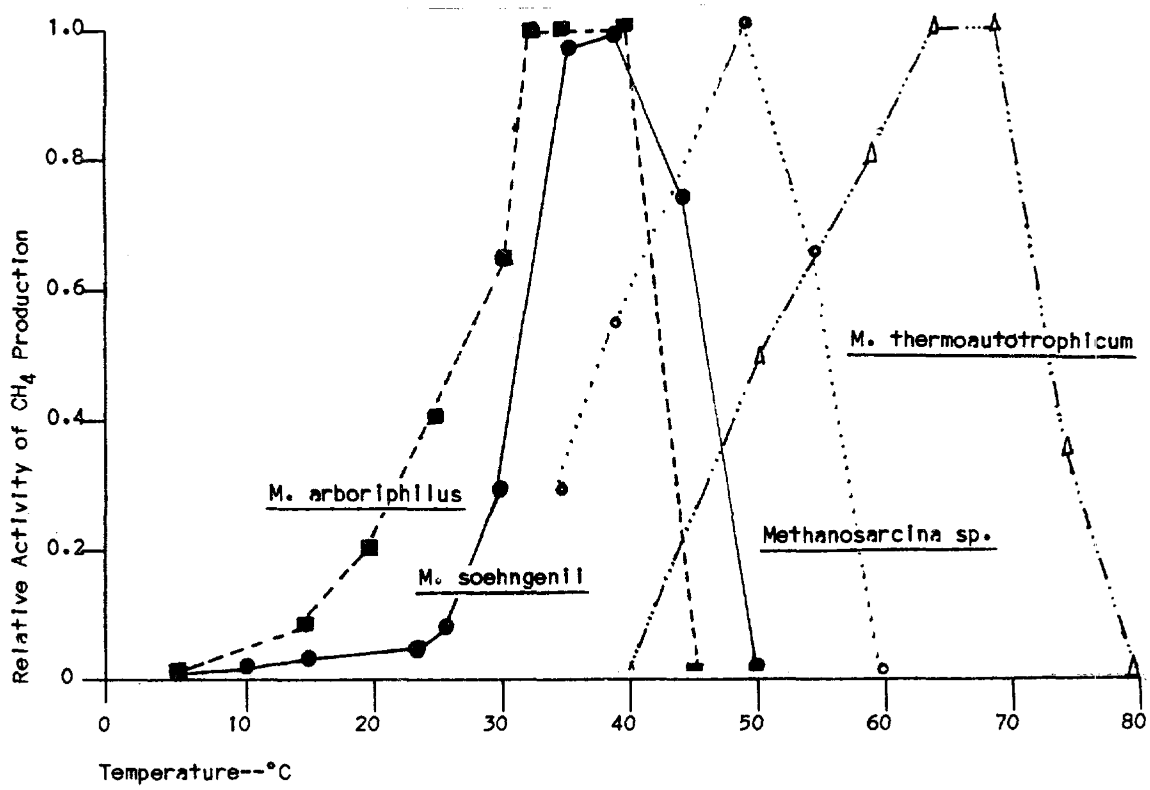
Reference: Adapted from Fair and Moore (1932, 1934, 1937).

regions (see Figure 2.2). Well defined mesophilic and thermophilic regions have been noted for activated sludge and refuse feedstocks (Malina, 1961; Pfeffer, 1974). For beef cattle manure, raw sewage sludge, and some agricultural residues the regions are generally the same, although not so well defined (Golueke, 1958; Chen et al., 1980; Nelson et al., 1939).

An advantage of thermophilic digestion is that the rate of methane production is approximately twice that of mesophilic digestion, so reactors can be half the volume of mesophilic digestors and still maintain the same overall process removal efficiences. Strong, warm, soluble industrial wastes give high volumetric gas yields of up to eight volumes of gas per volume of digester per day with immobilized cell designs. With warm (>55°C) wastes this has obvious advantages. However, with wastes which are at ambient temperatures, such as animal manures, considerable energy is needed to raise the temperature of the waste to 55°C. A number of detailed studies of gas yields and energy consumption have been carried out (Shelef et al., 1980; Converse et al., 1977; Schellenbach, 1980; Hashimoto et al., 1981).

Shelef et al. (1980) found that thermophilic digesters could accept higher organic loads than mesophilic systems at the same detention time (0). This advantage became more pronounced as the detention time decreased. With cattle manure at 12% total solids and 0 = 6 days they obtained volumetric gas yields of 5.5 (versus 3.0 at mesophilic), and found that only 20% of the energy produced was used for heating and mixing.

Figure 2.2. The Effect of Temperature on Methanogens. (Adapted from Zehnder and Wuhrmann, 1977; Huser et al., 1982.)



However, Converse et al. (1977), using dairy manure at 15.8% total solids, found that thermophilic operation (0 = 6.2, T = 60°C) gave lower net energy yields than mesophilic operation (0 = 10.4, T = 35°C). Schellenbach (1980) concluded that mesophilic cultures gave a higher methane yield per pound of volatile solids added than thermophilic, and that thermophilic cultures were more unstable and sensitive to mechanical or operational disruptions. This point has been raised by a number of researchers, although there is disagreement as to how unstable thermophilic digestion is. Full scale mechanically stirred thermophilic systems require temperature controls of ±0.5°C while mesophilic systems tolerate variations of ±2°C (Garber, 1954, 1975, 1977).

After five years of rigorous and detailed studies of thermophilic digestion of cattle manure in the United States, Hashimoto et al. (1981) concluded that thermophilic digestion gave a higher net energy production per unit of capital cost than mesophilic digestion. Excellent results were obtained with an influent concentration of 8 to 10% volatile solids and detention times of four to five days.

Nutrient Effects

In addition to an organic carbon energy source, anaerobic bacteria appear to have relatively simple nutrient requirements which include nitrogen, phosphorus, magnesium, sodium, manganese, calcium, and cobalt (Speece and McCarty, 1962). Nutrient levels should be at least in excess of the optimum concentrations needed by the methanogenic bacteria, since these are the most severely inhibited by slight nutrient deficiences. Nutrient additions are often required in order to permit growth in digestion of simple substrates such as glucose, substrates such as industrial wastes, and crop residues. However, nutrient deficiency should not be a problem with most complex feedstocks, since these substrates usually provide more than sufficient quantities.

An essential nutrient can become toxic to organisms if its concentration in the substrate becomes too great (see below). In the case of nitrogen, it is particularly important to maintain an optimal level to achieve good digester performance without toxic effects.

Toxicity Effects

Toxic compounds affect digestion by slowing down the rate of metabolism at low concentrations or by poisoning or killing the organisms at high concentrations. The methanogenic bacteria are generally the most sensitive, although all groups involved in digestion can be affected. Due to their slow growth, inhibition of the methanogens can lead to process failure in completely mixed systems due to washout of bacterial mass.

In order to control and adjust operation to minimize toxic effects, it is important to indentify inhibition in its early stages. The two main inhibition indicators are:

a. Reduction in methane yield over time, indicated by two or more consecutive decreases of more than 10% in daily yield at a constant loading rate; and

b. Increase in volatile acids concentration over time, generally occurring when the total volatile acids (expressed as acetic acid) exceed the normal range of about 250 to 500 milligrams per liter.

The major toxicants usually encountered with natural feedstocks are ammonia, volatile acids, and heavy metals.

Ammonia

Ammonia toxicity is often a problem in feedstocks with a high protein content. Ammonia is rapidly formed in a digester by deamination of protein constituents. Free ammonia has been found to be much more toxic than ammonium ion, and thus ammonia toxicity thresholds are very sensitive to pH below seven. In general, free ammonia levels should be kept below about 80 milligrams per liter to prevent inhibition (Anderson et al., 1982). A much higher concentration of about 1,500 to 3,000 milligrams per liter of ammonium ion can be tolerated (McCarty, 1964a; Fischer et al., 1979; Hart, 1963; Schmid and Lipper, 1969). Concentrations of free ammonia and ammonium ion are related by equilibrium reactions and pH.

Volatile Acids

High concentrations of volatile acids such as acetate, propionate or butyrate are associated with toxicity effects. It is not clear whether thse acids are themselves toxic, or whether acid buildup (pH <6.8) is merely a manifestation of toxicity. Among these acids, inhibitory effects have been demonstrated only for propionate, and only at relatively high concentrations of greater than 1,000 milligrams per liter (Hobson and Shaw, 1976).

Heavy Metals

Certain heavy metals are toxic to anaerobic organisms, even at low concentrations. Heavy metal ions inhibit metabolism and kill organisms by inactivating the sulfhydryl groups of their enzymes in forming mercaptides (Mosey et al., 1971). Since these reactions involve metal ions, it is the soluble fraction that is the toxic form and toxic effects are thus affected by the solubilities of heavy metals under various digester conditions (Theis and Hayes, 1979). Since many heavy metals form insoluble sulfides or hydroxides under pH conditions in the range of those found in digesters, one way to avoid heavy metal toxicity is to add chemicals such as sulfates which will form non-toxic complexes or insoluble precipitates. Toxic substances can also be removed from the feedstock or diluted to below the toxic threshold level.

Influence of Carbon/Nitrogen Ratio on Digestion

Nitrogen present in the feedstock has two benefits: (a) it provides an essential element for synthesis of amino acids, enzymes and protoplasm; and (b) it is converted to ammonia which, as a strong base, neutralizes the volatile acids produced by fermentative bacteria and thus helps maintain neutral pH conditions essential for cell growth. An overabundance of nitrogen in the substrate can lead to excessive ammonia formation, resulting in toxic effects (see above). Thus it is important that the proper amount of nitrogen be in the feedstock to avoid either nutrient limitation (too little nitrogen) or ammonia toxicity (too much nitrogen). The carbon/nitrogen (C/N) ratio of the feedstock has been found to be a useful parameter in evaluating these effects and providing optimal nitrogen levels. A C/N ratio of 30 is often cited as optimum (Fry, 1975; NAS, 1977; BORDA, 1980; UNEP, 1981). Since not all of the carbon and nitrogen in the feedstock are available to be used for digestion, the actual available C/N ratio is a function of feedstock characteristics and digestion operational parameters, and overall C/N values can actually vary considerably from less than 10 to over 90 and still result in efficient digestion.

BIODEGRADABILITY OF DIGESTER FEEDSTOCK

In general, most natural organic wastes can be digested; lignin is the major exception. In developing countries the primary substrate is cattle dung due to large cattle populations. This is a good substrate since it is moderately degradable and is well balanced nutritionally (C/N = 25:1). Swine and poultry manures produce even more biogas per unit weight and at higher rates. Human wastes (nightsoil), while high in nitrogen (C/N = 6), can also be digested easily, although carbohydrate wastes could be added to raise the C/N ratio and provide more gas.

Agricultural residues (e.g., wheat, rice straw) are usually readily available, and, while they have high C/N ratios, they can be digested in admixture with manures and nightsoil. These wastes are usually quite biodegradable, and can be made more so by physical size reduction, and by precomposting. However, problems can arise with these materials because they float in the digester and form hard scum layers on the surface.

Plants such as water hyacinth, duckweed, etc., can also be degraded easily, and give quite high gas yields. In these cases, digestion of these weeds can solve the problem caused by excess weed growth in canals and provide energy as well. Since their primary productivity is very high, the opportunity exists to create an "energy farm" by cultivating these weeds, perhaps in wastewater, which would also solve the problem of wastewater treatment.

Wastes generated in urban areas of developing countries (garbage, organic domestic and industrial wastes) are in principle also amenable to anaerobic digestion. However, these feedstocks have not been thoroughly explored in developing countries.

KINETIC MODELS

Although the basing of digester size on solids residence time or volatile solids loading is standard practice, a better understanding of anaerobic digestion can sometimes be obtained by examining kinetic models which describe the anaerobic process in terms of bacterial growth. Kinetic models are also useful as a basis for interpretation of laboratory or field performance data. In Appendix I several models which have been used to describe anaerobic digestion are presented and briefly discussed to indicate their potential use in the design of anaerobic systems.

HEALTH ASPECTS

One of the benefits of anaerobic digestion is its effect on public health. Pathogens discharged in fecal material include viruses, bacteria, protozoa and helminths. The spread of disease from these pathogens depends on a variety of factors, including amounts present, latency, persistence, multiplication rate, and infective dose. Disease can be controlled by appropriate treatment and disposal practices, and digestion of fecal wastes can result in a considerable reduction of pathogens. Nevertheless, due to the high concentration of pathogens present in fecal material, some digested sludges may still contain some pathogens and should be handled with care.

There are a number of factors which influence the survival of pathogens during digestion:

a. Temperature of the digester contents;

b. Detention time;

c. Chemical environment such as pH, ammonia concentration, and absence of oxygen;

d. microbial environment; and

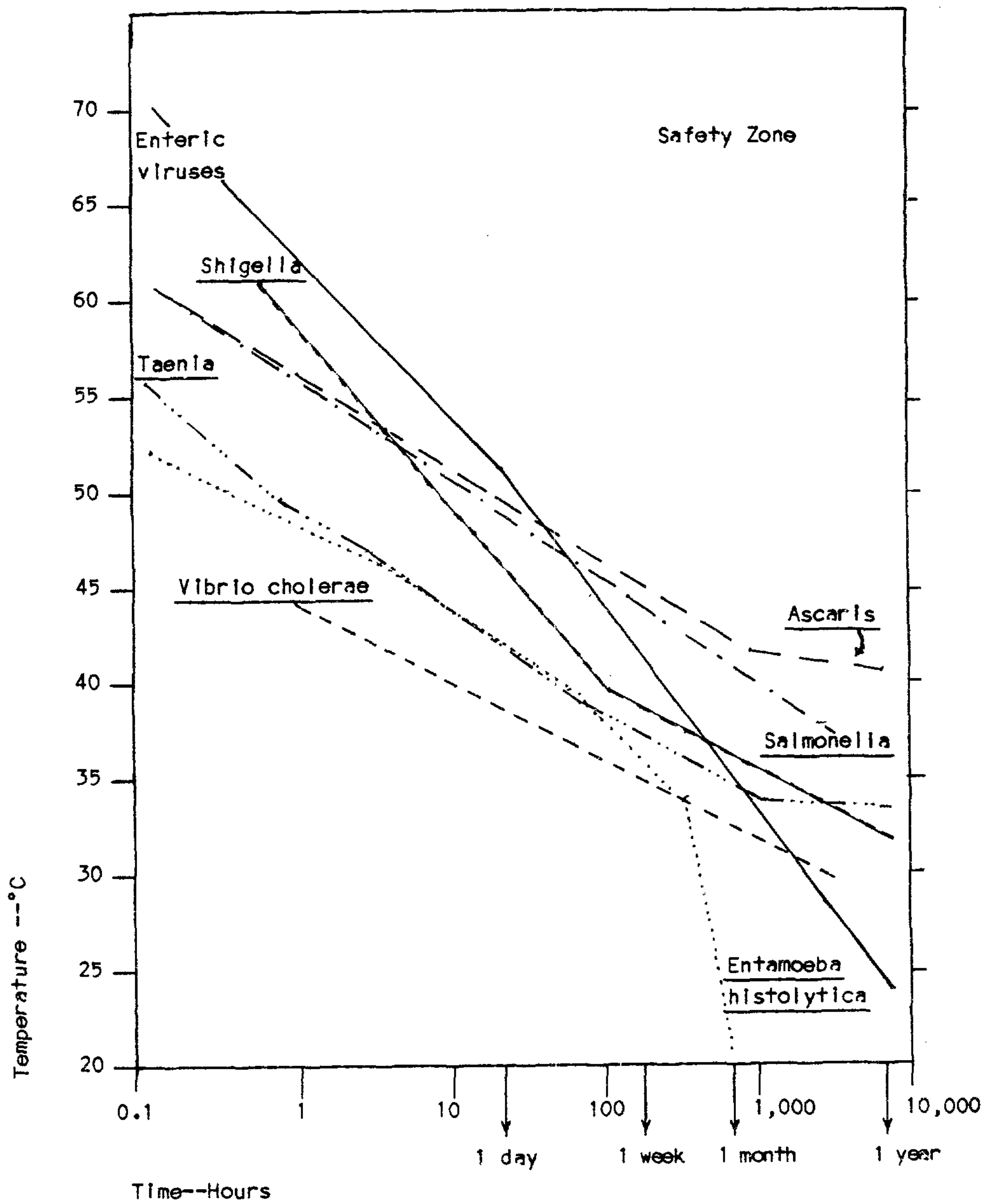
e. physical characteristics of the digester.

High temperature is the most effective method of killing pathogens since they are biological entities comprised of proteins which usually denature at temperatures in the range of 50 to 70°C. Time and temperature are intimately related. The higher the temperature, the shorter the time required for pathogen destruction, and vice versa. The influence of time and temperature on a number of pathogens is shown in Figure 2.3. The curves represent estimated time-temperature combinations for pathogen inactivation. Since considerable mortality occurs prior to inactivation, these are conservative upper limits. At thermophilic temperatures (55 to 60°C) the figure shows that detention times of only one day are required, and data gathered by Garber et al. (1975) and Garber (1977) on the kill rates of Salmonella and fecal streps at mesophilic and thermophilic temperatures bear this point out. With 20 days detention time kill rates of 10^2 and $>10^4$ were found for mesophilic and thermophilic temperatures respectively. However, even with thermophilic digestion, counts of fecal streps as high a 10^4/100 ml were measured in the effluent.

Numerous studies of pathogen die-off in biogas plants operating at lower than mesophilic temperatures have been carried out in China; in general, parasite egg removals of from 90 to 95% are possible, although at times Ascaris are only reduced by 30 to 40%. Semi-quantitative data (UNEP, 1981) also reveal that after digesters are installed in an area there are significant declines in parasite infections, enteritis, and bacillary dysentery.

Further treatment of the digested sludge (e.g., by air drying or composting) reduces pathogens still further, and in the latter case, if properly operated, produces a pathogen free product. Dried sludge may still contain some pathogens, but when applied correctly (e.g., ploughed under) presents no health risks. If suitable low cost methods for excreta disposal are not provided in a community, then digestion of nightsoil and animal manure will result in an improvement in environmental and public health.

Figure 2.3. Influence of Time and Temperature on Selected Pathogens in Nightsoil and Sludge. (Adapted from Feachem et al., 1983.)



Note: The line represents conservative upper boundaries for pathogen death--that is, estimates of the time-temperature combinations required for pathogen inactivation. A treatment process with time-temperature effects falling within the "safety zone" should be lethal to all excreted pathogens (with the possible exception of hepatitis A virus--not included in the enteric viruses in the figure--at short retention times). Indicated time-temperature requirements are at least: 1 hour at >62°C, 1 day at >50°C, and 1 week at >46°C.

CHAPTER THREE

METHANE PRODUCTION FROM SANITARY LANDFILLS

INTRODUCTION

The design of managed sanitary landfills for the disposal of municipal solid wastes (MSW) and the recovery of gas is receiving increased attention from engineers and municipal authorities (Farquhar et al., 1982; Franzius, 1982). The recovery of gas from sanitary landfills has been practiced since the early 1970s. At one time it was collected and flared to reduce explosion hazards, but now it is often used to produce heat and/or electricity or is cleaned up and transported with natural gas by pipeline to consumers. Only recently have concerted efforts been directed toward managing landfills to increase their gas production.

Methane is being extracted from landfills in England, West Germany, Brazil, Canada and the United States. Table 3.1 presents data on amounts of gas produced at selected landfills. There is no technical reason why gas production cannot be obtained from appropriately designed and operated landfills. This chapter summarizes technical information on some of the work that has been done on gas production from sanitary landfills; it does not address the site specific economic issues.

During the 1960s feasibility studies on digesting MSW were conducted at the University of California (Golueke et al., 1971). Research conducted at the University of Illinois (initially for EPA, NSF, and ERDA), Pfeffer, and others demonstrated the feasibility of digesting MSW in conventional digester systems when sewage sludge was added (Pfeffer, 1974; Brown et al., 1976; Cooney and Wise 1975; and Kispert et al., 1975, 1976). A plant capable of processing and anaerobically digesting 100 tons of MSW per day has been placed in operation at Pompano Beach, Florida (Mooij and Streit, 1982). Pohland (1975), Augenstein et al. (1976) and Buivid et al. (1981) reported on the possibilities of increasing the production of fuel gas from controlled landfills. Pacific Gas and Electric and Southern California Gas companies have constructed six large 5,000 to 6,000 (dry basis) metric ton MSW test cells at Mountain View, Caliornia based upon the earlier laboratory findings of Augenstein and Buivid (Halvadakis, 1983). Wise et al. (1981) have examined methods to provide additional nutrients, buffers and seed to accelerate the rates of gas production in existing landfills.

COMPONENTS AND COMPOSITION OF MSW

The composition of MSW varies greatly among countries, regions, and cities (see Table 3.2). Brown, Pfeffer and Liebman (1976) reported on the amounts of gas produced in experiments conducted under similar conditions using MSW from Champaign-Urbana, Illinois, Madison, Wisconsin and St. Louis, Missouri. The gas produced ranged from 0.31 to 0.39 cubic meters per kilogram of volatile solids fed to their laboratory digesters.

Table 3.1. Gas Production Rates at Selected Landfills.

Landfill	Location	Location	Fill Period	Surface Area Area (Hectares)	Avg. Depth (Meters)	Refuse tonnes (10x6 tonnes)	Estimated Gas Production (m^3/day)	Reference
North America								
Ascon	Los Angeles	California	1965-82	26	18	2.7	33,000	EMCON (1981)
Azuza	Los Angeles	California	1952-	30	50	6.5	39,000	Azusa Land Recl. Co. (1982)
Bradley	Sun Valley	California	1961-	27	33	8.3	80,000	GRCDA (1983)
Cinnimson	—	New Jersey	1951-80	25	18	2.3	20,000	GRCDA (1983)
CID (Getty)	—		1967	120	40	6.3	40,000	GRCDA (1983)
Davis Street (Getty)	Oakland	California	-80	80	24	5.3	85,000	GRCDA (1983)
Fresh Kills (Getty)	New York	New York		20	15	68	280,000	GRCDA (1983)
Hewitt	Sun Valley	California	1962-75	25	27	4.5	71,000	EMCON (1981)
Industrial Hills		California	1951-70	60	20	3.3	14,000	GRCDA (1983)
Inland Cement	Edmonton	Canada	1974	10	8	0.4	3,000	EMCON (1981)
Kitchener	Ontario	Canada		10	12		1,000(e)	Farquahar (1982)
Mountain View		California	1975-	12	12	1.1	14,000	EMCON (1981)
North Valley (Getty)			1956-	17	76	4.5	28,000	GRCDA (1983)
Operating Industries (Getty)	—	California	1948-	50	76	18	260,000	GRCDA (1983)
Palos Verdes (Getty)	—	California	1954-81	70	60	18.	50,000	GRCDA (1983)
Penrose (LAByPro)	Sun Valley	California	1957-	27	50	6.3	210,000	GRCDA (1983)
Puenete Hills (LACo)	Los Angeles	California	1963-	75	75	21.5	120,000	GRCDA (1983)
Scholl Canyon	Los Angeles	California	1963-74	18	49	4.3	34,000	EMCON (1981)
Sheldon-Arleta	Los Angeles	California	1962-74	18	30	5.3	108,000	EMCON (1981)
Germany (Fed.Rep.of)								
Ahrenshott	Husum		1971	15		1.7	9,600	Rettenberger (1982)
Am Lemberg	Ludwigsberg	near Stuttgart	1975-	16		0.0033	31,000	Franzius (1982)
Braunsweig	Braunschweig		1967-81	10		0.002	4,900	Franzius (1982)
Hohberg	Pforzheim		1972	10		0.003	3,200	Franzius (1982)
Gerolsheim	—		1968	15		4.0	36,000	Rettenberger (1982)
South America								
Bandeirantes	Sao Paulo	Brazil	1979-	3.5	60	0.9	43,200	Veit (1982)
Sapopemba	Sao Paulo	Brazil	1979-	8.0	50	2.1	93,600	Veit (1982)
V. Albertina	Sao Paulo	Brazil	1977-	4.0	80	2.6	96,000	Veit (1982)

Table 3.2. Composition of Urban Refuse, percentage by weight as received. (After Cointreau et al., 1984.)

Type of Materials	Brooklyn, N.Y.	London, England	Rome, Italy	Singapore	Hong Kong	Medellin, Colombia	Lagos, Nigeria	Kano, Nigeria	Manila, Philippines	Jakarta, Indonesia	Lahore, Pakistan	Karachi, Pakistan	Lucknow, India	Calcutta, India
	Industrialized			Middle Income						Low Income				
Paper	35	37	18	43	32	22	14	17	17	2	4	<1	2	3
Glass, ceramics	9	8	4	1	10	2	3	2	5	<1	3	<1	6	8
Metals	13	8	3	3	2	1	4	5	2	4	4	<1	3	1
Plastics	10	2	4	6	6	5	-	4	4	3	2	-	4	1
Leather, rubber	-	-	-	-	-	-	-	-	2	-	76	<1	-	-
Textiles	4	2	-	9	10	4	-	7	4	1	5	1	3	4
Wood, bones, straw	4	-	-	-	-	-	-	-	6	4	2	1	<1	5
Non-food total	74	57	29	63	60	34	21	35	40	15	27	4	18	22
Vegetative, putrescible	22	28	50	5	9	56	60	43	43	82	49	56	80	36
Miscellaneous inerts	4	15	21	32	31	10	19	22	17	3	24	40	2	42
Compostable total	26	43	71	37	40	66	79	65	60	85	73	96	82	78
TOTAL	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Note: The above values have been rounded to the nearest whole number, unless the percentage was less than 1.0.

The components of MSW in the United States are characterized as shown in Table 3.3. Table 3.4 shows an elemental analysis and important characteristics such as the moisture, volatile solids, ash and heat contents of the wastes. The volatile solids content is used to approximate the organic biodegradable portion and is an indicator of potential gas production when adequate nutrients, buffers, and moisture are present.

METHANE GENERATION

The various components of MSW are degraded anaerobically at different rates. For example, food wastes decompose more rapidly than paper products. Although leather, rubber and some plastics are also organic, they usually resist biological degradation. Some lignocellulosic materials, plastics, fabrics and other organic materials are very resistant to decomposition by anaerobic organisms. In addition, small amounts of the organic materials being anaerobically digested are utilized in the process of making new cells and thus do not contribute to gas production.

Table 3.3. Municipal Solid Waste Composition in the United States.

	Percent Dry Basis	Moisture Content
Food Wastes	12.0	72
Garden Wastes	12.0	65
Paper Products	42.0	10.2
Plastics/Rubber	2.4	2
Textiles	0.6	10
Wood	2.5	20
Metals	8.0	3
Glass/Ceramic	6.0	2
Ash/Dirt/Rock	11.0	10
Fines	3.0	-
Misc.	0.5	4

Reference: Adapted from American Chemical Society (1972).

Table 3.4. Chemical Analysis of U. S. Municipal Solid Wastes.

Chemical	Percent Dry Basis
Carbon	28.0
Hydrogen	3.5
Oxygen	22.4
Nitrogen	0.33
Sulfur	0.16
Ash	24.9
Volatiles	75.1
Heat Content	14,430 Kj/kg.
Moisture Content	26.7%

Reference: Adapted from American Chemical Society (1972).

In spite of the lack of uniformity, empirical formulas have been developed to predict the amount of methane and carbon dioxide that can be produced from cellulose and other organic material. For example Augenstein et al. (1976) used the following relationship:

$$C_6H_{10}O_5 + H_2O \rightarrow 3\ CH_4 + 3\ CO_2$$
(cellulose)

The equation indicates that equal quantities of methane and carbon dioxide are produced; however, since carbon dioxide is soluble in water which is lost as leachate, less is present in gas from landfills.

The actual yield of methane per kilogram of a substrate is related to its biodegradability and oxidation state (Stuckey, 1983). However, if one kilogram of cellulose in the above equation is degraded, 0.415 cubic meters of methane and 0.415 cubic meters of carbon dioxide are produced.

The period of time required for MSW to degrade and produce biogas depends upon a number of variables, including the number of organisms present, nutrients, temperature, pH, buffer capacity, moisture content and the density to which the materials are packed in the landfill. The effects of these variables upon the production of gas has been discussed by Buivid et al. (1981) and Halvadakis (1983). Designers and operators are improving ways to increase the amount of methane produced and decrease the amount of time needed for gas production.

Figure 3.1 shows hypothetical cumulative methane generation for "typical" MSW placed in a landfill based on studies by Augenstein et al. (1976), Engineering Science Inc. (1964), Tabasaran (1981) and Alpern (1981). Augenstein's data indicate that most of the gas will be produced in three years while extrapolation of Engineering Science Inc. data indicates five years. Tabasaran proposed that a 20 year period should be used in forecasts for conventional landfills and that 75% of the theoretical gas should be produced in that period; therefore even if the MSW were all biologically resistant cellulose, the quantities of gas produced would be represented by the above equation. The area under Tabasaran's curve (Figure 3.1) to the twentieth year represents 75% of the theoretical cubic meter per kilogram of methane produced from one kilogram of cellulose. Alpern's study of a Los Angeles, California landfill which has been producing methane for over 25 years indicates 75% of the theoretical gas production within 50 to 100 years.

In contrast, Brown, Pfeffer and Liebman (1976), Augenstein et al. (1976), and Buivid et al. (1981) calculated that most of the gas could be produced in the first year, and 90% could be produced within three years. For example, in an experiment conducted by Buivid (1981), 72.1% of the waste was converted to gas within 180 days (see Figure 3.2). He based percentages upon the assumption that the one kilogram volatile solids had the composition of cellulose shown in the above equation. These experiments plus data reported by Mooij et al. (1982), who digested MSW in a large stirred anaerobic digester, show that methane and carbon dioxide gas production can be accomplished in managed landfills in a three year period; therefore, the resulting gas production curve and the percentage per year would be as in Figure 3.3. At the Am Lemberg landfill near Stuttgart, West Germany five wells were installed in one section of a completed landfill. After three years one of the wells has ceased yielding gas and the three other wells were producing only 50% of their initial yield (Rottenberger, 1982). This indicates that the gas production in a traditional full scale landfill is slower than laboratory studies would indicate but more rapid than the rates estimated by Tabasaran.

The large differences reported between theoretical and operating landfill gas production are believed to be due to differences in original waste composition, age of fill, moisture content, efficiency of gas extraction and/or temperatures. The last is a function of fill geometry, since anaerobic digestion is exothermic; Halvadakis (1983) reported core temperatures of 55°C and still rising after 18 months in 5,000 to 6,000 metric ton (14,000 cubic meter) test cells. Wise (personal communication, 1983) reported temperatures of over 70°C in large fills.

VARIABLES AFFECTING LANDFILL GAS PRODUCTION

Although it would be convenient if a mathematical equation could be developed to describe the decomposition and predict the amount of gas

Figure 3.1. Potential Methane Production from Municipal Solid Waste Landfills.

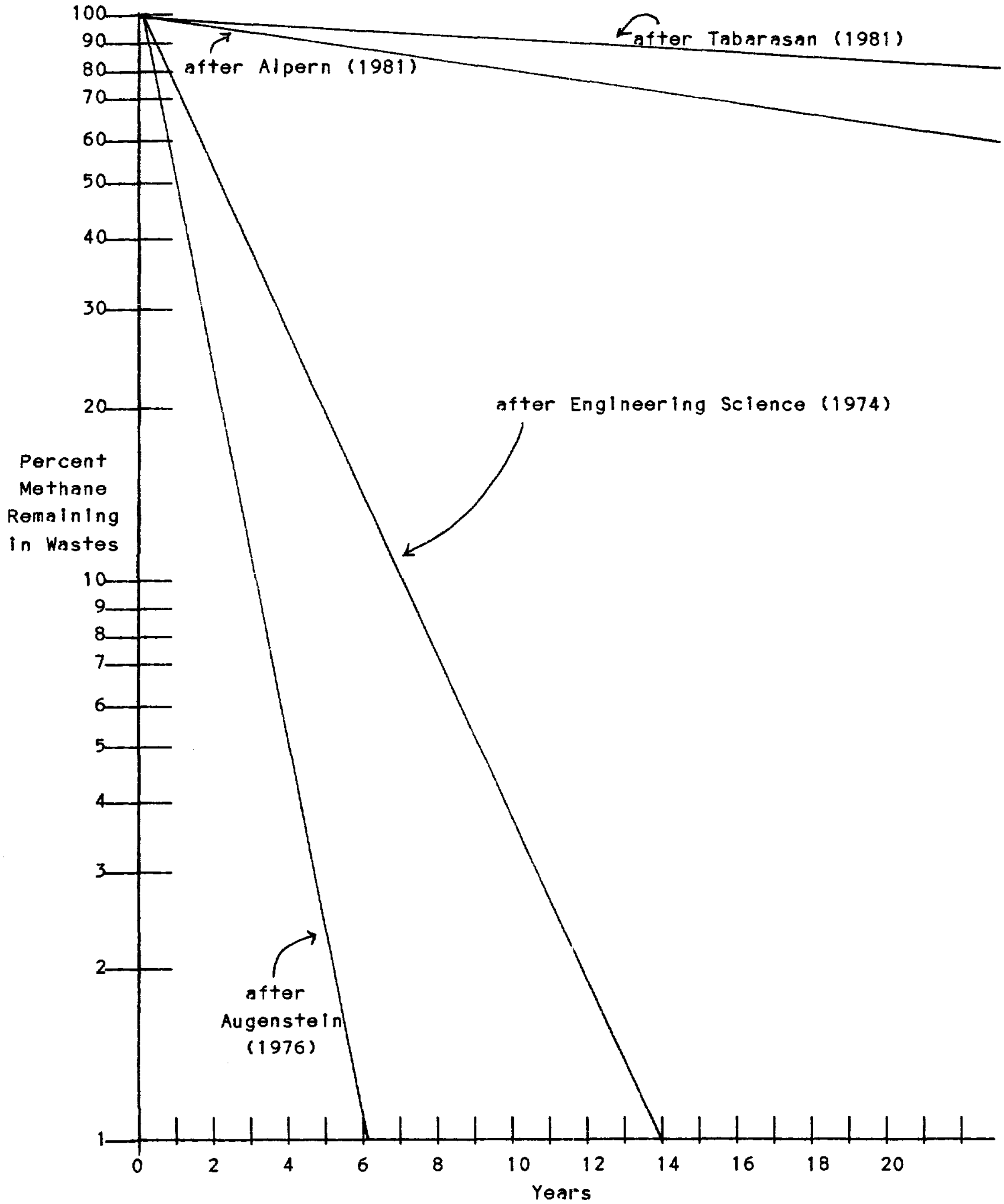
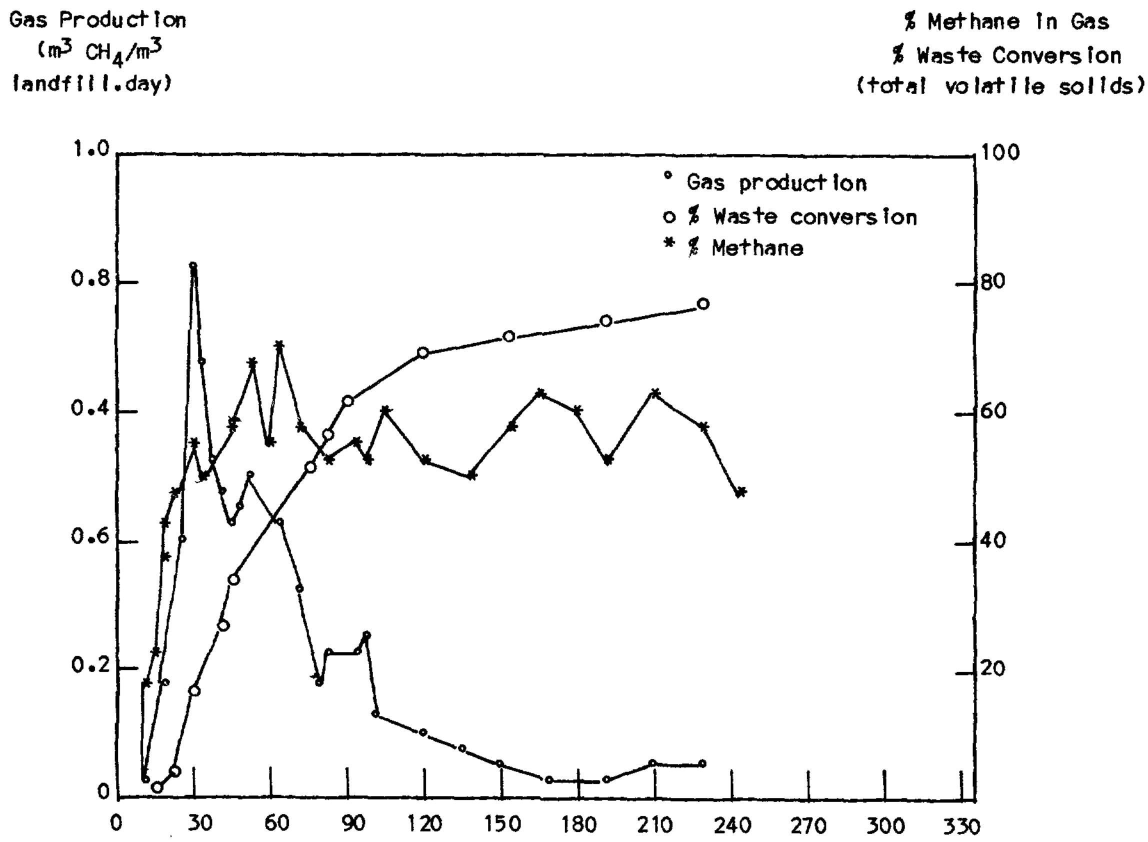


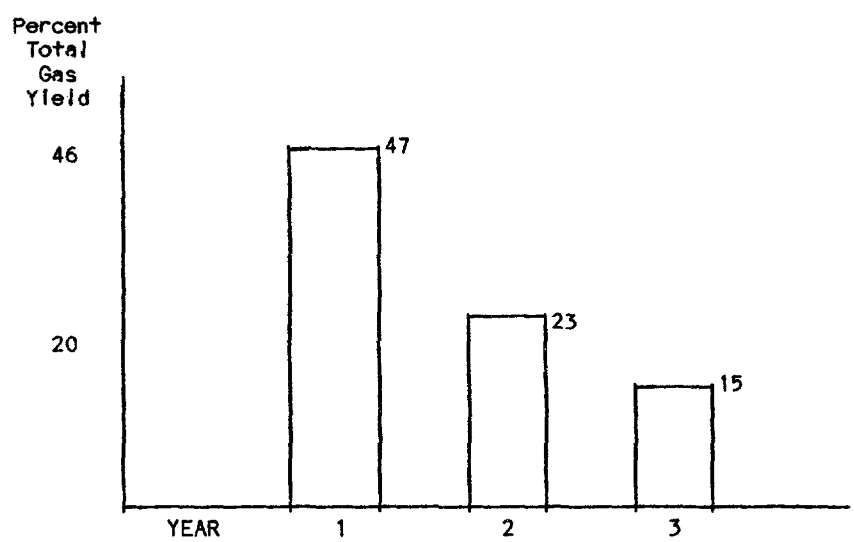
Figure 3.2. Solid Wastes Converted to Gas over Time.



Initial fermentation conditions: 37°C, 93% dry MSW solids, 7% dry nutrient solids, 75% total wet weight, 1200 wet lbs/yd^3 of flail-milled MSW.

Reference: Based on information in Buivid (1981).

Figure 3.3. Percent Total Gas Yield Per Year, Managed Landfill.



Reference: Adapted from Augenstein et al. (1976).

produced, those familiar with laboratory experiments dealing with the breakdown of pure substance are aware of the difficulties of using a single equation to define all reactions for a heterogeneous material such as MSW. EMCON (1980) reviewed several mathematical models, and Halvadakis (1983) developed two additional models, of time dependence of gas production, but it is difficult in a model to take into account all the variables which have an impact upon the rates of anaerobic decomposition. Some of these variables are listed below.

a. Composition of the Waste

The more food wastes present, the more rapid the gas production. Paper and similar organics degrade at a slow rate and are extremely resistant to biodegradation.

b. Moisture Content

Moisture content is one of the most important parameters in a controlled landfill. Buivid et al. (1981) found that by increasing the moisture content from 61% to 75%, a 10 to 20 fold increase in the rate of conversion was possible over short periods of time. Pohland (1975, 1980) has described means of recycling the leachate to maintain the moisture content.

c. Inoculum/Nutrient

Many anaerobic organisms in digesters are also found in the wastes of animals and human beings. While these organisms will develop naturally in landfills, the degradation process can be initiated more rapidly by seeding the wastes with sewage sludge which also serves as an additional nutrient moisture source. Phosphate has been reported by Pohland (1980) as the limiting nutrient in U.S. landfills.

d. Mixing

In a conventional sewage sludge digester, mixing brings the organisms in contact with the food supply. Recycling of leachate also promotes mixing of seed and nutrients with MSW in a landfill.

e. Compaction

Compacting the moist MSW with the seed material and nutrient is effective in bringing them into contact with the MSW. Compaction also reduces the space required per unit of MSW, the later settlement of the landfill and its cover layer, and, by reducing the air space and oxygen, probably reduces the time before methane is produced.

f. Size Reduction

Previous experience has shown that large materials should be reduced in size whenever possible. The smaller particles make compaction easier and present more surface area for the organisms to attack.

g. Temperature

The temperature within the landfill will rise slightly during the initial stages of aerobic breakdown which occurs prior to the utilization of oxygen initially contained within the fill. Anaerobic degradation is also slightly exothermic and therefore landfill temperatures, as stated above, are higher than the ambient air temperatures (Leckie et al., 1979).

h. Recycling of the Leachate

Experiments have been performed on leachate recycling, as described by Buivid (1981) and Pohland (1975, 1980). Leachate maintains the moisture content and provides a nutrient, buffer, inoculum and bacterial seed. Following the experiments of Veit and Zulaut (1982) at new Brazilian landfills, a system was devised to collect and recycle the leachate and the gas.

i. Gas Collection and Utilization

Empirical numbers such as 62 cubic meters of gas produced per metric ton of MSW as received are sometimes used to estimate gas yield (Baron et al., 1981). These numbers are usually based on site specific data which cannot be applied to other locations without normalizing them to take into account varying composition, moisture content, etc.

GAS COLLECTION AND UTILIZATION

Collection and sale of biogas from landfills require careful consideration. The percentage of gas recovered depends on the construction and operation of the fill. Ideally the landfill should be constructed so that all wastes and liquids are totally contained and all gas totally collected. Collection systems are sometimes installed while landfills are being filled. The system must recover the gas without interfering with the fill operation. A review of various gas collection and utilization systems is contained in reports by Baron et al. (1981) and Ham et al. (1979).

There have been varying degrees of success in commercially collecting, utilizing and selling the landfill gas in the United States. Veit (1982) estimated in a study of a proposed project at Recife, Brazil that 80% of gas produced could be sold. The amount of gas produced is sometimes difficult to estimate, however, because of unknown quantities of decomposable organic matter. Experiments at test cells in Mountain View, California as describe by Pacey (1982) and elsewhere should provide increasingly reliable estimates of gas production, collection, and sales; however engineers and municipal authorities need to know the probable range of values. The following example provides a method for estimating gas production and recovery.

Santos and Recife Analyses

Two analyses are available from studies made by Veit and Zulaut (1982) of MSW in coastal cities in Brazil; (1) the Santos analysis for MSW reported to be collected from areas near the beach and (2) the Recife analysis. The organic portions of the samples were:

	Santos %	Recife %
Paper	20.86	25.9
Other organics	19.9	49.5
Fabrics	2.57	1.9

The moisture content of the MSW was reported to be 60% for both samples.

In order to calculate the range of methane yields that might be collected and sold from a landfill in Brazil a number of assumptions must be made:

a. Total Dry Weight

The moisture content is assumed to be uniformly distributed among the components comprising the MSW. (In practice, variations occur because market and food wastes usually have a higher moisture content than street sweepings, paper and metals.) Total dry weight equals 400 kilograms per metric ton of refuse.

b. Organic Fraction

It is assumed that paper and other organics are biodegradable in the presence of adequate nutrients, buffers and seed, while the fabrics are not. In reality, the "other organics" fraction will contains plastics, lignocellulosic materials like wood, and other materials which resist anaerobic digestion. The rates of anaerobic decomposition are fastest for food wastes, followed in order by paper, grass clippings and tree trimmings, wood, and rubber.

The organic fractions as determined from the analyses above are:

Santos: (400)(40.76) equals 160 kilograms per metric ton
Recife: (400)(75.4) equals 300 kilograms per metric ton

c. Maximum Gas Yield

If cellulose were completely broken down to methane and carbon dioxide, 0.415 cubic meters of methane per kilogram of cellulose would be produced. Therefore, if the organic matter calculated above were all cellulose, then the maximum quantity of methane produced would be:

Santos: 160 kilograms times 0.415 cubic meters per kilogram equals 66 cubic meters of methane per metric ton
Recife: 300 kilograms times 0.415 cubic meters per kilogram equals 124 cubic meters of methane per metric ton

Assumed Gas Yields and Capture of the Methane

It is unlikely that all the organic matter in a landfill will decompose to methane and carbon dioxide or that all of the gas produced will be captured. The amount captured will depend upon the construction of the fill. The test cells at Mountain View, California are enclosed in an impermeable membrane and operated as batch reactors. Actual landfill surfaces may be porous, which will allow portions of the gas to escape rather than be captured. Assuming 50% of the maximum gas produced can be captured, the wastes at Santos would yield 33 cubic meters of methane per metric ton MSW and the wastes at Recife would yield 62 cubic meters of methane per metric ton.

Quantities of Gas Generated Per Unit of Time

The quantity of gas generated per unit of time depends upon the rate of decomposition. Two extremes were presented by Tabasaran (1981) for conventional landfills and Augenstein, et al. (1976) for managed landfills. Tabarasan stated that the breakdown would take place over a 20 year period to yield 75% of the gas (see Figure 3.1) while Augenstein (1976) estimated the breakdown could be 90% complete in three years. For these two cases the yields per year would be as follows:

YIELDS OF METHANE IN CUBIC METERS PER YEAR PER METRIC TON

Tabarasan (first ten years)

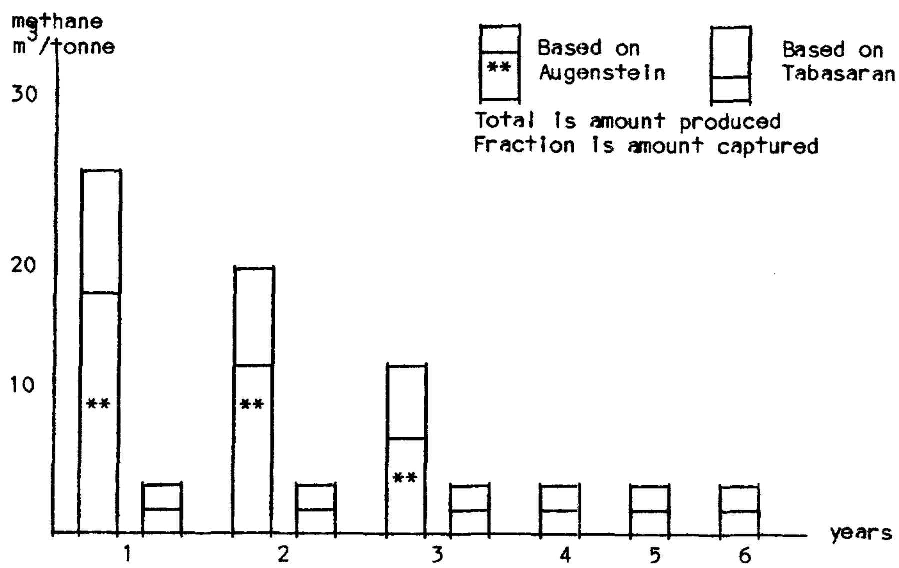
Years	1	2	3	4	5	6	7	8	9	10
Santos	2.2	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2
Recife	4.1	3.8	3.6	3.4	3.1	2.9	2.7	2.6	2.4	2.2

Augenstein

Years	1	2	3
Santos	15.5	7.6	5
Recife	29	14.3	9.3

The range of resulting values using the Tabarasan and Augenstein assumptions are presented in Figure 3.4. Sound engineering judgment must then be applied to determine an estimate of rate. Better information on both waste composition and production of methane is needed. For example, no data were available on the volatile solids content, which is an important parameter.

Figure 3.4. Gas Production from a Landfill in Brazil (an example). Cubic meters of methane per metric ton MSW/year.



Reference: Adapted from Augenstein et al. (1976), Tabasaran (1981).

SUMMARY

Although the anaerobic digestion process which occurs naturally in sanitary landfills is fairly well understood, only empirical approaches have generally been used to estimate both the quantities and rates of gas production. Laboratory and full scale experiments with municipal solid wastes have shown that with proper startup, most of the volatile organic solids can be decomposed in the first year with progressively smaller amounts being broken down thereafter. The larger test cells have shown a lag in startup of gas production when they are not seeded or buffered. Total gas production is best estimated using the dry weights and volatile solids contents of the wastes.

Rates of production depend upon composition and age of fill material, percent moisture, temperature, fill geometry, and operating practices. Gas extraction efficiencies depend upon fill and collection system geometry, density and settling within the fill, and integrity of the cell or fill boundaries. All of these may be optimized by designing and operating the landfills as batch reactors rather than disposal sites.

CONCLUSIONS

Review of the literature reveals that in order to design, build and operate a landfill for gas recovery the following information is required.

a. Characteristics of both the total waste and its various components which go into the landfill, such as biodegradability, moisture content, nutrients and pH;

b. Preparation of the materials going into the fill, such as shredding, seeding, compaction, buffering;

c. Site characteristics, materials used to cover the fill, and gas collection system; and

d. Rates of gas production from materials similar to those going into the fill.

CHAPTER FOUR

ANAEROBIC PROCESSES AND DIGESTER DESIGN

Various processes used to carry out anaerobic digestion are discussed in this chapter, and their stages of development are assessed. Methods of sizing digesters as well as considerations affecting design and optimization, heating, and mixing are described.

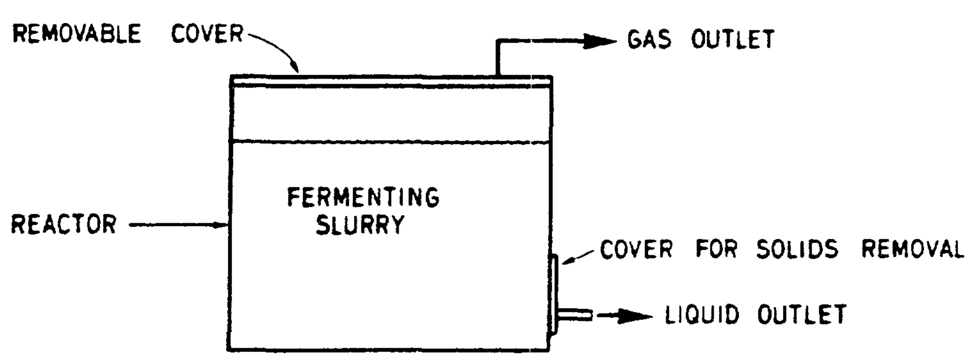
DIGESTER TYPES AND STAGES OF DEVELOPMENT

Carrying out anaerobic digestion in a closed reactor with sufficient volume for the biological reactions to occur without stress comprises the primary technical requirements. Based on external limitations such as capital cost, treatment efficiency, net energy yields and operational skill, the technology available ranges over a spectrum from very rudimentary to quite sophisticated. The fact that anaerobic digestion has been used in practical situations for over 80 years demonstrates that it is a viable technology; however problems can arise when there are external constraints such as limited capital and low operational skills. The following is a summary of the types of digesters in common use or being developed.

Batch and "Dry" Fermentation

This is the simplest of all the processes. Operation involves merely charging an airtight reactor with the substrate, a seed inoculum, and in some cases a chemical to maintain a satisfactory pH. The reactor is then sealed, and fermentation is allowed to proceed for 30 to 180 days. During this period the daily gas production builds up to a maximum and then declines. This fermentation can be conducted at "normal" solids content (6 to 10%) or at high concentrations (>20%), which is then known as "dry" fermentation. This design is shown in Figure 4.1.

Figure 4.1. Batch Digester.



Boshoff (1965) was one of the first workers to quantify batch fermentation. Using elephant grass at 27°C he obtained volumetric efficiencies (volume of methane produced per day per volume of digester) of 0.35 at 40 days detention time.

One of the most successful biogas programs using batch systems has been that of Maya Farms in the Philippines (Maramba, 1978). Using a 1:1 dilution of swine manure (12.5% total solids, 10.0% volatile) and a residence time of 30 days at 31°C, they obtained average volumetric efficiencies of around 1.0. This was achieved with a seed inoculum of 20% by weight of the total digester slurry, which resulted in maximum gas production rates. They have used more than 30 reactors extensively, emptying and recharging one each day on a 30 day cycle to ensure a constant supply of gas.

Hutchinson (1972), one of the early pioneers of biogas in Kenya, has used batch reactors in conjunction with continuously fed systems. The effluent from the continuous system is discharged into a batch reactor partially filled with dry agricultural residues. A cover is installed, and the batch reaction is allowed to proceed for 42 days. Three batch reactors are used in conjunction with one continuous reactor.

In Burkina Faso there is a UNEP sponsored program of batch fermentation. Approximately 14 digesters of two to four cubic meter capacity have been installed (El-Halwagi, 1982), and with 10% total solids (estimate), volumetric efficiencies of around 0.5 have been obtained with 50 days detention.

Considerable interest has been shown recently in "dry" fermentation, which process Jewell and his co-workers (Jewell et al., 1981) have worked on for a number of years. They found that fermentation can proceed at total solids concentrations up to 32%. With a feedstock of grass at 25% total solids and 35°C, using a manure inoculum of 30% by weight, they obtained volumetric gas productions of 0.79 over 60 days, which increased to around 3.0 at 55°C. They concluded that a reactor that would have to be started only once a year may be useful. Volumetric gas production would be around 0.2, which is a common figure achieved in simple semi-continuous digesters in developing countries.

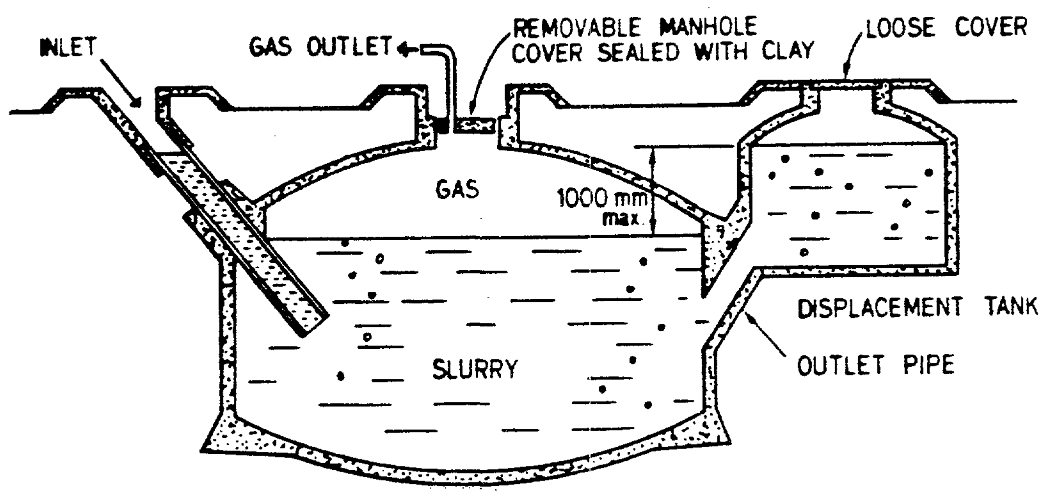
The stage of development of low solids batch reactors is quite advanced, and the technology has been used successfully for many years. With "dry" fermentation, the process parameters are not quite so well developed, and further work needs to be done. However, even at this stage it appears to be a viable technology, and its gas production rates are competitive with semi-continuous fed reactors.

Fixed Dome (Chinese)

A fixed dome biogas digester was built in Jiangsu, China as early as 1936 by Professor Zhon Peiyuan, and over the intervening years considerable research has been carried out in China on various digester models. The water pressure digester was developed in the 1950s. In one variation the displaced effluent flows onto the roof of the reactor, enabling the roof to withstand the gas pressure within more easily.

In terms of absolute numbers the fixed dome is by far the most common digester type in developing countries. The reactor consists of a gas tight chamber constructed of bricks, stone or poured concrete. Both the top and bottom of the reactor are hemispherical, and are joined together by straight sides. The inside surface is sealed by many thin layers of mortar to make it gas tight, although gas leakage through the dome is often a major problem in this type of design. The digester is fed semi-continuously (i.e., once a day) and the inlet pipe is straight and ends at midlevel in the digester. There is a manhole plug at the top of the digester to facilitate entrance for cleaning, and the gas outlet pipe exits from the manhole cover (see Figure 4.2).

Figure 4.2. Fixed Dome (Chinese) Digester



The gas produced during digestion is stored under the dome and displaces some of the digester contents into the effluent chamber, leading to gas pressures in the dome of between 1 and 1.5 meters of water. This creates quite high structural forces and is the reason that the reactor has a hemispherical top and bottom.

At the present time there are approximately six to seven million of these digesters in China (Chan U Sam, 1982), and many in India and other countries. The typical feed to these digesters is usually a mixture of swine or cattle manure dung, water hyacinth, nightsoil, and agricultural residues, depending on their availability and carbon/nitrogen ratios. Agricultural residues are usually pretreated by composting with nightsoil and lime before digestion (UNEP, 1981). Gas production rates are on the order of 0.1 to 0.2 volumes of gas per volume of digester per day (Chan U Sam, 1982), with detention times of 60 days at 25°C.

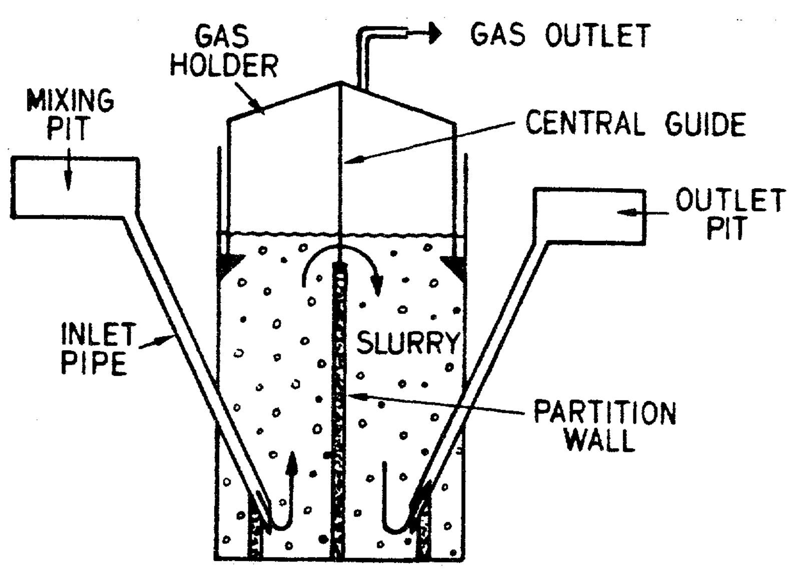
The state of development of fixed dome digesters is quite advanced and much is known about material, methods of construction, cost, suitable digester feedstock, and gas production rates.

Floating Cover (Indian or KVIC Design)

In India, the history of biogas technology has occurred in three stages: (1) experimental from 1937 to 1950; (2) pilot plant from 1950 to 1963; and field from 1964 to the present (FAO, 1981). The Indian Agricultural Research Institute (IARI) extended the study of anaerobic digestion from municipal sewage sludge to cattle dung in 1939, and subsequently a batch type reactor was developed in 1946. In 1950 Patel designed a plant with a floating gas holder which caused renewed interest in biogas in India. The Khadi and Village Industries Commission (KVIC) of Bombay began using the Patel model biogas plant in a planned program in 1962, and since then it has made a number of improvements in its design.

The floating cover design, upon which the KVIC model is based, is used extensively throughout the world. A typical KVIC design is shown schematically in Figure 4.3. The reactor wall and bottom are usually constructed of brick, although reinforced concrete is sometimes used. The gas produced in the digester is trapped under a floating cover which rises and falls on a central guide. The volume of the gas cover is approximately 50% of the total daily gas production, and the cover is usually constructed of mild steel, although due to corrosion problems other materials such as ferrocement, high density polyethelene and fiberglass have been used. The pressure of the gas available depends on the weight of the gas holder per unit area, and usually varies between four and eight centimeters of water pressure.

Figure 4.3. Floating Cover (Indian) Digester.



The reactor is fed semicontinuously through an inlet pipe, and displaces an equal amount of slurry through an outlet pipe. When the reactor has a high height to diameter ratio, a central baffle is included to prevent short circuiting. In cases of high water table a rectangular horizontal design is used, with walls that slope upward at an angle to the floating gas holder.

Most of the KVIC type digestors are operated at ambient temperatures, thus detention times depend on the variation in ambient temperature. Typical detention times are 30 days in warm climates such as Southern India where ambient temperatures vary from 20 to 40°C, 40 days in moderate climates such as the Central and Plains areas of India where minimum temperatures go down to 5°C, and 50 days in cold climates such as the hilly areas of Northern India where minimum temperatures go below 0°C.

The typical feedstock is cattle dung, although substrates such as agricultural residues, nightsoil and aquatic plants have been used. The cattle manure, generally about 20% solids, is diluted to 10% total solids before feeding by adding an equal quantity of water. The daily average gas yield varies from 0.20 to 0.60 volume of gas per volume of digester ratio in cold to warm climates.

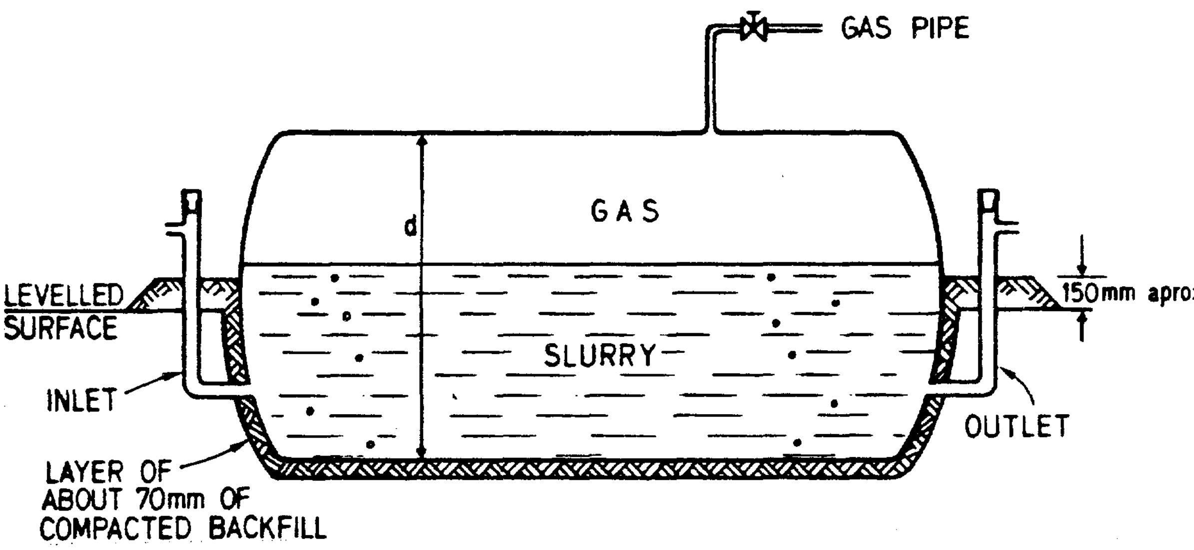
While this type of design has been in use for over 40 years in developing countries and a considerable amount of information is available, the design and operation of floating cover plants is still primarily empirical, with only recent attempts at optimization. Workers in Bangalore (Subramanian et al., 1979) have looked closely at a traditional KVIC plant, and using optimization procedures found that a similarly constructed digester with different physical dimensions could cost as much as 40% less. Further, when this plant was constructed, its gas yields were 14% higher. Thermal analysis also revealed that the major loss of heat was through the digester cover, and if a solar water collector were incorporated into the roof and the hot water used to charge the digester, then increases of 11% in gas yield resulted.

Many national laboratories, universities, and industries throughout the world, and especially in India, continue to improve the KVIC design. Efforts are being made to optimize the design parameters, to improve the volumetric efficiency, and make the facilities more economically and structurally sound. Heating, mixing and insulation have been introduced on an experimental basis, as well as modifications in geometric configurations and locations of inlets and outlets.

Bag Design (Taiwan, China)

The bag digester is essentially a long cylinder (length to diameter = 3 to 14) made of PVC, a Neoprene coated nylon fabric, or red mud plastic (RMP), a proprietary PVC to which wastes from aluminum production are reported to be added. Integral with the bag are feed inlet and outlet pipes and a gas pipe (see Figure 4.4). The feed pipe is arranged such that a maximum water pressure of approximately 40 centimeters is maintained in the bag. The digester acts essentially as a plug flow (unmixed) reactor, although it can be stored in a separate gas bag (Park et al., 1979).

Figure 4.4. Bag (Taiwan, China) Digester.



The basic design originated in Taiwan, China, in the 1960s (Hao et al., 1980) due to problems experienced with brick and metal digesters. The original material used, a Neoprene coated nylon, was expensive and did not weather well. In 1974 a new membrane, red mud plastic (RMP), was produced from the residue from aluminum refineries, was inexpensive, and had a life expectancy of around 20 years (Hong et al., 1979). Due to its availability, PVC is also starting to be used extensively, especially in Central America (Umana, 1982). The membrane digester is extremely light (e.g., a 50 cubic meter digester weighs 270 kilograms) and can be installed easily by excavating a shallow trench slightly deeper than the radius of the digester. Due to its simple construction and the fact that it is prefabricated, the cost of this digester is low, averaging around $30 per cubic meter installed.

The Taiwanese evolved the bag digester primarily to treat swine manure, which is also the most common substrate in Korea and Fiji. Due to its low cost and excellent durability the Chinese have also started producing these digesters, and claim that the cost is as low as $25 to $30 per cubic meter. Depending on the availablity of the plastic, a rapid expansion in the use of bag digesters is expected in China, and in time it may replace the fixed dome as the preferred type in China.

Typical detention times in bag digesters for swine waste vary from 60 days at 15 to 20°C, to 20 days at 30 to 35°C. One advantage of the bag is that its walls are thin. Hence the digester contents can be heated easily if an external heat source such as the sun is available. The

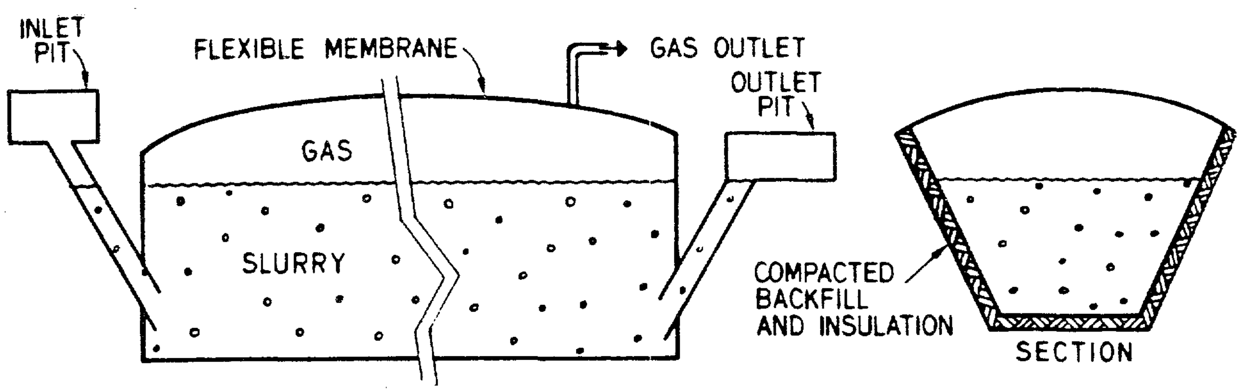
Chinese have found that average temperatures in bag digesters compared with dome types are 2 to 7°C higher. Hence volumetric gas rates can be from 50 to 300% higher in the bag (0.235 to 0.61 volumes of gas per volume of digester per day). Park et al. (1981) also found this to be true in Korea, and obtained volumetric gas productions varying from 0.14 in winter (8°C) to 0.7 in summer (32°C) for swine manure.

In their present state of development, bag digesters appear to be very competitive due to their low cost. However, more data is needed on their durability with regard to weather and mechanical failure (e.g., sharp objects piercing the bag). The potential for increasing their performance by heating with solar tents should also be explored.

Plug Flow

The plug flow reactor, while similar to the bag reactor, is constructed of different materials and classified separately. A typical plug flow reactor consists of a trench lined with either concrete or an impermeable membrane (see Figure 4.5). To ensure true plug flow conditions, the length has to be considerably greater than the width and depth. The reactor is covered with either a flexible cover gas holder anchored to the ground or with a concrete or galvanized iron top. In the latter type a gas storage vessel is required. The inlet and outlet to the reactor are at opposite ends, and feeding is carried out semicontinuously, with the feed displacing an equal amount of effluent at the other end.

Figure 4.5. Plug Flow Digester.



The first documented use of this type of reactor was in the Republic of South Africa in 1957 (Fry, 1975), where it was insulated and heated to 35°C. Volumetric gas rates of 1 to 1.5 were obtained with detention times of 40 days and loading rates of 3.4 kilograms total solids per cubic meter per day.

Jewell and co-workers at Cornell University have carried out a considerable amount of work on this design over the last eight years. Hayes et al. (1979) describe a comparison between a rubber lined plug flow reactor and a completely mixed digester. Both had a total volume of 38 cubic meters, and were fed on dairy manure at 12.9% total solids. Their results are summarized in Table 4.1. Digester temperatures were not stated, but it is assumed that both were maintained at 35°C.

Table 4.1. Comparison of Completely Mixed Digester with Plug Flow Digester.

	Completely Mixed		Plug Flow	
HRT (d)	15	30	15	30
Specific volume (m^3 gas/m^3 reactor/days)	2.13	1.13	2.32	1.26
Specific gas production (m^3/kg VS added)	0.281	0.310	0.337	0.364
Gas composition (%CH_4)	55	58	55	57
Volatile solids reduction (%)	27.8	31.7	34.1	40.6

Reference: Adapted from Hayes et al. (1979).

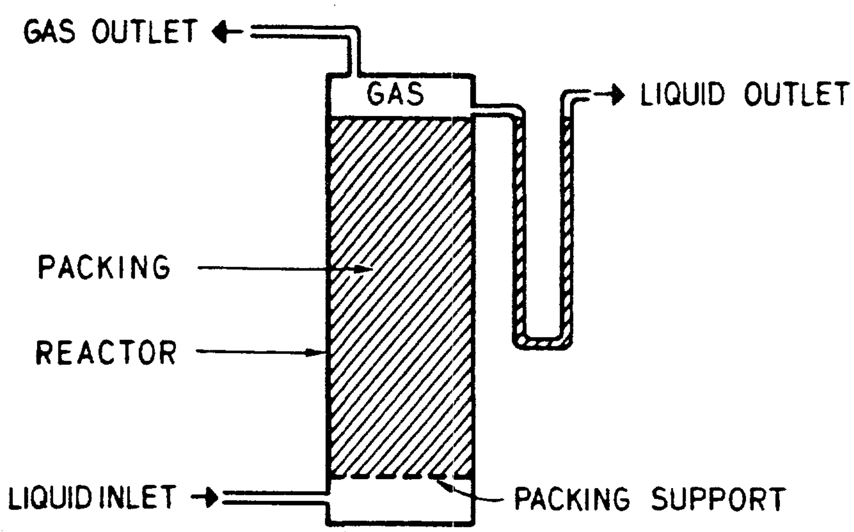
The plug flow reactor gave higher gas production rates than the completely mixed one. This is predictable using kinetics. The high volumetric gas production rates relative to typical fixed dome and floating cover figures of 0.1 to 0.3 are due to higher temperature and higher loading rates. At 20°C the plug flow reactor yields about 0.42 volumes of gas per volume of digester per day. At typical lower loading rates (9% versus 12.9% total solids) this figure would decrease to around 0.29.

Anaerobic Filter

Except for the batch digester, all the designs discussed above are known as suspended growth systems, and when there is no recycling of solids the hydraulic detention time (θ) is equal to the biological solids retention time (θc). Due to the slow growth of anaerobic organisms θc has to be on the order of 20 to 60 days, depending on the temperature, in order to prevent the active organisms from being washed out and process failure occurring. θ is also large, and reactor volumes are substantial, leading to low volumetric gas production rates.

In order to reduce reactor volume, a unit known as the immobilized growth digester has been evolved. One of the earliest and simplest types of this design was the anaerobic filter. This typically consists of a tall reactor (H/D = 8-10) filled with media on or in which the organisms can grow or become entrapped (see Figure 4.6). Media used have varied from river pebbles (void volume = 0.5) to plastic media (0.9), although any material which provides a high surface area per unit volume is suitable. The media of choice depends on considerations such as cost, void volume, availability and weight. The waste to be treated is usually passed upward through the filter, and exits through a gas syphon, although downflow configurations can be used. The organisms growing in the filter consist of two sorts: those attached to the media, and those entrapped in a suspended form within the interstices of the media. At low hydraulic loading rates both sorts are prevalent, while at high hydraulic loads the suspended organisms are washed out leaving only the attached forms. Due to entrapment and attachment, high θc's are possible at very low hydraulic detention times (θ).

Figure 4.6. Anaerobic Filter.

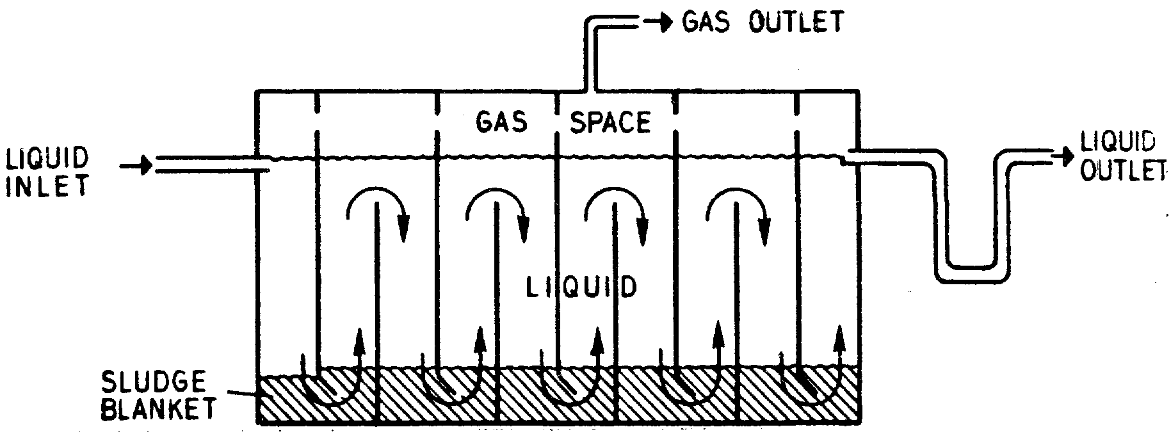


Because of the physical configuration of the filter, only soluble wastes can be treated without blockage, although a diluted pig waste has been treated successfully with a total solids content of 2.0% (Chavadej, 1980). Waste strengths from 480 milligrams per liter of COD up to 90,000 milligrams per liter of COD have been treated in filters, and detention times as low as 9 hours, based on void volume, are possible with COD removals of 80% (Young and McCarty, 1969). However, more typical detention times are on the order of one to two days (Arora and Chattopadhya, 1980), and at these times over 90% COD removals are possible. Loading rates as high as seven kilograms of COD per cubic meter per day are possible, and under these conditions volumetric gas production rates of four volumes of gas per volume of digester per day have been measured (Xinsheng et al., 1980).

Anaerobic Baffled Reactor

This design, which is very recent, was evolved by Bachmann and McCarty at Stanford University. The reactor is a simple rectangular tank, with physical dimensions similar to a septic tank, and is divided into five or six equal volume compartments by means of partitions from the roof and bottom of the tank (see Figure 4.7). The liquid flow is alternately upward and downward between the partitions, and on its upward passage the waste flows through an anaerobic sludge blanket, of which there are five or six. Hence the waste is in intimate contact with active biomass, but due to the design most of the biomass is retained in the reactor.

Figure 4.7. Anaerobic Baffled Reactor (ABR).



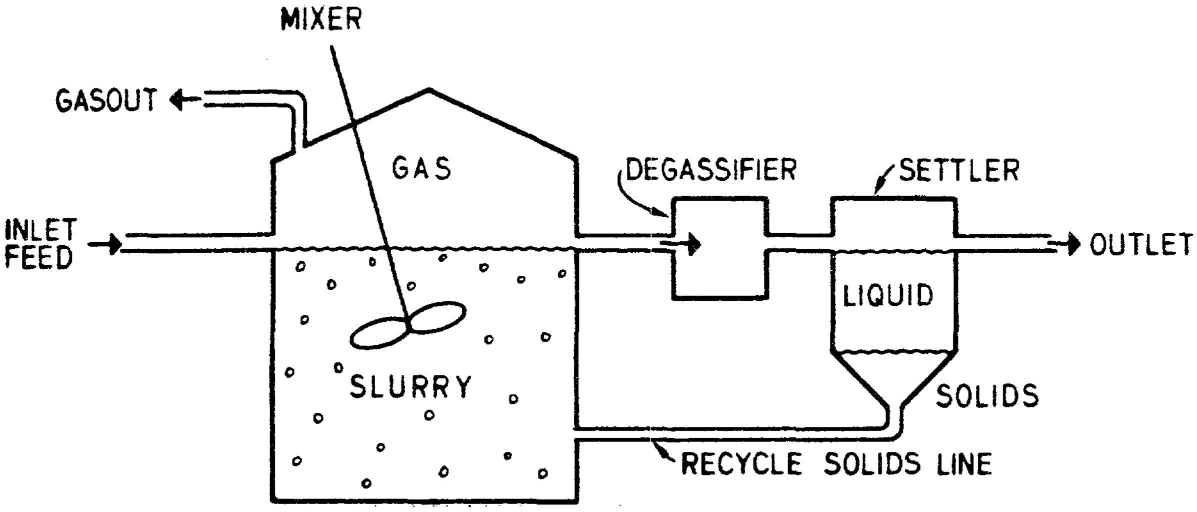
With a soluble waste containing 7.1 grams per liter of COD and a retention time of one day at 35°C, Bachmann et al. (1982) obtained 80% removal efficiencies of COD, with a volumetric gas production of 2.9. Similar tests have been carried out with dilute wastes (0.48 grams per liter of COD) and similar performance was obtained at 25°C. Due to its physical configuration this type of reactor appears to be able to treat wastes with quite high solids contents and hence may be an alternative to anaerobic filters. Since the process is new, little developmental work has has been done on it, but it could be applicable in developing countries in certain circumstances.

Anaerobic Contact Process

This process is similar to the aerobic activated sludge process in that cell recycle is used to maintain high θc at low θ. Hence good removal efficiencies can be obtained with small reactors. Since the anaerobic sludge is still actively producing gas when it exits from the digester, problems have been experienced in getting it to settle quickly. Various methods have been used to get around this problem, and include thermal shock and vacuum degasification (see Figure 4.8).

The first recorded instance of use of the anaerobic contact process occurred in 1955 (Schroepfer et al., 1955) where waste from a meat packinghouse (BOD 1.6 grams per liter) was treated successfully at detention times of only 12 hours at 35°C. BOD removals of 95% were obtained at loading rates of 3.2 kilograms BOD per cubic meter per day, and even at 25°C removals of 95% were achieved. Many food wastes can be treated efficiently using this process. With rum stillage (COD 54.6 grams per liter) removals of 80% were obtained at loading rates as high as 8.0 kilograms COD per cubic meter per day (Roth and Lentz, 1977). Raw sewage (COD 1.2 grams per liter) has been treated at 20°C with low detention times (22 hours) in a contact process, and high removals (90%) were obtained (Simpson, 1971).

Figure 4.8. Anaerobic Contact Digester.

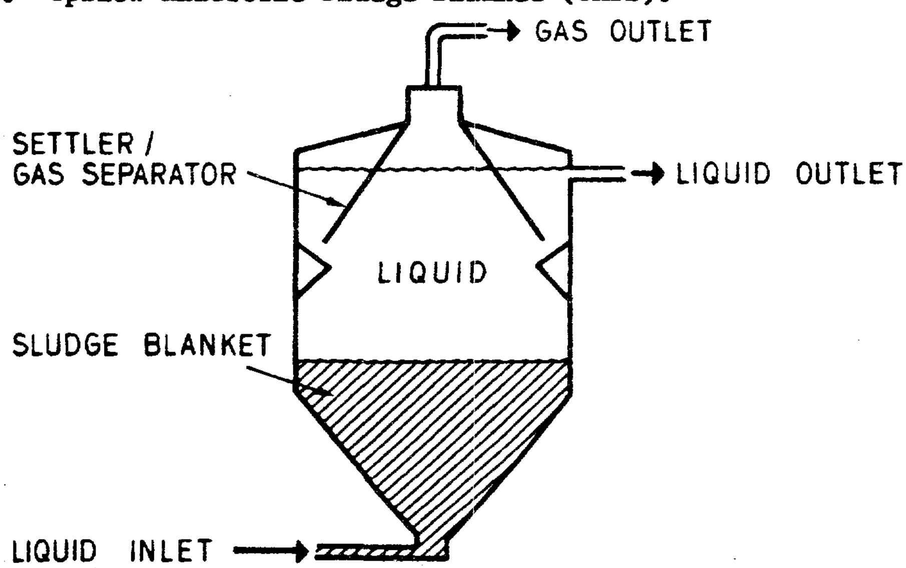


While some full scale plants are currently operating in developed countries, there are no known plants in developing countries. With high strength industrial wastes it would appear that other anaerobic processes (e.g., filter, ABR) would be just as efficient, easier to operate, and require less capital outlay.

__Upflow Anaerobic Sludge Blanket (UASB)__

This process is extremely recent, and was developed by Lettinga et al. (1979, 1980) in the Netherlands. The reactor consists of a circular tank (H/D = 2) in which the waste flows upward through an anaerobic sludge blanket which comprises about half the volume of the reactor (see Figure 4.9). An inverted cone settler at the top of the digester allows efficient solid-liquid separation. During start up the biological solids settle poorly, but with time a granular sludge develops that settles extremely well and the active biomass is retained within the reactor.

Figure 4.9. Upflow Anaerobic Sludge Blanket (UASB).



With predominantly soluble industrial wastes (potato processing wastewater) loading rates as high as 40 kilograms COD per cubic meter per day are possible with detention times as low as 3.5 hours. Under these conditions volumetric gas production figures of 8.0 are possible (Lettinga et al., 1980). Since the process does not use media to maintain the active biomass, total solids content in the feed can be as high as 3.0%.

At present there are approximately 11 full scale plants (100 to 400 cubic meters) in operation in Europe, and a 1,400 cubic meter plant is being constructed in the United States. Operation requires a relatively high degree of sophistication, especially during the critical start up phase. In most cases, alternative designs (filter, ABR) are available with a lower degree of complexity, and most of the advantages of the UASB process.

SIZING OF DIGESTERS

Designing a properly sized digester to maximize biogas production per unit of reactor volume is important in maintaining low capital construction costs. The digester should be sized to achieve desired performance goals, and must be large enough to avoid "washout."

As discussed in Chapter 2, anaerobic digestion depends on the biological activity of slowly reproducing methanogenic bacteria. The bacteria must be given sufficient time to reproduce so they can (1) replace cells lost with the effluent sludge, and (2) adjust their population size to follow fluctuations in organic loading. If the rate of bacteria lost from the digester with the effluent slurry exceeds the growth rate, the bacterial population in the digester will decline or be "washed out" of the system. Washout is avoided by maintaining a sufficient residence time for solids, and thus bacterial cells, within the digester.

Design goals could be the maximizing of gas production with minimal capital investment, achieving pollution control and reduction of pathogens, or simply the production of a reasonable amount of gas with a minimum of operational attention. Criteria must be established prior to design, since not all goals can necessarily be achieved with a single design. Assuming that adequate performance data are available for the feedstock under anticipated operating conditions, the designer can optimize the digester size and other features such as degree of heating and mixing to meet the desired criteria and avoid washout.

Sewage Sludge Digesters

A number of empirical methods have been employed in the design of conventional sewage sludge digesters, where emphasis has been pollution control rather than maximizing gas production. A discussion of sewage sludge digestion is included here since many laboratory and field studies made on this feedstock have led to our present day understanding of the digestion process. Conservative design parameters applicable to sewage sludge treatment, however, result in digester sizes of up to 50% larger than needed for plants designed to maximize methane production.

Design of large installations, particularly those with atypical feedstocks, is based on a fundamental understanding of anaerobic processes which achieve desired performance goals. Large installations can also afford considerable operational attention, allowing process optimization such as control of temperatures to improve gas production rate per unit digester volume.

A major sizing parameter normally used in the design of anaerobic digesters is the mean cell (or solids) residence time, θc. The mean cell residence time is defined as the mass of bacterial cells in the digester divided by the mass of cells removed from the digester per day. For a conventional digester without solids recycle, θc is equivalent to the hydraulic retention time, θ, and is thus directly related to digester volume. It has been found that at a given temperature most digester performance parameters of interest can be correlated with θc, and that washout can be be avoided if θc is maintained above a critical minimum value, θc^m.

Figure 4.10 illustrates the relationship between θc and the performance of a laboratory scale anaerobic digester fed with raw primary sludge. It shows how the production of methane, as well as the reduction of degradable proteins, carbohydrates, lipids, chemical oxygen demand, and volatile solids, are related to θc. As θc is reduced, the concentration of each component in the effluent gradually increases until θc reaches a value beyond which the effluent concentrations rapidly increase. This breakpoint indicates the θc at which washout of microorganisms begins; that is, the point at which the rate the organisms leave the system exceeds their rate of reproduction. If θc is lowered to a critical point, the process will fail completely.

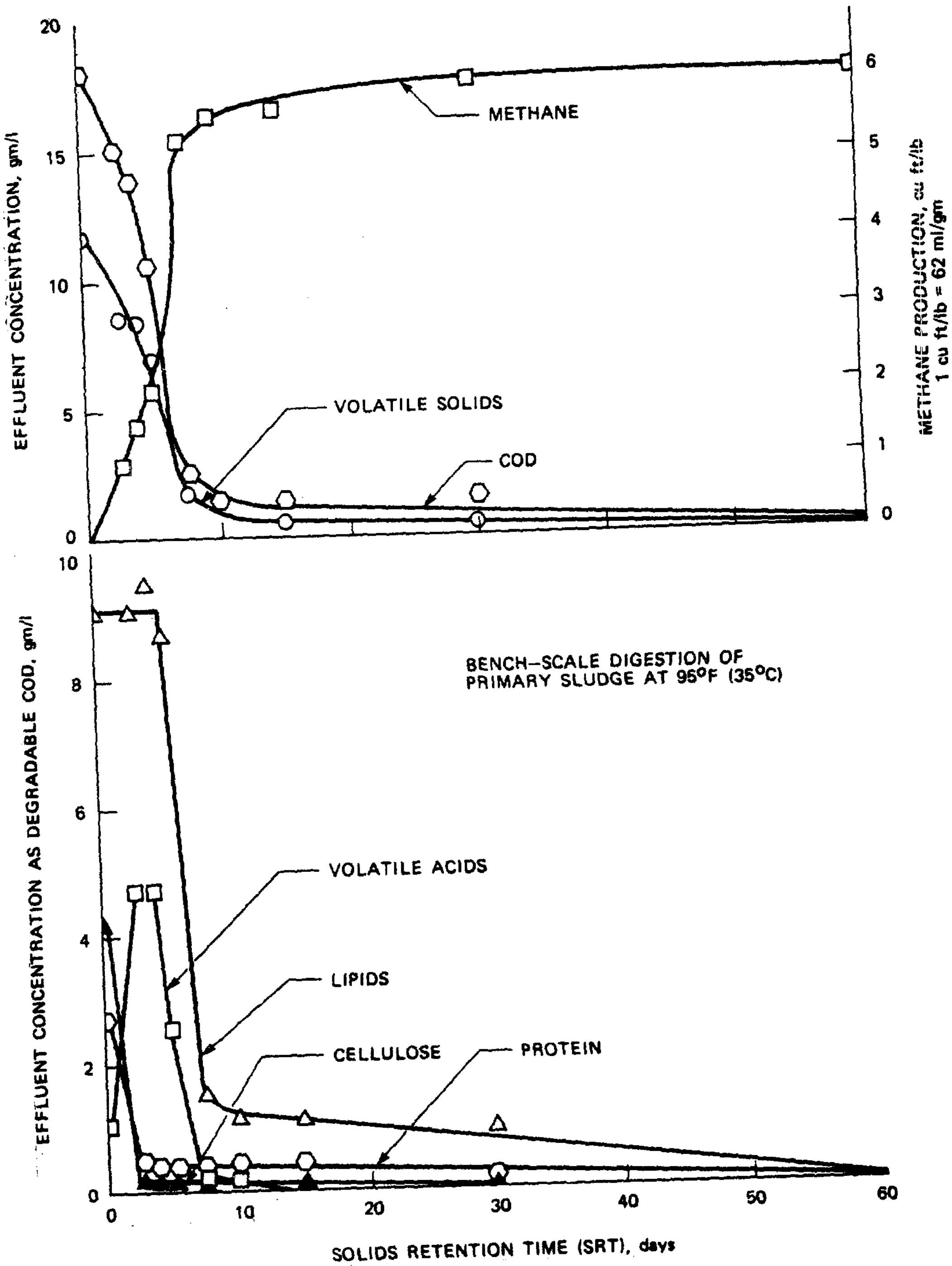
Temperature has an important effect on bacterial growth rates and, accordingly, changes the relationship between θc and digester performance. The critical mean cell residence time, θc^m, is also affected by temperature. O'Rourke (1968) found that the θc^m for the digestion of primary sewage sludge in a bench scale digester was 4.2 days at 35°C (95°F), 7.0 days at 25°C (77°F), and 10.1 days at 10°C (50°F). For sewage sludge digestion, it is normally recommended that the design θc be at least 2.5 times θc^m to provide a margin of safety for process stability.

In industrialized countries, heating of digesters is common practice and the trend has been toward thermophilic digestion, while in developing countries digesters are usually operated at ambient temperatures. Because the anaerobic digestion process essentially stops at 10°C, the digester contents must be maintained at a temperature higher than this for significant gas production. Therefore design is based on critical temperature periods of the year, using anticipated temperature within the digester rather than ambient air temperature.

Digestion of Agricultural Residues

Anaerobic digesters can utilize a large number of organic materials as feedstocks. These include animal manures, human wastes, crop residues, food processing and other wastes, or mixtures of one or more of these residues and wastes.

Figure 4.10. Effect of θc on the Relative Breakdown of Degradable Waste Components and Methane Production. (Source: Adapted from U.S. EPA, 1979; and O'Rourke, 1968.)



Animal manures are often selected as feedstocks because of the large quantities available throughout the world. They exhibit good nutrient balances, are easily slurried and are relatively biodegradable. The range of biodegradability reported varies from 28 to 70%. This variation is partly due to the diet of the animals. For example, Hashimoto et al. (1981) showed that as the percentage of silage is increased over the amount of ground corn, the degradability of the manure decreases, since silage contains a high percentage of lignocellulosic materials. Thus in developing countries where cattle are fed agricultural wastes the manure is less biodegradable than at cattle feedlots in the United States.

Jewell et al. (1981) reported that a dairy cow weighing about 450 kilograms produces approximately 39 kilograms of manure and urine per day, which contains about 4.8 kilograms total dry solids (see Table 4.2). Larger or smaller cows will produce wastes in similar proportions.

Table 4.2. Estimated Manure and Biogas Production Rates. Based on 450 kilograms liveweight.

	Dairy Cattle	Beef Cattle	Pigs	Chickens	Humans
Manure Production kg/day	39	26	23	27	11
Total Solids kg/day	4.8	3.4	3.3	7.9	≈ 1.0
Volatile Solids kg/day	3.9	2.7	2.7	5.8	≈ 0.6
Digestion Efficiency %	35	50	55	65	50
Gas Production l/kg influent VS*	219	325	381	490	—

Note: Values may vary from these due to differences in feed ration and management practices.

*Based on theoretical biogas production rate of 831 liters per kilogram of volatile solids destroyed, and assuming the CH_4:CO_2 ratio is 60:40 and conversion of volatile solids to COD is 1.42.

Reference: Adapted from Jewell et al. (1981).

Fresh manure is much more biodegradable than aged and/or dried manure because of the substantial loss of volatile solids over time. Table 4.3 shows the effects of type of holding area and frequency of collection on composition of cattle manure.

Table 4.3. Composition of Cattle Feedlot Manures.

	Paved and Covered Lot	Paved Lot (manure collected at 1-3 mo. intervals)	Dirt Lot (manure collected at 2-6 mo. intervals)
% Water	85	65	29
% Total Solids	15	35	71
Volatile Solids (% of Total Solids)	78	67	35
Manure Production--Total Solids--kg/animal/day	4.5	2.6	4.4*

*Includes dirt from feedlot when dry manure is collected.

Reference: Adapted from Schmid (1975).

Digester Design Emphasizing Methane Production

Gas production rates per unit volume of digester, sometimes known as specific yield, are often used in design analyses. Chen and Hashimoto (1978) adapted the Contois (1959) kinetic model to describe the mathematical relationship which would allow one to predict volumetric methane production:

$$V_s = (B_o S_o/HRT)\ [1 - K/(HRT \cdot \mu_m - 1 + K)]$$

where:

V_s = specific yield (volumetric methane production rate in cubic meters per day per cubic meter of digester);
B_o = ultimate methane yield in cubic meters of methane per kilogram of volatile solids added;
S_o = influent volatile solids concentration in kg/m^3;
HRT = hydraulic retention time in days;
K = a dimensionless kinetic coefficient; and
μ_m = maximum specific growth rate of the microorganism in day^{-1}.

The equation states that for a given influent volatile solids concentration and a fixed hydraulic retention time, the volume of methane produced per cubic meter per day varies with the ultimate methane yield of feedstock, the maximum growth rate of the microorganisms and the kinetic coefficient. The ultimate yield of methane which would result from the breakdown of volatile solids fed to the digester is obtained by multiplying B_o times S_o. The specific yield for the design time (HRT) is determined by multiplying the correction coefficient $[1 - K/(HRT \cdot \mu_m - 1 + K)]$ times the $B_o S_o$ value. This coefficient takes into account the effects of temperature and concentration of the solids upon the breakdown of the solids. At low detention periods a negative correction coefficient is obtained which indicates digester failure (washout).

Hashimoto et al. (1981b) reported the following values for B_o:

Beef Manure--Grain Ration, Concrete Slab	0.35 (±0.05)
Beef Manure--Grain Ration, Dirt Lot	0.25 (±0.05)
Dairy Cattle Manure	0.20 (±0.05)
Pig Manure	0.50 (±0.05)

These values also indicate that ultimate gas production per kilogram of volatile solids fed to digesters will vary with both animal type and diet. For example, pig manure is more digestible than manure derived from dairy cows fed a highly lignocellulosic diet.

In the above equation Hashimoto et al. developed K values for specific feedstocks. For example:

$K = 0.8 + 0.0016e^{0.06\ S_o}$ for cattle manure; and

$K = 0.5 + 0.0043e^{0.091\ S_o}$ for pig manure.

The relationships between growth rate of digester microorganisms and temperature were expressed as:

$$\mu_m = 0.013(T) - 0.129$$

where T is the digester temperature in °C. This equation shows that the anaerobic digestion process essentially ceases at 10°C. Values of μ_m were determined empirically by using temperatures between 20 and 60°C, and the equation was developed based upon a fit of the data within this temperature range.

References to volumetric efficiencies are available in the literature, as seen in Table 4.4, or can be developed from laboratory studies of particular feedstocks.

Table 4.4. Reported Volumetric Efficiencies at Temperatures between 27°C and 35°C. Cubic Meters of Gas per day/Cubic Meter of Digester.

Type	Volume per day/ Digester Volume	HRT Days	°C	Feedstock	Reference
Batch	0.35	40	27	Elephant grass	Boshoff (1965)
Continuous	0.83	40	27	Elephant grass	Boshoff (1965)
	1.0	30	31	Swine manure	Maramba (1978)
	0.79	60	35	Grass	Jewell (1981)
	0.2	365	35	Grass	Jewell (1981)
Chinese	0.1-0.2	>60	25	Manure/nightsoil/crop residues	Chan U Sam (1982)
Indian	0.2-0.3	50	27	Cattle manure 9% solids	ESCAP (1980)

Reference: Adapted from Ward (1984).

Use of the concept of volumetric efficiencies, expressed as the volume of methane produced per day per cubic meter of digester capacity, leads to design analyses which optimize methane production by using small and therefore low cost digester units. For mixed systems, volumetric efficiency (specific volume) increases with (1) increasing operating temperatures, (2) increasing percentage of volatiles and thus decreasing age of feedstock, (3) decreasing particle size, and (4) increasing percentage of solids in the feedstock. In general, up to about ten percent solids can be readily handled with conventional sewage sludge pumps. Higher percentages, up to about 20 percent, can be pumped at thermophilic temperatures (~60°C) according to Marchaim (personal communication, 1982) because of improved rheological properties of the feedstock. This method of analysis, and comparison with other methods of sizing digester facilities, is discussed below.

Design Example—Digester Size Determination

Given

A dairy farmer has ten cows which weigh an average of 450 kilograms each. They are confined so that the manure and urine can be collected for digestion to produce methane in a cost effective manner. Each cow produces an average total volume of manure and urine of 40 liters containing five kilograms of total solids on a daily basis. The fresh feedstock volatile solids concentration is 80% of the total solids.

Required

Provide design analysis to determine the appropriate size digester and the amount of methane produced when operating at 20°C and/or 35°C for the following cases:

1. Fresh manure and urine, collected daily;
2. Manure collected at one to three month intervals, animals on concrete slab;
3. Manure collected at two to six month intervals and often mixed with dirt, animals in dirt pens;
4. Fresh manure, five large biogas facilities at dairies;
5. Fresh manure, floating cover Indian type digester;
6. Chinese type digester; and
7. Fresh manure, conventional volatile solids loading criteria.

Solution

The following design approaches are based upon a review of numerous digesters designed to maximize energy production, which was presented at the 1984 Cairo Conference, State of the Art on Biogas Technology, Transfer and Diffusion (Ward, 1984).

Case 1—Fresh Manure and Urine, Collected Daily

Assume that the ten cows weighing 450 kilograms each are held in a covered pen where the fresh manure and urine can be transferred directly to the digester. The feedstock volume is 400 liters per day, containing 50 kilograms of total solids (dry basis). Under fresh manure conditions the solids are 80% volatile, for a total volatile solids loading per day of 40 kilograms.

Using the volumetric methane production equation described above, the following values would be used:

B_o = 0.20 cubic meters of methane per kilogram of influent volatile solid (see chart above for dairy cattle);

S_o = 40 kilograms influent volatile solids per 400 liters, or 100 kilograms per cubic meter;

HRT = variable, ranging from 10 to 50 days;

$K = 0.8 + 0.0016e^{0.06(100)}$, or 1.445; and

$\mu_m = 0.013(20) - 0.129$, or 0.131, for 20°C,
$0.013(35) - 0.129$, or 0.326, for 35°C, and
$0.013(55) - 0.129$, or 0.586, for 55°C.

Based on these values, the equation for a ten day retention time at 20°C would be:

$$V_s = (B_o S_o/HRT)\,[1 - K/(HRT \cdot \mu_m - 1 + K)]$$

$$V = [(0.20)(100)/10]\,[1 - 1.445/((10)(.131) - 1 + 1.445)]$$

Solving the equation similarly for detention times of 10, 20, 30, 40 and 50 days, and at temperatures of 20 and 35°C, results in the values shown in Table 4.5.

Table 4.5. Relationship among Temperature, Digester Size and Methane Production--Case 1.

HRT (days)	Digester Volume (cubic meters)	Specific Yield (cubic meters per day/ cubic meter of digester volume) 20°C	35°C	55°C	Methane Production (cubic meters per day) 20°C	35°C	55°C
5	2	washout	washout	2.6	washout	washout	5.2
10	4	0.36	1.22	1.54	1.44	4.88	6.16
20	8	0.53	0.79	0.88	4.24	6.32	7.04
30	12	0.45	0.57	0.61	5.40	6.84	7.32
40	16	0.37	0.44	0.47	5.92	7.04	7.52
50	20	0.31	0.36	0.38	6.20	7.20	7.60

Table 4.5 indicates that if the temperature in the digester were maintained at 35°C, an optimum design size would be a volume sufficient to provide an HRT of approximately 10 days, since the highest daily methane production rate per cubic meter of digester occurs at this loading. Heating a digester for ten cattle, however, would require equipment and controls excessive for the size of the facility. (In general, heating to 35°C--mesophilic temperatures--is justified for 30 or more cattle and to 55°C--thermophilic--for 50 or more.) For this Case 1, an unheated 20°C digester would be more appropriate. Based on this data, at a temperature of 20°C, an HRT of 20 days would be appropriate since the specific yield of methane production per day is highest at this HRT.

The above HRT values of 10 and 20 days are only first approximations to determine the range of digester sizes for maximum production of methane per cubic meter of digester capacity. Using smaller increments of HRT and the previous equations, the data in Table 4.6 show that the optimum digester size at 20°C would be the capacity for an HRT of 17 days, at which size the specific yield would be 0.56 cubic meters of methane per day per cubic meter of digester. The data also indicate the digester would not function at an HRT of less than eight days because of washout of methane forming organisms.

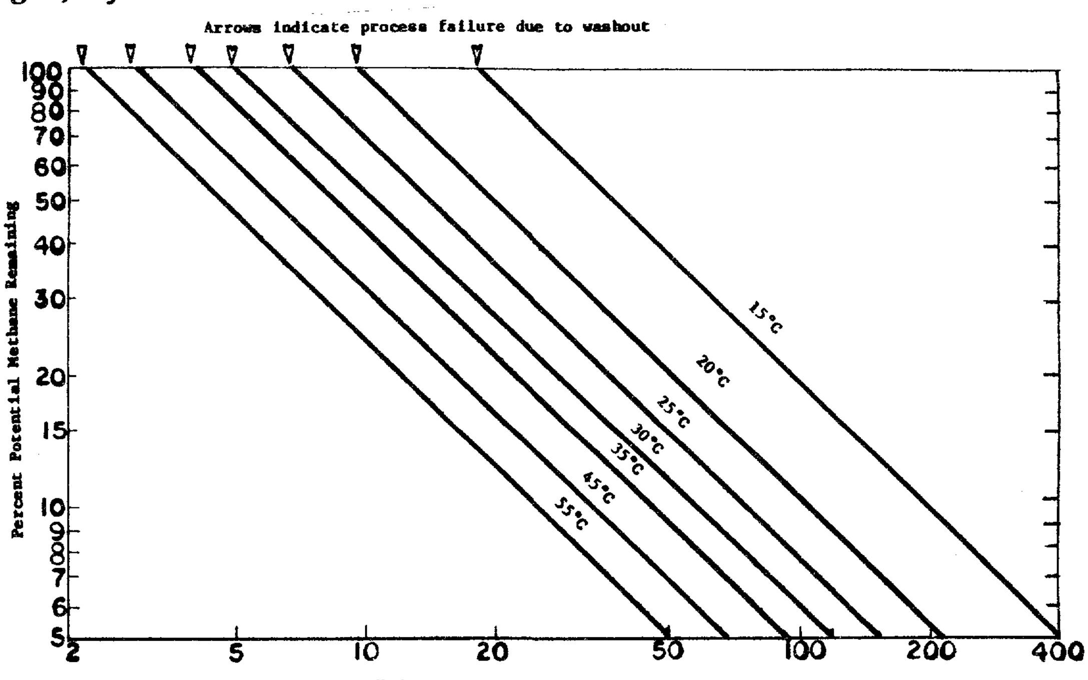
By developing cost data for each size of digester and giving the gas produced a value, one can select the appropriate size for maximum return on the biogas energy investment. While Table 4.6 shows that highest volumetric methane production rate occurs at an HRT of 17 days, the rates continue to be nearly optimum at an HRT of 20 days (eight cubic meters). Increasing the size of the digester by 50% from eight to 12 cubic meters, increases gas production by 27%.

An HRT slightly greater than the 17 day optimum methane production value shown in the table, such as 20 days, would be used because of the sensitivity of the methane forming bacteria to temperature and the ease with which they could become upset due to environmental changes at temperatures near 20°C.

Table 4.6. Relationship between Digester Size and Methane Production. Case 1--20°C, Fresh Manure.

HRT (days)	Digester Volume (cubic meters)	Specific Yield (cubic meters per day/ cubic meters of digester volume)	Methane Production (cubic meters per day)
7	2.8	no gas--washout	no gas--washout
8	3.2	0.14	0.44
9	3.6	0.20	0.88
10	4.0	0.36	1.44
11	4.4	0.42	1.84
12	4.8	0.46	2.24
13	5.2	0.50	2.60
14	5.6	0.52	2.92
15	6.0	0.53	3.20
16	6.4	0.54	3.44
17	6.8	0.56	3.80
18	7.2	0.54	3.88
19	7.6	0.54	4.04
20	8.0	0.53	4.24
21	8.4	0.52	4.36
22	8.8	0.51	4.52
23	9.2	0.50	4.64
24	9.6	0.50	4.76
25	10.0	0.49	4.88
26	10.4	0.48	5.00
27	10.8	0.47	5.08
28	11.2	0.46	5.20
29	11.6	0.45	5.24
30	12.0	0.45	5.28
**			
40	16.0	0.37	5.92
**			
50	20.0	0.31	6.20

Figure 4.11. Interrelationships between Hydraulic Retention Time, Operating Temperature, and Methane Production in Anaerobic Digestion (Biogas) Systems for Cattle Manure.



An alternative and rational approach to digester design is to fix the minimum percentage for recovery of methane for the feed. Results of calculations, based on the modified Contois (1959) model and Hashimoto's (1981) equations and rate coefficients for cattle manure, are presented in Figure 4.11. A methane rcovery of 50 percent can be obtained with a hydraulic retention time of 4 1/2 days at 55°C or 37 days at 15°C. If the HRT is 30 days, 40 percent will be recovered at 15°C and 92 percent at 55°C. A design can then be based on local climate, construction costs, and insulation efficiencies at the high operating temperatures.

Optimization of methane production per cubic meter of digester capacity must allow a margin of sizing safety equal to several days additional retention beyond "optimum" to ensure that occasionally stressful environmental conditions will not upset maintainance of a viable methanogenic bacterial population. The extremely large safety factor used in conservatively designed sewage sludge digesters to enhance pathogen destruction and pollution control of even toxic feedstock is not the most cost effective for methane production. Therefore desired results must be determined prior to making sizing decisions.

Case 2—Manure Collected at One to Three Month Intervals, Concrete Slab

This case assumes that the cows are held in an area which is paved to provide an impervious surface. Since the period between collections may typically vary from one to three months, the manure dries partially prior to collection. During drying some of the volatile solids are destroyed by aerobic breakdown, thereby reducing potential methane production. Since the manure is partially dry, water is added to create a slurry prior to transfer of the feedstock to the digester. After slurrying, the total dry solids are assumed to be 10%.

Because urine is not totally collected and due to partial loss of volatile solids through aerobic oxidation, the total solids collected can be assumed to be 2.6 kilograms per day per cow and the volatile solids concentration is reduced to about 65% of the total solids (see Table 4.4). Assuming that dairy manure behaves like feedlot manure:

Total solids = 10 cows times 2.6 kilograms per cow = 26.0 kilograms per day, contained in 260 liters per day; and
Volatile solids = 65% of 26.0, or 18.6 kilograms per day.

Ultimate gas production from beef cattle manure which has partially dried is about 70% that of fresh manure (Hashimoto et al., 1981b). Therefore:

B_o = 70% of 0.20, or 0.14;
S_o = 18.6/0.26, or 71.5;
HRT = 10 to 50 days;
$K = 0.8 + 0.0016e^{0.06(71.5)}$, or 0.916; and
μ_m = 0.131 for 20°C,
0.326 for 35°C, and
0.586 for 55°C.

Table 4.7. Relationship between Digester Size and Methane Production--Case 2.

HRT (days)	Digester Volume (cubic meters)	Specific Yield (cubic meters per day/ cubic meter of digester volume) 20°C	35°C	55°C	Methane Production (cubic meters per day) 20°C	35°C	55°C
5	1.3	washout	0.80	1.30	washout	1.04	1.69
10	2.6	0.25	0.71	0.83	0.64	1.84	2.17
20	5.2	0.32	0.43	0.46	1.66	2.23	2.39
30	7.8	0.25	0.30	0.31	1.96	2.35	2.45
40	10.4	0.21	0.23	0.24	2.19	2.40	2.48
50	13.0	0.17	0.19	0.19	2.20	2.45	2.51

Using the same equation for methane production as for Case 1, the values in Table 4.7 are obtained.

These data indicate that digestion of aged animal manure is most cost effective using retention times of approximatley ten days for mesophilic conditions and 20 days at 20°C. Daily methane production figures provide little incentive to construct energy producing plants with capacities larger than ten to twenty day retention times for 35°C and 20°C operations respectively, because incremental methane production increases do not warrant the higher investment required. Further refinement of size requirements can again be produced using smaller HRT increments, as was done in Table 4.6.

Note that the digester sizes in Table 4.7 are smaller than in Table 4.5, because of reduced available slurry. The lower volatile solids content resulted in substantially less methane production at either temperature, as well, demonstrating the advantage of using the freshest possible feedstock.

Case 3--Manure Mixed with Dirt as Collected at Two to Six Month Intervals, Dirt Pens

In Case 3, assume that the cows are held in a dirt pen where manure dries partially prior to collection, then is slurried to 10% solids before being used as feedstock in the digester. In a dirt feedlot, substantially all of the urine is lost, and there are often two to six months between manure production and collection, with considerable volatile solids destruction via aerobic oxidation prior to digestion. This results in a lesser quantity of manure yield per animal, and less methane per kilogram of feedstock. Site specific studies may be needed to determine precise feedstock characteristics, but for the purpose of this case we will assume criteria based on the data of Schmid (1975), Table 4.3, which indicates that after two to six months the volatile solids concentration is 35% of total solids, including dirt, or 1.08 kilograms per day per cow (10.8 kilograms per day for ten cows).

In developing countries dirt pens are usually used for cattle confinement, but since little if any mechanized equipment is used for manure collection there would be only a minumum amount of dirt associated with the manure. Utilizing data from Tables 4.3 and 4.4 on the effects of aging beyond that of Case 2 on the characteristics of the feedstock, and an essential lack of dirt in the manure in developing countires, the total and volatile solids yield per cow are assumed to be 1.8 and 1.08 kilograms per day, respectively. For ten cows this becomes 18 and 10.8 kilograms per day and at a slurry concentration of 10% the volume added to the digester is 180 liters per day.

Using the Hashimoto et al. (1981b) figure of 70% reduction in methane gas production from aged compared with fresh manure, the factors become:

B_o = 0.14;

S_o = 10.8/.180, or 60;

HRT = 10 to 50 days;

K = $0.8 + 0.0016e^{0.06(60)}$, or 0.86; and

μ_m = 0.131 for 20°C,
0.326 for 35°C, and
0.586 for 55°C.

The relationships between digester volume and methane production, in accordance with the volumetric methane production equation, are shown in Table 4.8.

Table 4.8. Relationship between Digester Size and Methane Production--Case 3.

HRT (days)	Digester Volume (cubic meters)	Specific Yield (cubic meters per day/ cubic meter of digester volume) 20°C	35°C	55°C	Methane Production (cubic meters per day) 20°C	35°C	55°C
5	0.9	washout	0.63	1.16	washout	0.57	1.04
10	1.8	0.22	0.60	0.68	0.40	1.08	1.23
20	3.6	0.27	0.36	0.38	1.98	1.29	1.37
30	5.4	0.22	0.25	0.26	1.18	1.36	1.41
40	7.2	0.17	0.20	0.20	1.23	1.44	1.44
50	9.0	0.15	0.16	0.16	1.35	1.44	1.45

As in Cases 1 and 2, the most efficiently sized digesters, according to Table 4.8, would have retention times of approximately 20 and 10 days when operated at 20 and 35°C respectively. At these retention times the specific yields are 0.27 and 0.60 cubic meters of methane per cubic meter of digester capacity at the two temperatures. Using detention periods of 10 day increments in the calculations provide only the first approximations of the proper size digesters to maximize specific yield of methane per cubic meter of digester, as stated previously, and the sizing can then be refined by calculating specific yields at shorter detention time increments, as shown in Table 4.6.

Cases 1, 2 and 3 show the impacts of different feedstock collection methods on methane production. Note that as the volatile solids concentration, S_o, decreases under the effects of age and aerobic action, much of the power to produce methane is lost prior to its use in the digester, with a loss in digester production. These data emphasize the need to the use freshest possible feedstock for maximum methane production.

Case 4--Fresh Manure, Five Large Biogas Energy Facilities at Dairies

As biogas energy technology has improved over the past decade, increasing numbers of facilities are being constructed at dairy farms as private investments for the primary purpose of energy production. Described in this section as Case 4 are five such installations in the United States, as reported by Mullan et al. (1984). The installations represent investments by independent farmers and practical business people, and energy production must measure up to the rigors of performance imposed by profit motivated farm managers/owners.

Design and operating parameters include the following:

a. Fresh manure is fed to the digesters daily;
b. The feedstock is 10 to 12% solids, with volatile solids making up 80% or more of the total solids;
c. No toxic substances are included in the feedstock;
d. The pH of the feedstock must be 7.0 to 7.2;
e. The digester temperature is maintained at 35°C ±2°C; and
f. Typical retention time is 15 days.

The methane produced is used for one or several of the following purposes at the five plants:

a. Heating to maintain mesophilic operating temperature;
b. Heating for on-farm use such as hot water, drying, and pasteurization; and
c. Generating electricity.

Uses of the digested solids include fertilizer, bedding, and refeeding back to the animals.

Table 4.9 lists design and operating data for the five facilities. The design data can be compared with Case 1 above, where fresh manure is digested at 35°C and the size (cost) of the facility is made as small as possible to optimize methane production per unit volume of digester. Hydraulic retention times are about 15 days, except for one facility, and the specific yields are approximately 1.0 cubic meter of methane per day per cubic meter of digester volume.

Table 4.9. Design and Operating Data for Five Large Dairy Manure Digesters--Case 4. (After Mullan et al., 1984.)

Farm	Number of Animals	HRT (days)	Digester Capacity (cubic meters)	Specific Yield (cubic meters per day/ cubic meters of digester volume)
Colorado State University	400	15.4	450	1.00
Mason-Dixon	1,200	24.0	1,590	0.75
Baum Dairy	800	15.9	680	0.96
Walker Crech	900	15.0	900	1.10
Carrell Bro.	300	14.3	450	0.94

Comparing Tables 4.5 and 4.9 reveals that the HRTs used for large successful operating digesters are between the 10 and 20 day retention periods in Table 4.9, as is the volumetric methane production rate. As discussed above with respect to Table 4.6, it is important not only to optimize the digester size in order to achieve maximum methane production per unit volume of digester capacity, but it is also necessary to provide a sufficient margin of safety to allow for occasional environmental stress within the digester caused by such conditions as temperature variations and irregular periods and volumes of digester loadings. From these data we can see that the five large units are designed so as to optimize methane production in a cost effectiove manner.

Case 5—Fresh Manure, Floating Cover Indian Type Digesters

A number of guidelines are available which discuss the design of Indian type floating cover digesters. These include the Guidebook on Biogas Development (1980) published by the Economic and Social Commission for Asia and the Pacific, Methane Generation from Human, Animal, and Agricultural Wastes by the National Academy of Sciences (1977), and others. These are all largely based upon KVIC publications.

Nearly all biogas plants in India are designed for average ambient temperature operation, which is taken to be 27°C. Note that the monthly average summer temperatures are reported to vary from about 28°C in the south to as much as 35°C in the Deccan Plain. Corresponding winter temperatures range from 26°C to about 10°C at elevations below 300 meters (Walter et al., 1975). The approach has been to select a gas production rate for the digester based on the type of feedstock. For example, with the Indian design ESCAP has assumed that one kilogram of as-received cattle manure mixed with one liter of water will produce an average 36 liters of biogas per day over a 50 day digestion period at 27°C.

The KVIC model is conservative. First, the assumption that 50 days are required at 27°C to produce 22 to 40 liters of biogas per kilogram of manure does not take into account the feedstock's biodegradability or age. Fresh manure is more digestable than dried manure, and although the feedstock is assumed to be relatively fresh, in many cases it has been subjected to considerable drying and aerobic biological action prior to collection. Second, data by O'Rourke (1968) and others indicate that at 27°C approximately 80% of the digestible matter is degraded in 15 days, and 90% in 30 days. Third, the assumed addition of one liter of water per kilogram of manure will produce a total solids concentration of 3 to 12% depending on the age of the manure. Marchaim (1982) reports operating digesters at 16 to 18% solids. The least amount of water necessary to make up the slurry should be used to keep the digester to a minimal size.

Recent publications indicate the Indian design criteria is changing to HRTs of 30 days for south India, 40 days for central India, and 55 days for the cooler mountain areas.

Using the given conditions of ten cows producing 400 liters of manure per day, the volume of an Indian style digester with a 50 day retention time is determined by adding an equal amount of water to the manure and multiplying by 50 days. The size in this case is 0.4 cubic meters times two times 50 equals 40 cubic meters. Forty and 30 day retention times would require 32 and 24 cubic meter digesters, respectively. These sizes are all substantially larger than even the approximately twenty cubic meters required when optimizing the design for biogas production at a temperature as low as 20°C, as discussed in Case 1.

Daily biogas production from an Indian style unit would be 36 liters per day per kilogram of fresh manure times 400 kilograms per day, or 14.4 cubic meters, of which 8.6 cubic meters would be methane (60:40 methane to carbon dioxide ratio). This would result in a volumetric methane production rate of 0.17 cubic meters of methane per day per cubic meter of digester capacity, as compared with 0.53 cubic meters of methane per cubic meter digester capacity at an HRT of 20 days at 20°C (see Table 4.5). Comparison of volumetric methane production values also demonstrates the conservative nature of the Indian style design.

Case 6—Chinese Style Digesters

Translations of The Chinese Biogas Manual are available in many languages. In its English translation (van Buren, 1979) this manual describes the objectives of the initial development of the Chinese Digester: to dispose of human excreta to prevent disease; to produce a soil conditioner and fertilizer; and to provide energy which could be used for cooking.

In many areas of China both manure and nightsoil are applied to agricultural land as soil conditioners. Digesters are made large to provide storage, which minimizes loss of ammonia nitrogen from animal and human wastes prior to application. Slurry is removed twice a year for use. Therefore storage is a primary design criterion and the volumetric efficiency for methane production does not apply.

Normal size criteria are 1.5 to two cubic meters of digester volume per person contributing nightsoil, and one cubic meter per approximately 20 kilograms liveweight of pigs on premises. Additional volume may be required for other animal wastes and agricultural crop residues added.

Table 4.2, which includes data on cow and pig manure production based on 450 kilograms liveweight, indicates that more cow than pig manure is produced at the same animal weight. Therefore 10 cows weighing a total of 4,500 kilograms produce more digester feedstock than their equivalent weight of pigs. Designing according to the criteria above would produce so large a digester as to have little relationship to the concept of design to optimize biogas production. Biogas becomes merely a useful additional benefit to pathogen destruction, soil conditioning and storage.

Case 7—Fresh Manure, Conventional Volatile Solids Loading Criteria

A standard design criterion for sizing mesophilic sewage sludge digesters is the weight of volatile solids which are fed daily per unit volume of digester capacity. So-called "high rate" digestion uses from 2.4 to 6.4 kilograms of volatile solids per day per cubic meter of digester capacity. In our given design problem, the volatile solids loading from ten cows is forty kilograms per cubic meter per day (dry basis). The highest volatile solids loading criterion from Table 4.2 results in a digester volume of 40 divided by 6.4, or 6.25 cubic meters. From Table 4.6, optimal biogas production efficiency requires a digester of approximately four cubic meters. Use of traditional parameters results in digesters oversized by at least 50%, which is not cost effective for biogas production.

COMPARISON OF ALTERNATIVE DESIGN APPROACHES

Table 4.10 presents digester sizes calculated according to criteria for Indian (KVIC), USEPA (1979), Mullan *et al.* (1984), and this report. The 27°C temperature is based upon current Indian practice. Both the Indian and USEPA approaches result in larger and, from an operating stability standpoint, conservative sizes. As previously noted, rational designs of digestion systems can be based upon data such as that in Figure 4.10.

Table 4.10. Comparison of Calculated Digester Sizes Operating at 27°C Ambient Temperatures.

CASE	INDIAN (KVIC)[a]			WARD/SKRINDE[b] (this report)			USEPA (1979)[c]		SHAEFFER/MULLAN*		
	Size m^3	HRT days	CH_4 m^3 day	Size m^3	HRT days	CH_4 m^3 day	Size m^3	HRT days	Size m^3	HRT days	CH_4 m^3 day
Case 1 & 5 Fresh Manure 10 cows[d]	40	50	3.6	3.6	10	3.6	40	100	6	15	3.6
Case 2 Manure, Concrete Slab 10 cows[d]	13	50	2.5	2.6	10	1.5	20	78	-	-	-
Case 3 Manure and Dirt 10 cows[d]	9	50	1.3	1.8	10	0.88	10	50	-	-	-
Pig Manure Fresh 75 to 80 pigs[e]	30	50	0.8	5.0	10	7.88	28	55	-	-	-

a Based on ESCAP (1980) using 27°C.
b Based on Hashimoto equations using 27°C.
c Based on equivalent size assuming 80 grams per capita per day solids from 90 people weighing 4,500 kilograms.
d Assumes 4,500 kilograms total cattle weight (average 450 kilograms per animal).
e Assumes 4,500 kilograms total live weight, manure collected fresh and flowing by gravity to a digester (with 260 liters water per day to overcome inhibition). The S_o resulting is 54 Kg/M^3.
* Mullan *et al.*, 1984.

CHAPTER FIVE

OUTPUTS AND THEIR USES

COMPOSITION AND USES OF BIOGAS

Composition

The proportion of methane to carbon dioxide in biogas depends on the substrate, and can be predicted by the Symons and Buswell's equation.[1/] Factors such as temperature, pH and pressure can alter the gas composition slightly. Typical gas compositions for carbohydrate feeds are 55% methane and 45% carbon dioxide, while for fats the gas contains as much as 75% methane.

Pure methane has a calorific value of 9,100 kilocalories[2/] per cubic meter at 15.5°C and one atmosphere; the calorific value of biogas varies from 4,800 to 6,900 kilocalories per cubic meter. In terms of energy equivalents, 1.33 to 1.87, and 1.5 to 2.1 cubic meters of biogas are equivalent to one liter of gasoline and diesel fuel respectively. Biogas has an approximate specific gravity of 0.86 (air = 1.0), and a flame speed factor of 11.1, which is low, and therefore the flame will "lift off" burners which are not properly designed (ESCAP, 1980).

Domestic Uses

The primary domestic uses of biogas are cooking and lighting. Because biogas has different properties from other commonly used gases such as propane and butane and is only available at low pressures (four to eight centimeters of water), stoves capable of burning biogas efficiently require special design. To ensure that the flame does not "lift off," the ratio of the total area of burner parts to the area of the injector orifice should be between 225 and 300:1 (FAO, 1981). Recent Indian designs have thermal efficiencies of around 60% (Mahin, 1982). In China the Beijing-4 design has a thermal efficiency of 59 to 62%, depending on the pressure (Chan U Sam, 1982).

Lighting can be provided with a gas mantle, or by generating electricity. Highest lamp efficiencies require gas pressures of 40 cm, which are only possible with fixed dome digesters.

Reported gas consumptions for cooking and lighting are 0.34 to 0.41 cubic meters per capita per day and 0.15 cubic meters per hour per 100 candle power respectively (NAS, 1977). A typical family of six uses approximately 2.9 cubic meters a day of biogas.

1/ $C_nH_aO_b + (n - \frac{a}{4} - \frac{b}{2})H_2O \longrightarrow (\frac{n}{2} - \frac{a}{8} + \frac{b}{4})CO_2 + (\frac{n}{2} + \frac{a}{8} - \frac{b}{4})CH_4$

2/ 1 kilocalories (kcal) = 3.968 British Thermal Units (Btu) = 1.163 x 10^{-3} kilowatt hours (kWh) = 4.187 megajoules (MJ).

Agricultural and Industrial Uses

Biogas can be used as a fuel in stationary and mobile engines, to supply motive power, pump water, drive machinery (e.g., threshers, grinders) or generate electricity. It can be used in both spark and compression (diesel) engines. The spark ignition engine is easily modified to run on biogas by using a gas carburetor. Ignition systems need not be altered other than minor timing adjustments. At the standard compression ratios a decrease in power results. Supplementary fuels can be used with biogas in spark ignition engines.

Where the biogas supply varies or there is a small quantity available, dual fuel diesel engines have been used successfully. Normally the modifications are simple. The engine is usually started with pure diesel fuel and the biogas increased gradually until it comprises around 80% of the fuel intake. If the gas supply is interrupted, normal operation can still proceed with 100% diesel fuel. With 80% biogas, engine performance is good and 20% more horsepower is delivered than with diesel alone (Sharma, 1980).

Normal thermal efficiencies of these engines are 25-30%, and they use approximately 0.45 cubic meters of biogas per horsepower-hour. Converting this to electricity, approximately 0.75 cubic meters of biogas is required per kilowatt hour. There were 301 small biogas power stations in China at the end of 1979, generating 1,500 kilowatts in Sichuan province alone. A recent report describes a 90 kilowatt station operating on biogas from nightsoil digestion (National Office for Biogas Development, 1982).

Due to the low thermal efficiency of these engines a large fraction of the biogas energy can be recovered from the cooling water and exhaust gases. This energy can be used to heat the digester or for space heating of animal sheds, greenhouses, and buildings.

A concern in the use of biogas in internal combustion engines is that the hydrogen sulphide in the gas is slightly corrosive. However, in China engines were run for five years with no internal corrosion noted (Chan U Sam, 1982). In general, the operating lives of the engines are expected to be between 12,000 and 20,000 hours, depending on the engine speed and horsepower (Picken and Soliman, 1981).

Biogas is not a very convenient fuel for motive power, since it is difficult and expensive to compress due to its low critical pressure. However, if stored in one to two cubic meter bags it can power small farm tractors with diesel engines for limited distances.

COMPOSITION AND USES OF DIGESTER SLURRY

Composition

The slurry discharged from a digester contains 2 to 12% solids and consists of refractory organics, new cells formed during digestion, and ash. The slurry can be used in its liquid or solid fractions, dried, or as total slurry. Components of slurry which provide fertilizer and soil conditioner properties are soluble nutrients and trace elements, insoluble nutrients, and the organics present in the solids (humic materials).

Biomass Uses in the Absence of Anaerobic Digestion

There are many possible methods in which biomass resources can be used. To illustrate the most efficient way to provide fertilizer, soil conditioner and/or fuel from a given amount of biomass, this analysis is made on cattle dung. The processes described occur to a greater or lesser extent with all biomass resources. Emphasis is placed on nitrogen since this element is usually important in terms of both quantity and effect on crops.

Biomass in the form of cattle manure can be used by:

a. burning;

b. applying to the field surface;

c. applying to the field and ploughing under;

d. composting and applying to the field;

The effect of use on the nitrogen present in the biomass is discussed below.

Option A, burning, is common in many developing countries, and results in the complete loss of nitrogen through volatilization and mineralization. Phosporus, potassium and the trace elements remain in the ash. The biomass is often burned in traditional three stone fires which have a thermal efficiency of 10 to 15%. If an improved stove is used, the efficiency can reach 30%. Burning leaves virtually no fertilizer, and the traditional fuel efficiency is considerably lower than for biogas produced from the same amount of biomass.

Option B, applying biomass directly to the field surface, is practiced in most countries, and the fate of the nitrogen depends on the composition of the biomass. Nitrogen is present in cattle dung in two forms: organic and ammonia. Most organic nitrogen is in the form of proteins, while the ammonia nitrogen is present as either the ion, NH_4^+, or free ammonia, NH_3. For fresh cattle dung, ammonia nitrogen can vary from a low of 3% (Idnani and Varadarajan, 1974) through 20% (Hamilton Standard, 1980) to as high as almost 40% (Hashimoto et al., 1981a). For dairy manure equivalent figures are 24% (Hart, 1963) and 37.6% (Jewell et al., 1976); for swine, around 18% (UNEP, 1981); and for fresh chicken manure, 8%.

When fresh manure is spread on the surface of a field, almost all the ammonia nitrogen is lost through volatilization. Lauer et al. (1976) hypothesize that this volatilization occurs in stages due to urea hydrolysis followed by drying. Field application is not an efficient use of biomass resources.

Option C, ploughing fresh manure into the field, prevents loss of ammonia through volatilization, and almost all the nitrogen is conserved. However, under certain conditions organisms can nitrify free ammonia to nitrite (NO_2^-) and nitrate (NO_3^-). These ions are relatively soluble and can be leached from the soil. Implementation of this option is relatively time consuming, especially if the biomass is manure produced daily, and is not practiced often.

Option D, composting, is a common way of recycling biomass in developing countries. The biomass is piled in a heap (with agricultural residues some animal manure is added) and left to decompose aerobically. The pile is occasionally turned over or otherwise aerated. Compost may be stored for an indefinite period of time before it is applied to the field. The composted biomass has few degradable organics, is essentially inoffensive to handle, is reduced in volume, and does not attract flies or other insects. However, there is a loss of nitrogen during composting and storing. Data on nitrogen loss reported by Yawalkar and Agrawal (undated) is listed in Table 5.1.

Table 5.1. Nitrogen Loss Due to Composting or Digestion.

Field Practice	Nitrogen Effectiveness Index (percent)
Manure spread and ploughed in immediately	100
Effluent from digester introduced immediately into irrigation water	100
Dried digester plant effluent spread and ploughed	85
Manure piled 2 days before spreading and ploughing	80
Manure piled for 14 days	55
Manure piled for 30 days	50

Biomass Uses Following Anaerobic Digestion

Anaerobic digestion provides both fuel and fertilizer, while options A through D above provide one or the other, but not both. Nitrogen can be lost during digestion only by reduction of nitrate to nitrogen gas and volatilization of ammonia into the biogas. Since there is very little nitrate present in manure, the loss through reduction is otherwise insignificant. Loss of nitrogen through volatilization has attracted little attention; in one study the loss amounted to only 1.3% of the total Kjeldahl nitrogen (TKN) (Idnani and Varadarajan, 1974).

Since there is a destruction of organic matter during digestion, the percentage of nitrogen measured in the slurry rises. Nitrogen is conserved during anaerobic digestion. For example, a 23% reduction in total solids concentration is accompanied by a corresponding increase in the nitrogen content of the remaining solids. This may create an illusion of "new" nitrogen if only the Kjeldahl nitrogen is considered. Jewell et al. (1976) found that the TKN for dairy manure increased from 5.2% to 6.9% of the solids during digestion and Hart (1963) found increases from 3.7% to 3.9% of the solids. Rajabapaiah et al. (1979) also carried out detailed mass balances on a KVIC digester and found that nitrogen was conserved.

The ammonia fraction of the TKN in digester slurry has an important influence on its fertilizer value, since ammonia is the form of nitrogen most easily taken up by plants. In its organic form the nitrogen is released more slowly, and some fraction may not be degraded, thus being unavailable to plants. With animal manures the ammonia nitrogen concentrations increase during digestion, and Jewell et al. (1976) found that the ammonia nitrogen in dairy manure increased from 37.6 to 44.6% of the TKN during digestion. Similarly, Hart (1963) found an increase of from 24.0 to 49.0% during digestion.

Digestion followed by drying results in the loss of some of the ammonia. Jewell et al. (1981) found that 35% of the ammonia nitrogen was lost during drying over 72 days (see Table 5.2). The amount of ammonia nitrogen lost during drying will depend on a number of factors such as its concentration in the slurry, the pH of solution, and the temperature of drying.

Table 5.2. Ammonia Losses from Stored Mesophilic Effluent (grams per liter).

Time day	Total Solids	NH_4^+	NH_3
1	90.4	3.319	0.328
8	91.7	3.261	0.322
16	92.5	3.019	0.241
23	92.5	3.086	0.246
30	95.8	2.695	0.174
36	97.0	2.701	0.173
43	96.7	2.501	0.161
49	98.3	2.450	0.157
65	100.4	2.186	0.113
72	98.1	2.260	0.117

Reference: Adapted from Jewell et al. (1981).

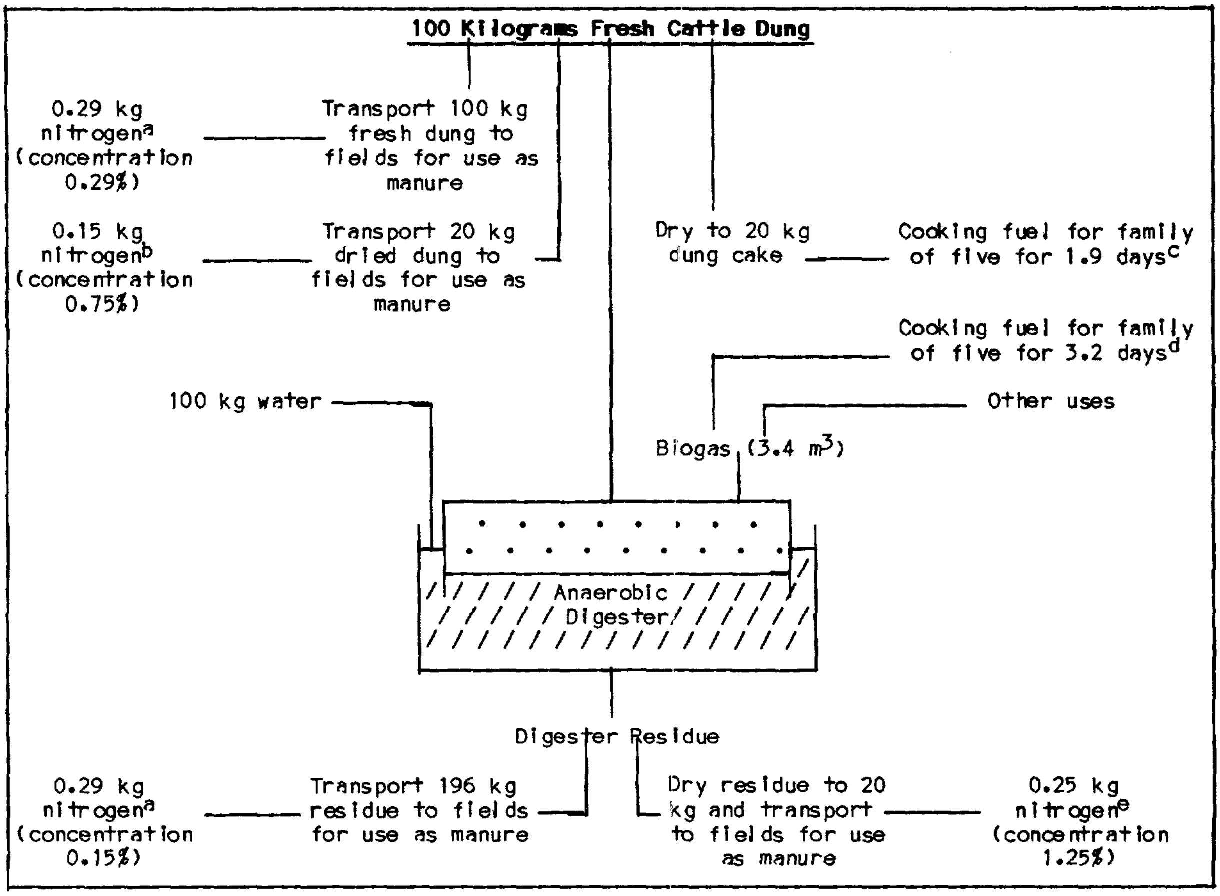
Santerre and Smith (1980) quantified the above options for use of biomass both with and without anaerobic digestion (see Figure 5.1). Their analysis has a number of important implications with regard to the utilization of biomass as a fertilizer (see Table 5.3). Analysis of the benefits of anaerobic digestion based on nitrogen alone tends to neglect humus, micronutrients, trace elements and water in the slurry. Taking these factors into account, the value of digested slurry may be considerably higher than an analysis based on only nitrogen indicates.

Table 5.3. Estimated Quantities of Manures or Fertilizers Needed to Supply One Kilogram of Nitrogen to Any Given Area of Cropland.

Nitrogen availability	Quantity needed (kg) 100%	50%	25%
Ammonium phosphate	9		
Ammonium superphosphate	33		
Ammonium sulphate	5		
Urea	2		
Cattle dung (fresh)	345	690	1,380
Cattle dung (dried to 20% of fresh weight)	133	266	530
Anaerobically digested cattle dung sludge (wet)	676	1,350	2,700
Anaerobically digested cattle dung sludge (dried to 10% of wet weight)	80	160	320

Note: The nitrogen present in inorganic fertilizers is assumed to be potentially 100% available to plants. For comparative purposes, the availability of nitrogen in organic manures is assumed to range from 25% (e.g., see Idnani and Varadarajan, 1974) to 100%. Both inorganic fertilizers and organic manures often contain plant nutrients in addition to nitrogen, and organic manures provide important soil conditioning factors. Although important for sustained maintenance of soil fertility and plant growth, these are not presented in this table for the sake of simplicity. Nitrogen values of manures are based on Rajabapaiah et al., 1979.

Figure 5.1. Some Alternative Options for Utilization of 100 Kilograms of Fresh Cattle Dung. Values are approximations based on best available information. (After Santerre and Smith, 1980; Rajabapaiah et al., 1979; Bhatia and Niamir, 1979.)



[a] Assumes nitrogen content of 0.29 kg and no losses between digester and field.

[b] Assumes nitrogen decreases by storing in open air from 1.7% to 0.9% of total solids. (Note: Change in solids concentration with storage time is not given.)

[c]
1. Assumes the daily per capita energy requirments for cooking = 578 kilocalories (kcal) of useful energy.
2. Assumes dung cakes thermal value = 2,444 kcal per kg which are used at 11.2% efficiency for cooking, having a useful energy content of 273.7 kcal per kg.
3. Household daily dung requirements for cooking:

$$\frac{(578 \text{ kcal/capita})(5 \text{ persons})}{273.7 \text{ kcal/kg}} = 10.6 \text{ kg dung cakes}$$

4. At assumed manufacturing rate of 20 kg dung cakes per 100 kg fresh dung, 10.6 kg dung cakes = 53 kg fresh dung required by family of 5 per day. 100 kg fresh dung thus provides for 1.9 days of cooking fuel.

[d]
1. Assumes energy content of biogas = 4,500 kcal per m^3, which is used at 60% efficiency by biogas stove (Srinivasan, 1978), and has a useful energy content of 2,700 kcal/m^3.
2. Household daily biogas requirement for cooking:

$$\frac{(578 \text{ kcal/capita})(5 \text{ persons})}{2{,}700 \text{ kcal/m}^3} = 1.1 \text{ m}^3 \text{ biogas}$$

3. Assuming conversion rate of 28.2 kg fresh dung into one m^3 biogas, then daily household requirement for dung = 1.1 m^3 × 28.2 kg = 31 kg fresh dung. 100 kg fresh dung thus provides for 3.2 days of cooking fuel.

[e] Assumes nitrogen decreases by storing in open air from 2.2% to 1.9% of total solids. (Note: Change in solids concentration with storage time not given.)

Kladivko and Nelson (1979) found that the application of anaerobically digested wastewater sludge to three different soils led to significant increases in pore size, organic carbon and cation exchange capacity. Kabaara (1969) investigated the effect of digested sludge in comparison with inorganic fertilizers on soil properties. He found that the sludge caused a slight increase in pH and soil potassium, and a large increase in soil phosphorus, particularly in the topsoil. In contrast, while inorganic fertilizers also increased soil phosphorus and manganese, their beneficial effect on soil properties was much less than that of the sludge. Data from China (National Office for Biogas, 1982) on the application of digested sludge at 38 metric tons per hectare showed considerable improvement in soil quality over a period of two or three years (see Table 5.4).

Table 5.4. Effect of Digester Sludge on Physical and Chemical Properties of Soil.

Location	Time	Treatment	Organic matter%	Total N%	Total P_2O_5%	Available %	Volume wt. gm/cm^3	Porosity %
Chu-Xian	2 years	1. Control	1.04	0.064	0.096	13.2	1.44	45.66
		2. Digester Sludge	1.21	0.068	0.110	14.4	1.41	46.59
	3 years	1. Control	1.31	0.0744	0.114	29.6	-	-
		2. Digester Sludge	1.48	0.0892	0.127	33.7	-	-
Dayi	1 year	1. Control	1.035	0.071	0.109	16.3	1.27	52.59
		2. Digester Sludge	1.286	0.101	0.11	20.4	1.26	57.09
	2 years	1. Control	1.122	0.0706	0.118	37.2	1.363	50.09
		2. Digester Sludge	1.384	0.057	0.108	66.7	1.207	57.14

Equally significant are reports from Kyoto, Japan. After years of using subsidized fertilizers on small intensively farmed holdings, an increasing number of farmers are reportedly making private arrangements with householders to collect nightsoil. Although the city provides regular vacuum truck collection of nightsoil from househould vaults, the incentives for returning to traditional utilization of nightsoil in order to maintain soil fertility were sufficiently strong that the number of households involved had risen to 8,000 by 1977 (Kalbermatten et al., 1982).

The Chinese system of operating anaerobic digesters is to batch load agricultural residues and continuously feed nightsoil and swine manure. The slurry produced is comprised of two fractions: daily supernatant, which is fairly low in total solids since most of the agricultural residues settle and remain in the digester; and the sludge within the digester, which is quite high in total solids and is removed and applied to the fields only every six months.

Application of digested sludge over a period of years has provided continuing increase in crop production. This may be due to the effect of slow release nitrogen compounds and improved soil structure. Similar results with coffee plants were reported by Hutchinson (1972).

In order to utilize low grade phosphorite, a new type of fertilizer--biogas sludge phosphohumate--has been developed in China. This is made by mixing the sludge with phosphorite powder in ratios of 10:1 to 20:1, and composting for one to three months. Its effect on crop yields is shown in Table 5.5. In soils lacking phosphorus the use of this material may increase yields by over 20%.

Table 5.5. Effect of Biogas Phosphohumate on Some Major Crops. (After National Office for Biogas, 1982.)

Crops			Control	Phosphorite 40-50 jin/mu powder	Sludge 400-1000 jin/mu	Phosphohumate 440-1050 jin/mu
Rice (2)	Yield (jin/mu)		581.5	620.0	634.3	653.3
	Increase	jin/mu	-	38.5	52.8	71.8
		%	-	6.6	9.1	12.3
Wheat (13)	Yield (jin/mu)		528.5	558.6	581.4	611.7
	Increase	jin/mu	-	60.0	72.8	83.1
		%	-	11.4	13.8	15.7
Sweet Potato	Yield (jin/mu)		277.2	295.9	325.0	330.2
	Increase	jin/mu	-	18.7	47.8	53.0
		%	-	6.7	17.6	19.1
Rape	Yield (jin/mu)		246.0	246.0	260.2	268.0
	Increase	jin/mu	-	0.0	14.2	22.0
		%	-	-	5.8	8.9

Note: The figures in brackets indicate the number of experiments.
1 jin = 0.5 kg; 1 mu = 0.66 ha.

Typical compositions of manures after anaerobic digestion are shown in Table 5.6. Note that the three fertilizer elements, nitrogen, phoshorus and potassium, are each present in the range of one to 1.5%.

Table 5.6. Chemical Composition of Organic Digested Manures (Oven Dry Basis).

	N %	P %	K %	Fe ppm	Mn ppm	Zn ppm	Cu ppm
Liquid slurry	1.45	1.10	1.10	4000	500	150	52
Sun dried slurry	1.60	1.40	1.20	4200	550	150	52
Farmyard manure	1.22	0.62	0.80	3700	490	100	45
Compost	1.30	1.00	1.00	4000	530	120	50

Algae Production

Digester effluent has been added to a number of experimental ponds to evaluate its effect on algae production. In Taiwan, China, Hong et al. (1979) grew the bluegreen algae *Spirulina platensis* in the effluent from a swine manure digester. The algae were harvested from the surface with nets, and productions of 7.3 and 9.7 grams per cubic meter (equivalent to 1.9 x 2.5 metric tons per hectare per year) were achieved during winter and summer respectively. The harvested algae contained 57.5% protein.

Filtering, collection and drying of unicellular algae is costly and requires large areas of land and volumes of water. Addition of chemical coagulants such as alum increases costs and reduces the acceptability of the dried protein as an animal feed. Boersma et al.

(1981) concluded that the production of algae from digested swine manure was not the optimal use of the slurry. Maramba (1978) point out that soybean oil meal is a less expensive protein source.

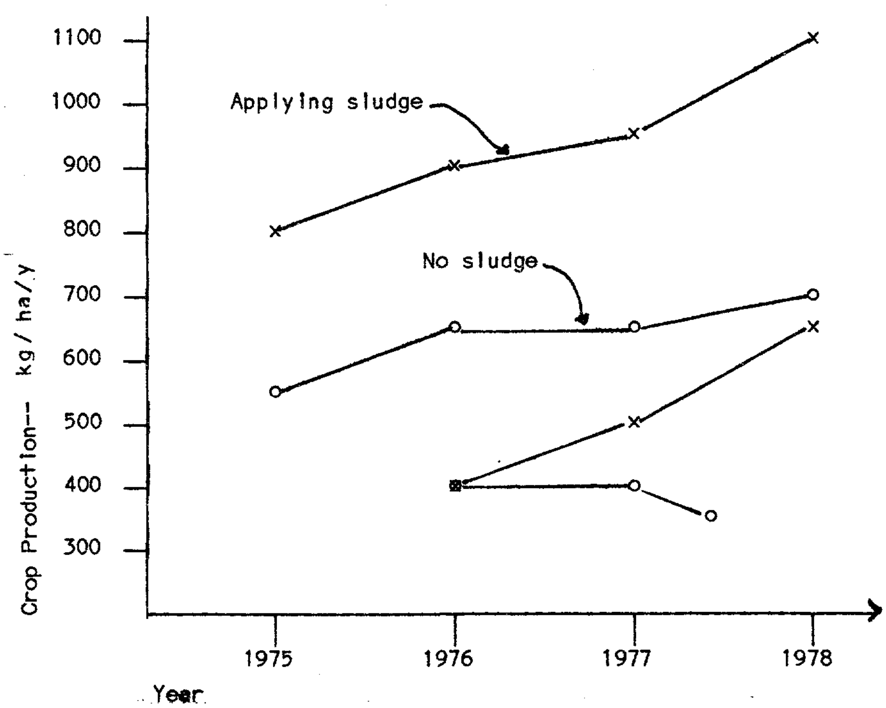
Feed for Fish Ponds

When digester slurry is used in ponds, the nutrients stimulate the growth of both phytoplankton (algae) and zooplankton (daphia and crustaceans), which the fish harvest. Alviar et al. (1980) investigated the growth of fish in an integrated farming scheme in the Philippines. The average yield of Tilapia niotica was 25 kilograms per square meter every two months (19 metric tons per hectare per year).

In southern China, cultivation of fish in ponds is common. Normally the fish are fed concentrated wheat bran. In recent years digester slurry has been used as a feed supplement, increasing fish production and decreasing costs for feed (National Office for Biogas, 1982).

In Israel, Marchaim and Criden (1981) reported on comprehensive tests carried out on the use of thermophilically digested cattle manure as fish food. After one season it was concluded that fresh manure and digested slurry were equally effective fish foods, but the yields were lower than with 100% commercial feed. On the other hand, when 50% of the commercial pellets were replaced by digested sludge the yields remained the same (approximately 120 kilograms per hectare per year) (see Figure 5.2) and costs were cut in half.

Figure 5.2. Average Standing Crop of Fish in Fish Pond Experiments in which Fish Were Fed with Different Combinations of Commercial Pellets and Thermophilically Digested Slurry of Cow Manure.



Reference: Adapted from Marchaim and Criden (1981).

Refeeding to Animals

Refeeding of digested animal wastes to cattle, hogs and poultry has been demonstrated to be a potential use of the effluent product. When organic materials are digested anaerobically, a significant fraction is reduced to ammonia, some of which is taken up by growing bacterial biomass and converted to new amino acids. With cattle waste, increases of 230% have been measured after digestion (Table 5.7). In addition, considerable quantities of vitamin B_{12} are synthesized during digestion, and preliminary results from work at Maya Farms (Maramba, 1978) indicate concentrations of over 3,000 milligrams of B_{12} per kilogram of dry sludge. In comparison, the main sources of B_{12} in animal feeds, fish and bone meal, contain 200 and 100 milligrams per kilograms respectively. Digested sludge thus has potential as an animal feed supplement and, due to the high costs of these supplements ($200/MT for cottonseed meal), could enhance the financial viabilty of biogas plants.

Table 5.7. Comparison of Amino Acid Composition of Cattle Waste, Dried Centrifuged Fermenter Biomass, Fermenter Influent and Fermenter Effluent.

Item	Cattle waste	Centrifuged biomass	Fermenter influent	Fermenter effluent
Aspartic acid	9.3	12.3	12.7	24.8
Glutamic acid	18.4	20.9	24.6	45.4
Alanine	13.1	8.2	20.7	16.3
Glycine	6.2	7.6	15.2	13.8
Serine	3.7	4.3	4.8	8.3
Proline	5.6	6.9	6.7	11.4
Tryosine	3.2	2.8	3.3	7.9
Phenylalinine	5.0	5.3	6.2	12.6
Threonine	4.3	5.7	6.2	10.9
Methionine	3.3	1.5	2.6	4.9
Valine	6.1	6.8	7.6	15.3
Leucine	8.9	11.0	11.1	21.2
Isoleucine	5.0	6.2	6.3	13.7
Lysine	5.4	6.2	7.7	14.8
Histidine	1.7	2.4	2.7	4.4
Arginine	2.7	5.3	4.4	9.6
Total amino acids	102.0	113.4	142.8	235.3

Note: Data, expressed as milligram amino acids per gram DM, obtained following 72 hours of acid hydrolysis in evacuated, sealed flasks. Values represent mean of three determinations on composite material during two separate weeks.

Reference: Adapted from Prior and Hashimoto (1981).

At Maya Farms in the Philippines (Judan, 1981), solids are recovered in settling tanks and dried in the sun. The feed material from the sludge provides 10 to 15% of the total feed requirement of swine and cattle, and 50% for ducks. At this concentration it was found that weight gains for swine were slightly higher than a control group (Maramba, 1978). Alviar et al. (1980) also found that dried sludge could be substituted in cattle feed with satisfactory weight gains and savings of 50% in the feed concentrate used.

While these empirical feeding tests demonstrate that dried sludge can be recycled with considerable savings in feed costs, more detailed tests in developed countries tend to draw less positive conclusions. Ward

(1982) reviewed most of the data currently available on the refeeding of cattle. The following is a brief synopsis of his findings.

Early tests in 1975 revealed that it was possible to use dried slurry in place of cottonseed meal, but that it required almost twice the amount of slurry to provide the same amount of digestible protein (Table 5.8).

Table 5.8. Protein Digestability Coefficients.

	Protein %	Protein Digestion Coefficient	Digested Protein
Cottonseed meal	44.80	81.03	36.30
Digester effluent	25.76	72.71	18.70
Digester effluent as % cottonseed meal	58	90	52

Reference: Adapted from Hamilton Standard (1981).

Other recent tests indicate that inclusion of 25% slurry from a 1,000-cubic-meter thermophilic digester (55 C., 15 days' detention) reduced the digestibility of an otherwise conventional high-protein feed (Harris <u>et al.</u>, 1982). Decreased weight gains of up to 20% per kilogram of feed consumed have been noted (Table 5.9). Slurry fed cattle would have to be fed more and held longer to achieve the same weights as a control group. The actual additional feeding period is probably a site-specific factor.

Table 5.9. Influence of Digester Effluent on Metabolism, Digestability and Growth of Beef Steers.

	(1) Control (Conven'l Feed)	(2) Control + Soy Bean Suppl.	(3) Control + Dig. Slurry Suppl.
Metabolism			
Dry matter (kg/day)	5.40	5.291	5.495
N intake (g/day)	86.0	93.7	108.2
Urine N (% intake)	23.5	34.4	23.4
Fecal N (% intake)	35.6	38.6	38.6
N retained (g/day)	7.8	6.2	10.1
Digestibility			
DM (dry matter)	77.6	76.1	73.9
N	70.5	61.5	61.5
Growth Exp.			
Average daily gain (kg/day)	0.93	0.99	0.79
Final weight (kg)	450.	459.	419.

Reference: Adapted from Prior and Hashimoto (1981).

Much of the data on cattle refeed relate to beef cattle feedlots. Since swine have different digestive systems, they may be able to utilize the slurry more effectively.

CHAPTER SIX

INTEGRATED RESOURCE RECOVERY SYSTEMS USING ANAEROBIC DIGESTION

The most efficient use of biogas systems in developing countries is incorporation into food and fuel cycles in integrated resource recovery schemes. This section examines several possible systems in relation to their effect on fuel and food supplies. A general methodology is described which enables rational choices in selection of integrated resource recovery (IRR) systems, and constraints and optimization procedures for IRR systems are discussed. In addition, several state-of-the-art IRR systems in developing countries are presented and analyzed.

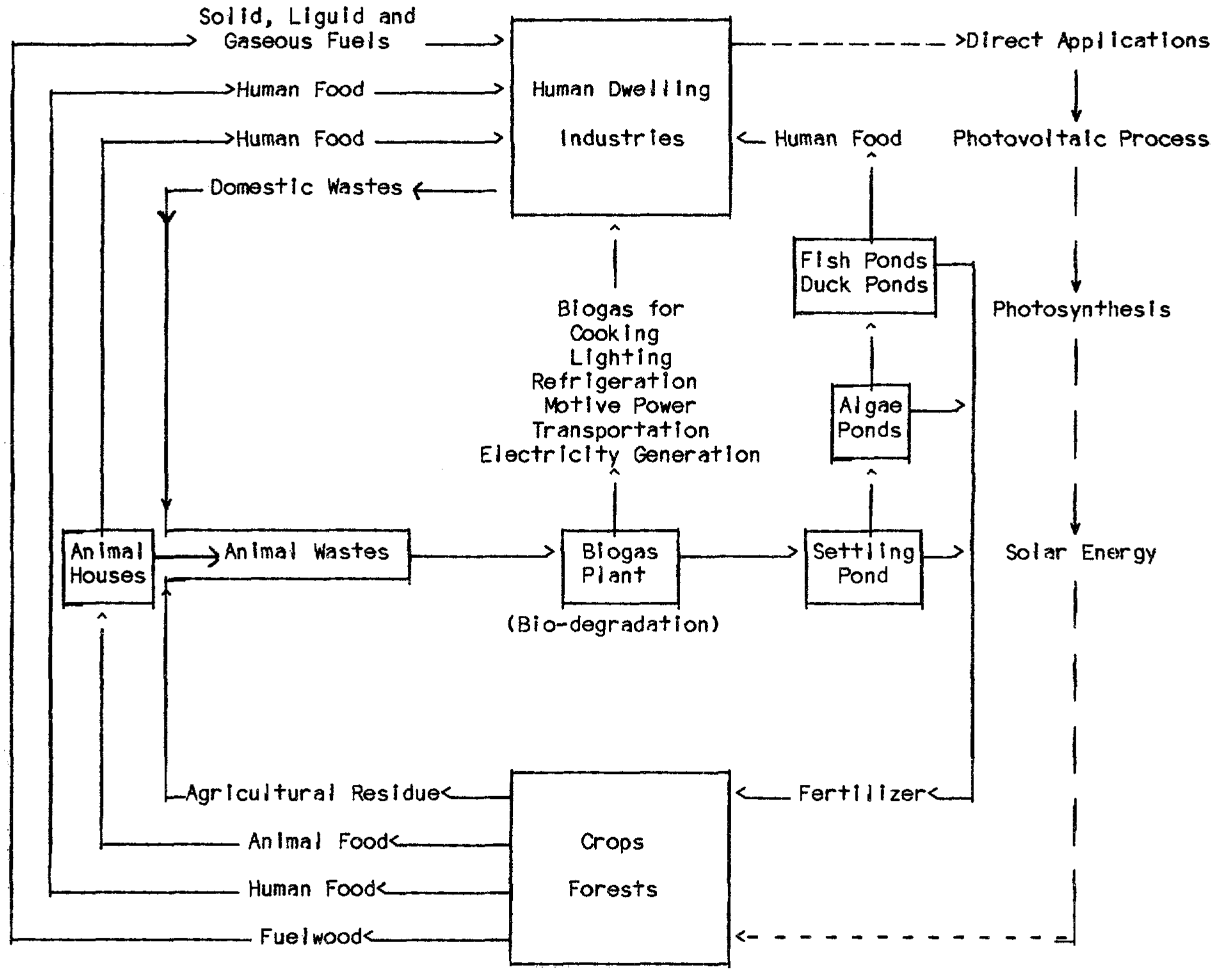
POSSIBLE IRR SYSTEMS

The variety of feeds, biogas techniques, and end uses of biogas and slurry results in a large number of possible IRR systems. The interactions between fuel, food and fertilizers in an IRR system are complex (see Figure 6.1). If fuel supply is the desired primary output from such a system, then the nutrients present in the slurry could either be recycled back to the fields to grow more crops and provide residue for feedstock, or be used to grow feedstock directly. For example, the high primary productivity of water hyacinths would provide a high yield of biomass, resulting in corresponding energy yields.

The end use to which the biogas is put also has implications in terms of fuel production. If it is used solely to satisfy cooking and lighting requirements, it will not result in any feedback into fuel production. However, if some of the gas is used in a dual fuel engine, the power generated can be used to irrigate fields, resulting in increased agricultural residues available for digestion. In addition, the waste heat produced by the engine can be used as heat for household purposes, or to heat the digester, which would allow a smaller digester to produce the same amount of gas, reducing capital investment. The net result could be an energy loop leading to increased amounts of energy available from a given amount of land. The relative fractions of gas used for cooking and power generation influence the amplitude of this loop, and optimization techniques would maximize the gains from these "feedback" loops.

Food production is influenced by the presence of nutrients within the slurry. The most common method of using this slurry in integrated systems is to recycle it to the fields as a fertilizer/soil conditioner. The method of handling the slurry can influence its efficacy as a fertilizer, and hence the quantity of food and residuals produced. However, there are other methods of utilizing the slurry which can increase the amount of food, including refeeding to animals and growing algae or fish. Also, the end use of biogas is important in this context since utilization of all the gas for pumping irrigation water and powering tractors as opposed to cooking and lighting would increase the quantity of food produced from a given amount of land.

Figure 6.1. Components of the Integrated Bio-Energy System.



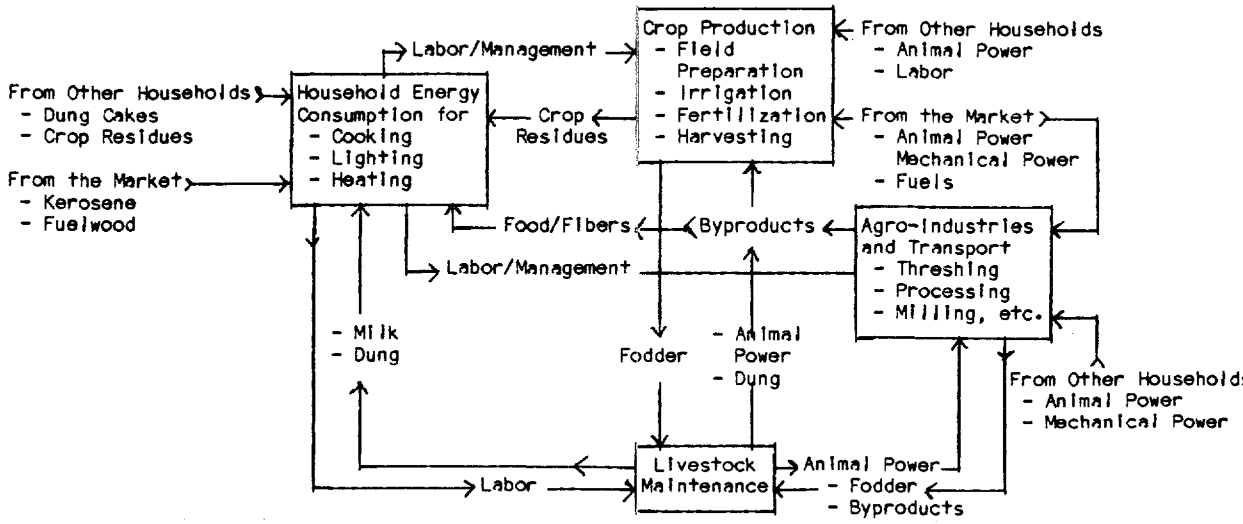
METHODOLOGY TO ASSESS IRR SYSTEMS

In evaluating IRR systems it is important to define the boundaries of the system being studied. In many rural situations in developing countries, ecosystems can be defined which are relatively "closed;" i.e., there are few inputs or outputs of fuel and feed outside the system. However, in many urban areas the systems are quite "open," with fuel and food inputs balanced by monetary outputs. The primary focus of development in recent years has been on satisfying the basic needs of the rural poor. Since the methodology is slightly simpler for closed than for open systems, this discussion will concentrate primarily on the former.

Let us consider a typical small village in a rural area. System boundaries arbitrarily include the village and all the agricultural land which supports it. Any fuel or food entering the system, in addition to solar radiaton, is an input, while that leaving the system is an output. The first task in assessing the potential of IRR systems to improve the quality of life within such an ecosystem is to evaluate the food and energy sources, and their flows and transformations. This establishes a baseline "carrying capacity."

The modelling of ecosystems based on material and energy flows, and energy conversion efficiencies was pioneered by Odum (1971, 1976). Figure 6.2 documents the general inputs and interactions in our village ecosystem.

Figure 6.2. Energy Generation and Use in Rural Areas. (After Bhatia, 1980.)



Reddy and Subramanian's (1979) rural development approach included: (i) elucidation of current rural energy consumption patterns; (ii) translation of these patterns into a set of energy needs arranged according to priority; (iii) consideration of feasible technological options for satisfying these energy needs with the available resources; (iv) selection of the "best" option for satisfying each category of need; and (v) integration of the selected options into a system.

Data gathered by Ravindranath et al. (1980) on rural energy consumption patterns were converted to kcal units (see Table 6.1). Ninety-seven percent of the inanimate energy comes from firewood, and domestic cooking, which utilizes about 80% of the total inanimate energy, is based entirely on firewood. This data was translated into a set of end use energy needs ranked in order of decreasing magnitude (see Table 6.2).

Based on this hierarchy of needs, the availability of renewable energy sources such as fuelwood, biogas, solar and wind and such nonrenewables as electricity and kerosene, was evaluated. This evaluation leads to the selection of a limited set of energy paths subjected to the following constraints: time dependence of the energy utilizing task; self-reliance; environmental soundness; power requirements of certain tasks; and the availability of the technology (see Table 6.3).

Using this information, Reddy and Subramanian (1979) evolved an energy scheme for Pura based on a community scale biogas unit (see Figure 6.3).

Table 6.1. Pura Energy Source Activity Matrix (millions of Kcals/year).

	Agriculture	Domestic	Lighting	Industry	Total
Human	7.97	50.78	-	4.97	63.72
(Man)	(4.98)	(20.59)	-	(4.12)	(29.69)
(Woman)	(2.99)	(22.79)	-	(0.85)	(29.63)
(Child)	-	(7.40)	-	-	(7.40)
Bullock	12.40	-	-	-	12.40
Firewood	-	789.66	-	33.93	823.59
Kerosene	-	-	17.40	1.40	18.80
Electricity	6.25	-	2.65	0.71	9.61
Total	26.62	840.44	20.05	41.01	928.12

Reference: Adapted from Ravindranath et al. (1980).

Table 6.2. End Uses of Energy in Pura.

Inanimate and Animal Energy

	End Use	Input energy/year (kcal/10^4)	Efficiency (Estimates)	Output energy/year (kcal x 10^4)
1.	Heating (95-250°C)	688.9	5	34.4
2.	Heating (55°C)	112.4	5	5.6
3.	Heating (800°C)	23.8	5	1.2
4.	Lighting	20.1	2.5	0.5
4.1	Lighting (electrical)	(2.7)	10	(0.3)
4.2	Lighting (kerosene)	(17.4)	1	(0.2)
5.	Mobile Power	12.4	20	2.5
6.	Stationary Power	7.0	80	5.6
6.1	Water Lifting	(6.3)	80	(5.0)
6.2	Flour Milling	(0.7)	80	(0.6)
	Total	864.6		49.8

Human Energy

	Human Activity	Human Energy Expenditure: Hours/year	Hours/day/ household	kcal year x 10^4
1.	Domestic	255,506	12.5	50.8
1.1	Livestock Grazing	(117,534)	(5.7)	(23.4)
1.2	Cooking	(58,766)	(2.9)	(11.7)
1.3	Firewood Gathering	(45,991)	(2.3)	(9.1)
1.4	Fetching Water	(33,215)	(1.6)	(6.6)
2.	Agriculture	34,848	1.7	8.0
3.	Industry	20,730	1.0	5.0
	Total	311,084	15.2	63.8

Reference: Adapted from Ravindranath et al. (1980).

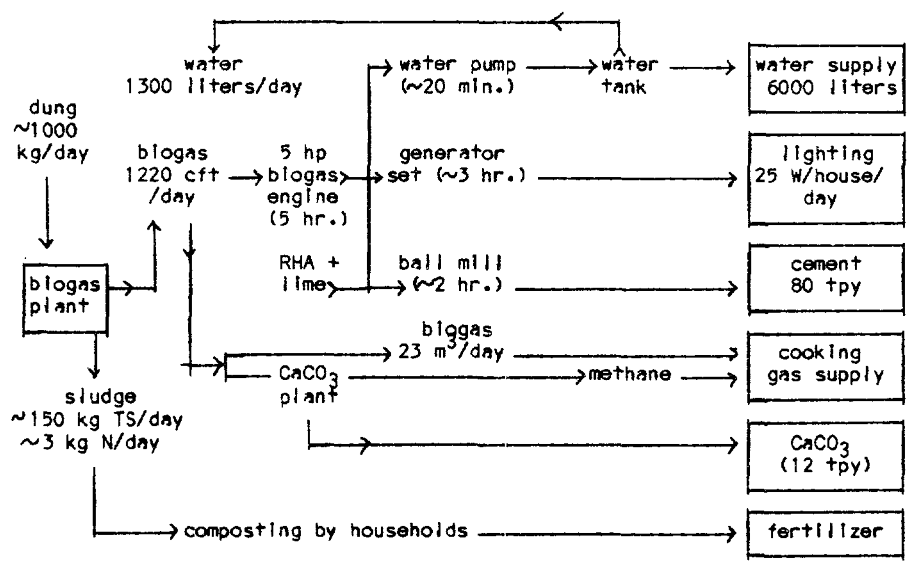
Table 6.3. Selection of Sources and Devices for Pura.

TASK	ALTERNATIVES	
	Sources	Devices
(1) medium temperature heating	biogas	gas burner
	energy forests	wood/charcoal stoves
(2) low temperature heating	waste heat	wood/charcoal stoves
	solar	solar waterheater/ solar dryer
(3) lighting	electricity	incandescent lamps fluorescent tubes
(4) stationary power	draft animals	animal powered devices
	human labor	pedal powered devices
	wind	windmills
	biogas	biogas engine
	energy forests	producer-gas engine
	ethanol	internal combustion engine
	electricity	electric motor
(5) mobile power	draft animals	animal powered devices
	human labor	pedal powered devices
	ethanol	internal combustion engine
	energy forests	producer-gas engine
	biogas	biogas engine
(6) high temperature heating	biogas	furnace
	charcoal	furnace

Note: The sources and devices within boxes correspond to those proposed for phase I of rural energy center for Pura.

Reference: Adapted from Ravindranath et al. (1980).

Figure 6.3. Community Plant for Pura Village.



Reference: Adapted from Reddy and Subramanian (1979).

This integrated scheme relies on a number of key concepts:

a. selection of the most appropriate sources to match tasks;

b. cascading; i.e., using waste heat from a high quality source to perform tasks requiring low quality sources;

c. combining energy sources; e.g., using solar to preheat water before being boiled by biogas;

d. spatial task integration; and

e. time sharing of energy devices.

OPTIMIZATION OF BIOGAS WITHIN IRR SYSTEMS

Within the broad context of optimization of IRR systems described above, there is a role for the optimization of individual techniques. This involves emphasizing such considerations as energy, nutrient recycling, public health or the environment.

For energy the prime parameter to optimize is the volumetric gas production rate. This gives a measure of the amount of energy produced per day per unit of capital invested, or size of digester. While typical rates for developing country designs vary from 0.1 to 0.4 volumes of gas per volume of digester per day, these can be much higher when using optimized design and operating conditions.

Since nutrients are essentially conserved during digestion, optimization for highest yields depends on the available C/N ratio in the feed and the retention time. Public health considerations are dominated primarily by the retention times and temperature of the waste in the digester. At mesophilic temperatures of 35°C, excreta needs retention times of 40 to 50 days to be rendered essentially pathogen free and biochemically stable.

EXISTING IRR SYSTEMS

In recent years a number of IRR systems have been established in developing countries (Chan, 1973; Alviar et al., 1980; Solly 1980; Marchaim et al., 1981; Meta Systems, 1981). Probably the most well known of these are Maya Farms in the Philippines and Xinbu village in China.

Maya Farms evolved to utilize a byproduct of flour milling (i.e., pollard) as a pig feed. The farm was established near Manila on 24 hectares. In the early seventies the primary concern was to reduce the odors from pig manure. Anaerobic digestion was investigated and found to reduce the odors, but the effluent slurry presented water pollution problems, so sludge conditioning techniques were developed. In late 1973 due to rising oil prices Maya Farms commenced experiments on the possible uses of both biogas and the slurry produced. A research program was set up to investigate the various digester designs (Maramba, 1978) and possible uses of the slurry as an animal feed, to grow algae and fish and irrigate crops. By 1981 the farm covered 36 hectares and contained 25,000 pigs, 70 cattle and 10,000 ducks.

Maya Farms designed and implemented three integrated farming systems, varying in size from a small family farm model to a large commercial feedlot venture (Judan, 1981). The family farm is based on 1.2 hectares of land with 1.0 hectares being used for crops (rice or corn) and the rest devoted to a cattle shed, fishpond, biogas works, accommodation and a pig sty containing four sows. The digester is a two chamber continuously fed unit which is fed the swine waste and manure from two water buffalo. The gas produced is more than enough to supply the family's energy requirements for cooking, and also powers a refrigerator and gas mantle lamp. Solids in the slurry are refed to the pigs and constitute 10% of their feed, while the liquid slurry is used to raise fish in a 200 square meter pond and to fully fertilize all the cropland throughout the year.

The medium scale system is based on 12 hectares of land and a 48 sow piggery. The gas is sufficient to pump water for the farmhouse and livestock and to irrigate the 12 hectares of cropland. The large system was designed for 500 sow units and no agricultural land, approximating an intensive animal feedlot. The gas produced is used for pumping water, lighting the pigpens and operating a feed mill; however, in this case there is a gas surplus amounting to roughly 40% of the output. Various end uses of this gas have been suggested. Payback periods varied from 18 to 39 months (for the family farm system).

In these examples the IRR system evolved empirically. More efficient systems are possible if all the energy and food flows within the system are fully integrated. With more "open" systems such as intensive animal feedlots, the prime parameter to optimize may be financial returns.

The Xinbu production brigade is situated in the delta of the Pearl River in Guangdong Province, China, and comprises 282 families with 1,570 persons. The brigade controls 1,528 mu (100 hectares) of farmland and fresh water fish ponds: 834 mu for fish ponds; 321 mu for mulberry fields; 188 mu for sugarcane; and the remaining 180 mu are separate plots (Hu Bing-hong, 1982). The brigade started to install biogas units in 1976 and by the end of 1977 80% of the families were utilizing biogas. These units supply some 50% of the families' fuel requirements, and in addition 17 families are using solar roof panels which, with biogas, supply 70 to 80% of their energy needs. The biogas is used for cooking and generating electricity for lighting, and the waste heat from the engine is used to dry silkworm cocoons. Solar dryers are also used to carry out the latter task. The slurry is used to feed fish ponds and fertilize the fields growing mulberry, sugar cane and Napier grass. In addition, some of the slurry is used to grow mushrooms. In the six years the scheme has been in operation, the output from the brigade (in yuan) has risen by 150% (Hu Bing-hong, 1982), and the general sanitary conditions of the village have improved considerably.

CHAPTER SEVEN

ECONOMIC JUSTIFICATION

INTRODUCTION

For economic analysis, biogas facilities can be broadly divided into two categories: (1) those in which there is a significant economic cost associated with the handling and disposal of organic feedstocks, and (2) those in which this cost is negligible. Examples of the first area include sewage disposal, industrial waste treatment, and manure disposal from intensive livestock farming. The second category includes household and community scale plants in poor rural communities.

While industrialized countries have experience in area (1), there is a shortage of experience and data on which to base relevant economic analyses. However, a few studies do provide some preliminary indication of economic justification.

The special attraction of biogas plants in area (2) is that, unlike traditional usages, both fertilizer and fuel are obtained from the same source material. Most of the economic data and analyses come from the Indian biogas program.

ECONOMIC EVALUATION—DEFINITIONS AND PROBLEM AREAS

Economic evaluation of small scale biogas plants requires measuring and valuing the fertilizer and fuel output, then comparing the gross value of output with the costs of plant construction and operation to arrive at a benefit-cost ratio or other index of value.

Financial and Economic Analyses

In this review both financial and economic (social) analyses are considered. Financial analysis identifies "the money profit accruing to the project operating entity, whereas social profit measures the effect of the project on the fundamental objectives of the whole economy" (Squire and van der Tak, 1975). Financial analysis is based upon market prices, including taxes and subsidies, and can be applied at the household, firm, sectoral or national level, according to the purposes of the evaluation. Economic (social) analysis is typically undertaken at the national level and uses shadow (or accounting) prices that reflect the true economic worth of project inputs and outputs to society.

An intermediate approach is based on using shadow rather than market prices to value costs and benefits. The terms "financial" and "social" will be used to distinguish between the use of market and shadow prices, respectively. Following Gittinger (1972), "financial" also includes the imputed values of such inputs and outputs of biogas plants which are produced and consumed at home rather than purchased or sold in the market.

Secondary benefits and costs should be incorporated into an economic evaluation. Biogas plants can generate a variety of social and environmental benefits that are sometimes relevant to financial analysis (e.g., reduced medical bills), and generally relevant to social analysis. These benefits have been examined in detail in Barnett (1978) and Bhatia (1980).

A major force behind renewable energy technology research and development, including biogas, has been the need to eliminate deforestation by using substitutes for traditional fuelwood. The issues raised, apart from the use of reforestation costs to value fuelwood substitutes, include climate, agricultural productivity, and local institutional and market effects of deforestation. These secondary benefits create two problems for analysis: the first is one of measurement and valuation of secondary benefits, and the second is one of comparability of biogas with other energy technologies that have a different, and commonly smaller array of secondary benefits.

In China, improved sanitation has been a principal objective of some biogas programs. Secondary benefits include improved health.

REVIEW OF PAST STUDIES

Several reviews of cost benefit studies of biogas have been published, notably, Barnett (1978), Sanghi (1979), Mukherjee and Arya (1980), ESCAP (1981), de Lucia and Bhatia (1980) and Mazumdar (1982). These reviews relate almost solely to Indian experience. While Chinese experience is almost as extensive, the only economic evaluation found is one study of Ximbu village in Guangdong province (Nian-guo, 1982). The Chinese (fixed dome) design has, however, been evaluated in Thailand (Thongkaimook, 1982) and India (Singh and Singh, 1978). Limited information is available on small scale and community units for the Philippines (Galano et al., n.d.; Alicbusan et al., n.d.), Nepal (Berger, 1976; Pang, 1978; Pradhan, n.d.), Thailand (Prasith-raithsint et al., 1979; Thongkaimook, 1982), Bangladesh (Rahman, 1976), Ethiopia (Tarrant, 1977), Kenya (Pyle, n.d.), Honduras (Roesor, 1979), Pakistan (Qurishi, 1978) and Fiji (Chan, 1975).

Only four of these studies were based on household level fieldwork: Moulik and Srivastava (1975), and ICAR (1976) in India, Prasith-raithsint et al. (1979) in Thailand, and Galano et al. (n.d.) in the Philippines. These did not actually measure physical inputs and outputs, but relied on questionnaires, which may limit the reliability of conclusions. There was no consensus on methods of analysis, and many studies did not provide sufficient information to appraise the suitability of the methods used. None of the studies attempted to value secondary benefits.

The Indian studies, however, include ten substantive evaluations from which tentative conclusions can be drawn. A major problem with these studies so far as their relevance for future programs is concerned is that they are all based on the Khadi and Village Industries Commission (KVIC) floating dome designs which are very expensive to construct in comparison with the Chinese designs--mainland (fixed dome) and Taiwanese (bag). However, the KVIC design continues to be the major design promoted in India. These studies are also valuable because India, which has a large cattle population and regions where the scarcity of fuelwood is becoming a major problem, represents one of the potentially most favorable locations for diffusion of biogas technology. While currently available studies do not allow regional differences within India to be analyzed except at the most basic level (e.g., the effect of lower winter temperatures in the north), even tentative conclusions on the determinants of economic viability will be useful in identifying possible locations in other countries. In addition they illustrate the methodological problems in evaluation, and help define one of the requirements for future studies.

Two Prominent Indian Case Studies

K. S. Parikh wrote the first comprehensive economic cost-benefit analysis of Indian biogas units in 1963, and produced a revised version in 1976 in which he concluded that family sized biogas plants have "a gross return of 14-18 per cent purely in financial terms...(and) from a social benefit/cost point of view, the plants are even more attractive." In contrast Bhatia, who has written extensively on renewable energy technologies and cost-benefit analysis, concluded (1977) that "the present estimates of benefits and costs do not indicate that investment in biogas units is economic from the viewpoint of society."

Both these studies are based upon KVIC two cubic meters of gas per day plants (see Table 7.1). But while Parikh shows substantial benefits, Bhatia demonstrates substantial losses from an investment in the plant. This is even more difficult to explain than the bare figures suggest, for Bhatia used shadow prices and Parikh market prices. In most cases, Bhatia's shadow prices of inputs and outputs decreased the market values of costs, and, in the case of the fertilizer value of slurry, increased the value of benefits.

Bhatia improved upon most sensitivity analyses in biogas evaluations by varying the values of three parameters at the same time, rather than just one or two. His selection of the five parameters for alternative valuation (gas end use, value of manure, plant investment cost, calorific value of alternative fuels and plant size) also reflects the uncertainties that prevent consensus on the economic worth of plants. Other analysts have also done this but often in a less systematic way; for instance, uncertainty about the most appropriate fuel to use for valuing gas results in several fuels being used, without any guidance as to what is thought to be correct. Bhatia also provided convincing arguments (see below) for not assuming any additional fertilizer value for digested slurry. His shadow prices put 20% premiums on steel and cement and 30% on foreign exchange for fertilizers and kerosene, and used a zero shadow wage rate for unskilled labor.

Bhatia improved the methodology of biogas cost-benefit studies, particularly with regard to his sensitivity analysis and the thoroughness

Table 7.1. Alternative Evaluations of the KVIC Two Cubic Meter Biogas Plant.

		Parikh	Bhatia
A.	Investment (est. Rs)	2,332	2,830
B.	Annual Operating Costs	50	59
C.	Present value of Lifetime Operating Costs	426	502
D.	N content 1 Kg digested dung N content 1 Kg composted dung	1.92	1
E.	Effective Cooking Heat (kcal) per cubic foot biogas	82	81/70
F.	Use of Gas (Cubic feet daily): Cooking for 5 Lighting	 59.5 4.5 (1 lamp x 1 hr.daily)	 5 2 (2 lamps x 2 hrs. daily)
G.	Imputed Value of Biogas per effective kcal ($X10^3$) in cooking (Rs)	0.16	0.09
H.	Value of N (Rs per Kg)	4.5	3.24
I.	Gross Annual Benefits	348/414	290
J.	Net Present Value (Rs)	205/767	-863
K.	Benefit--Cost Ratios	1.07/1.20	0.74

N.B. i) The two values given by Parikh in rows I, J and K depend upon whether dung was previously burnt or composted.

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

iii) For explanatory notes on differences between Parikh and Bhatia see below.

Notes to Table

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

A. We have used a 1975 (Rs2332) value of investment costs including pipeline and appliances from KVIC for Parikh in order to make a fair comparison with Bhatia's analysis. His original 1974 value was Rs2000. Bhatia's shadow prices reduce the cost of unskilled labor to zero and put a 20% premium on steel and cement (approximately 40% of costs).

B. Rs50 is the agreed cost of painting. Rs9 is half the cost of the hose pipe which is replaced every two years according to Bhatia. Bhatia assigns a zero shadow price to labor and water for plant operation. Parikh does not mention these costs.

C. Discount factor of 8.51349 (x B).

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

E. Both are based on 135 kcals per cubic foot of biogas and 60% burner efficiency; Bhatia uses an alternative value of 70 in his sensitivity analyses because both the assumptions made are open to question.

(cont.)

Table 7.1 (cont.)

F. Bhatia's estimate is higher here bacause he assumes a 70 cubic foot (2 m^3) output, whereas Parikh assumes the plant only produces 64 cubic feet. This difference in output for the same plant reflects a confusion in technical knowledge, but also shows how important the other differences are for Parikh establishes a far superior benefit-cost ratio with a 10% smaller yield of gas. (Both Parikh and Bhatia have taken account of seasonal differences in gas output.)

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

H. Bhatia's nitrogen value is based upon a cif price of urea (50% nitrogen) of $135 per tonne with a 30% foreign exchange premium and a Rs300 per tonne transport cost. Parikh's nitrogen value is assumed, without any explanation, to be Rs4.5 per kg.

---

of his discussion of parameters. For example, he discussed the effect on NPV of changes in the transport cost of coke, and in the effective heat available from biogas. Of the criticisms which have been made (Mukherjee and Arya, 1980), two have not been effectively dealt with by the author. First, and of less practical consequence, he used a value of less than 1¢ (U.S.) per kilowatt hour for electricity, only citing a reference to an earlier paper of his in justification, whereas Tyner and Adams (1977) calculated the shadow price of a centrally generated electricity supply at from 2.2 to 8.5¢ (U.S.) (at only 10% capacity utilization). In practice this difference, which at minimum doubles his estimate, is not important because Bhatia uses the higher kerosene figure to value the light from biogas in his reference analysis. The second criticism concerns his use of a zero shadow wage for the "unskilled" labor in mining coal and producing soft coke. Since this results in a large reduction in the replacement cost of biogas for cooking, and since cooking is the major use of biogas, use of a zero shadow wage substantially reduces the value of biogas.

Bhatia's use of the opportunity cost of soft coke, the most abundant energy resource in India suitable for cooking, to value the gas can also be criticized. Kerosene, firewood, crop residues and dung are the source of cooking fuel for most villagers. The biomass replacement cost of biogas has a much lower value than kerosene replacement if the market price of wood is used, and as Moulik et al. (1978) demonstrated, with low costs of firewood, investment in biogas incurs major losses.

Prior to Bhatia's paper, Parikh's 1963 analysis remained the most thorough study available on the economics of biogas. In that study he suggested that where dung was burned, the prospects of biogas were best and therefore that within India Madras (Tamil Nadu), Uttar Pradesh, West Bengal and Kerala should develop biogas programs. He compared biogas with wood, gasoline and diesel as the cheapest alternatives at 1963 prices, and also argued that other fuel possibilities, such as electricity, kerosene and coal, were too expensive. Like Bhatia he assumed a zero shadow wage, and looked at variability in effective heat according to volume of biogas, methane content and end use efficiency. He argued that slurry gives more nitrogen, and consequently more food than composting, based on the all-India average figure of 36% of available dung used as fuel. He also drew attention, as did Bhatia, to the non-nitrogen benefits in using slurry for soil improvement, and to the social and economic benefits of improved health through use of smokeless fuels.

This study formed the basis for Parikh's later paper, although he made significant changes in assumptions between the two analyses. First, he used only purchased dung cakes, instead of wood and dung cakes, as the traditional fuel replaced by gas. Second, he assumed in the later study that the quality of fertilizer in the slurry was better than from composted manure. The consequence of the first assumption was that in his analysis, households that now burned dung could save Rs298 per year by investing in a biogas unit, whereas households that composted dung would receive a benefit of Rs364. In his earlier study, the input cost of wood per kcal used in cooking was higher than that of dung. The second change was to give the digested slurry an assumed nitrogen value of 2% of the dry weight of slurry compared with 1.5% in dung, and to assume a larger quantity of fertilizer (0.72 to 0.5 kilograms) was available as slurry from one kilogram of dry dung. In his earlier study he referred to such a difference, but did not include it in his analysis; as a consequence of this change, the economics of biogas units improved considerably.

The differences between Parikh and Bhatia are due to their choice of fuels with which to measure the replacement of biogas in cooking, and their valuation of the fertilizer content in digester slurry and composted manure. Bhatia's use of shadow prices tends to reduce differences between them, except for the price he used to value gas. Parikh's use of dung cakes valued at market prices led to much larger savings through adoption of biogas for cooking than did Bhatia's use of soft coke at shadow prices. Parikh's estimate of the enhanced fertilizer value in slurry (52.6 kilograms of nitrogen annually) compares with Bhatia's assumption of no difference between the two.

Other Indian Studies of Household Units

Other studies also confirm the sensitivity of economic analyses to the value of biogas and slurry. Moulik et al.'s study (1978) was based on a field survey in four Indian states and is of particular value, since most other analyses are desk based. They draw attention to two major points of interest. Using the price of firewood to value gas, the study measured the gas replacement cost at different levels of firewood prices to calculate the break even points of NPV of plants. It established substantial economies of scale which are important when considering development of large biogas plants for community use. It also emphasized the problem of poor financial returns when plant owners did not purchase fuels prior to installation; only in the very largest plants was the return from fertilizer alone sufficient to make the plant viable. The authors did not say how this was calculated, but they used the price of local compost rather than the price of imported chemical fertilizer to value the slurry. Their analysis included a 20% subsidy of capital costs received by farmers from KVIC to promote biogas. To achieve financial viability a more substantial subsidy would be required when firewood has a low opportunity cost. This is more likely to occur when it is collected rather than purchased. In such cases even a 100% subsidy of the initial purchase price could not improve cash flow, because generally neither the gas nor the slurry could be traded to generate cash for meeting maintenance costs.

Only a few, comparatively rich farmers in India have plants. Sathianathan (1975), ICAR (1976) and Sirohi (1977), though they discuss the problem of cash flow, are all advocates of biogas despite this distributional bias; using basically similar assumptions they all demonstrate benefit-cost ratios higher than one. Such results, however, depend on assumptions that appear to bear little relationship to actual farm-level choices. Unlike Bhatia, these authors do not argue that their assumptions are based on the most appropriate alternative from society's viewpoint. For example, Sirohi (1977) valued slurry fertilizer at two times the value of an equivalent amount of farmyard manure. He also used the opportunity cost of kerosene to value all biogas.

Contrasting this advocacy literature with the analyses presented by skeptics highlights the sensitivity of conclusions to choice of assumptions. Sathianathan, for example, following KVIC, assumes no labor costs in operation, while in other analyses such costs are the single largest item, and account for the negative NPV. French (1979) produces similarly negative results, and again treatment of labor was the critical factor.

To draw even broad conclusions from these different studies is difficult given the doubts that exist concerning the validity of some of the assumptions. For example, in some studies (e.g., Parikh, 1976) the value of dung as fuel is greater than its value as compost; in others (e.g., Bhavani, 1976) the reverse is true.

Community Level Plants in India

The introduction of large scale (greater than 40 cubic meter) plants for use by rural communities has been prompted by two important considerations. First, the alternative of a household plant is not an option for most Indian households. Only 5% of the cattle owning households have the minimum five animals needed to provide feedstock (Prasad et al., 1974), and perhaps even less could bear the additional cash outlays involved in the substitution of biogas for fuelwood and dung that was previously collected by family labor. Second, economies of scale are one of a number of potential techno-economic advantages of community over household plants. Offsetting these considerations are the diseconomies of scale involved in a community gas distribution network, in the larger volumes of dung required at one site, and in the greater organizational requirements.

Two community plants have been evaluated in some detail; one at Fateh Singh Ka Purwa in Uttar Pradesh by Bahadur and Agarwal (n.d.), Ghate (1979), and Bhatia and Niamir (1979), and one in Kubadthal, Gujarat by Moulik (1982). Evaluating community plants has the same drawbacks as household units in valuing inputs and outputs, so it is not surprising that three evaluations of the Uttar Pradesh plant arrived at three different economic benefit-cost ratios; 1.14:1, 1.54:1 and 0.6:1. Moulik's financial analysis of the Gujarat plant did not include a final estimate of financial viability, but it was evident from current performance that the profit from plant operation would not meet the loan and interest payments due. Other analyses agreed that the plant was not financially viable, though Ghate (p. 24) suggested that at least part of the deficit on the costs of cooking, lighting and water supply (from a biogas powered tubewell) could be met through a surplus generated by the dual fuel engine used for crop processing.

Financially nonviable plants can be justifiably supported through state subsidies if economic analysis is sufficiently positive. The authors of the four studies cited above agreed that at present the basis for an accurate economic benefit-cost analysis is lacking, and, therefore, that their conclusions were tentative. Bhatia and Niamir, who found a benefit-cost ratio less than one, summarize the problems of economic analysis as follows:

> "It is interesting to note that the entire economics of biogas technology seem to rest on the following assumptions:
>
> a. The calorific content of different fuels such as cow dung cakes, fuelwood used in cooking, plant residues, kerosene and biogas.
>
> b. The efficiencies with which these fuels are being used currently, or the possible equipment which could lead to higher efficiencies.
>
> c. The NPK contents of different organic fertilisers, and the yield-fertiliser response under different agronomic conditions and crop rotations.
>
> d. The behavioural aspects of the energy sources or organic fertilisers such as present use patterns, actual and perceived constraints to their use etc...
>
> Unfortunately, the sponsoring of research to collect data on these parameters is not considered important by the scientific community, or by policy makers."

One important difference from the analysis of household plants is the greater complexity of community plant end use possibilities. Gas availability varied in the Fateh Singh Ka Purwa plant from below 1900 cubic feet per day in winter, to above 2700 cubic feet in summer (Bhatia and Niamir, Table 10). This gas was used for cooking; a generator to supply lighting and to power a tubewell; and a dual fuel engine running a flour mill, a thresher and a chaff cutter. The proportion of gas distributed to these different end uses has been considered to be a critical determinant of both the financial and social worth of the plant because both market and shadow prices of the gas will vary. An alternative approach to economic evaluation assumes the highest value use until the demand is met, then the next, etc. This higher use(s) requires a unique fuel characteristic with unique replacement value. The combination of end uses that will maximize benefits depends upon the assumptions used to value gas put to different end uses. In their social analysis all three studies used the shadow price of soft coke or coal to value biogas in cooking. They arrived at three different estimates: 11.6, 15 and 38.3% as the share of cooking in the total benefits. Bhatia and Niamir (1979) also used the social price of dung and fuelwood to value biogas in cooking to give a second estimate of 63% of total benefits from this end use. In this second estimate, dung was valued using the shadow price of imported fertilizer. Under this assumption over half of the total benefits were due to the use of dung for fertilizer instead of for cooking which is now carried out using biogas. Since cooking uses about 60% of the gas, these widely differing percentages (11.6 to 63%) can be used to support a case for or against the use of biogas for cooking in preference to other end uses (different initial investment and operating costs will also affect the calculation). Financial analysis of the value of different end uses was less equivocal; non-cooking uses, particularly diesel substituting ones, are better.

What these ambiguous results demonstrate is the inability of social and financial analysis to determine policy in the absence of a strategic energy policy framework. The possible deforestation and loss of agricultural output associated with fuelwood and dung use has to be evaluated in conjunction with the foreign exchange costs of diesel imports in the case above, but this is only one example of the types of valuation implicit in all energy policy decisions. A second, and equally crucial limitation, is the difficulty analysts face in incorporating secondary benefits. Some, such as health benefits, are extremely difficult to quantify, while others, such as improved community spirit through a successful biogas program, are impossible. In the community programs discussed above, a variety of secondary benefits were acknowledged by participants as being very important to their perception of the value of biogas plants. This was particularly true of women who benefited from improved kitchen conditions, and savings on cooking time.

The technology evaluated in the above studies was an expensive KVIC design. In a Southern Indian village a community plant is being built to meet the specific village energy requirements, and financial viability is possible (Lichtman, 1983). It is worth noting, though that both the plants discussed above were also financially viable on paper. A second, and critical feature of the Southern Indian program is the involvement of the villagers in the planning of the biogas plant. In both the plants discussed above the chief reasons for their difficulties were organizational, rather than economic or technical. Moulik in the Gujarat study, and Bahadur and Agarwal in the Uttar Pradesh study, provide detailed descriptions of numerous organizational and operational problems that were related to village social structure, and the relationship between the villagers and the implementing agency. All the authors of these studies agree that the solution of such social problems with community plants requires the involvement of users from the very first stages of planning.

A Case Study in China

While several technical studies (Shian et al., 1979), and information on approaches to extension organization (McGarry and

Stainforth, 1978; van Buren, 1979; Sheridan, 1981; Stuckey, 1982) are available, economic analyses in English are less common, and only one is currently available (Nian-Guo, 1982). The evaluation is of 86 household plants and one community plant in a village of 90 households in South China. The data employed are itemized, but the study does not describe the assumptions behind the data estimates uses, or whether they were based on actual user experience. A six cubic meter household plant was estimated to cost ¥209.93 (about US$105) to construct. Operating benefits were estimated at ¥34.32 per year for fuel saving, ¥105 for labor saving, and ¥36 for the fertilizer value of the slurry. These are presumed to be net operating benefits as no operating or maintenance costs are given. Based on these figures, Nian-guo calculates a 1.25 year payback period, while the life of the digester was estimated at 10 to 15 years.

The community plant consisted of seven digesters totalling 200 cubic meters, with a construction cost of ¥7,000. Auxiliaries cost around ¥3,500, and the generator, switchboard and grid cost ¥5,000, giving a total investment cost of ¥15,500. Net of operating costs, annual benefits from electricity, fuel saving, labor saving and food processing were valued at ¥4,163 which gave a 3.75 year payback period. Additional benefits not included were: increased by-product income due to the enhanced fertilizer value of digested manure, better quality biogas-dried silkworm cocoons, sanitary improvements, and better living style.

On a recent trip to China, Stuckey (1982) obtained some data on current costs and benefits from family size units (six to eight cubic meters). The estimated cost of these units was ¥150 (materials and labor), and savings in fuel (coal) and fertilizer (urea) amounted to around ¥50 to 70 per year. Based on these figures, the payback period was less than 3 years, making family size units in China financially viable.

Both Thongkaimook (1982) and Singh and Singh (1978), in comparing the Indian and Chinese designs, concluded that the Chinese design is superior on economic grounds. The chief disadvantage of the Indian design is its high cost and the short life of the gas holder. The Chinese design is now being used in the multi-model biogas program in the Indian Sixth Plan, and further detailed economic comparison should be possible soon.

However, the successes of the Chinese program in diffusing biogas (as reported in non-economic literature) are products of determined experimentation, careful organization and diversification in operation as much as better technology. In fact, there have been many failures for technical reasons, which have provided lessons, particularly on construction techniques for gas domes, and the failure rate of new plants is now very low (Stuckey, 1982).

Experience of Economic Evaluation in Other Countries

Evidence on household and community plants from other countries is extremely scarce and provides little additional knowledge that might resolve some of the uncertainties that the India studies have raised. Only a few of the studies available were based on actual user experience. Rahman (1976) gives a breakdown of costs and benefits of a modified Indian design used in Bangladesh, without any firm conclusion on its economic viability. However, with a net annual operating profit of Tk.581, and an initial construction cost of Tk.7,600, only very low interest rates on a loan for construction would make the plant financially viable.

Of three Nepalese desk studies based on Indian design (three cubic meter) plants, only Berger (1976) estimated a positive benefit-cost ratio (1.67:1), while Pradhan (n.d.) and Pang (1978) argued that construction cost reductions were critical if biogas was to be financially feasible for any but the richer farmers.

In Thailand, an empirical study of Indian design plants by Prasith-raithsint et al. (1979) found that household plants on average had a payback period of five years. No other estimates of economic worth were calculated. No benefits were claimed for the slurry as this was not used by plant owners. The high cost of plants, a lack of technical know-how, the availability of other fuels, and the shortage of dung were the main reasons given by the 94.5% of current nonusers who said they did not want a plant.

In the Philippines, an empirical study by Galano et al. (n.d.) reported positive financial benefit-cost ratios for 21 locally designed household plants and that larger plants had the best ratios. They stated that their use of liquified petroleum gas rather than traditional fuels may have resulted in an overevaluation of benefits. Based on this analysis, they provided a number of recommendations for hastening diffusion of biogas in the Philippines. A more detailed economic analysis by Alicbusan et al. (n.d.) reached similar favorable conclusions, with an estimated payback period of 2.3 years for a 510 cubic foot plant.

A Kenyan desk study by Pyle (n.d.) investigated the economic viability of two local designs. He found both to have positive net present values at all levels of plant life, but that there were significant economies of scale when comparing a one cubic meter with a four cubic meter plant. The smaller plants were only a marginal proposition when a low value for slurry was used, and generally the results were extremely sensitive to the value placed on the slurry. He concluded that more detailed and accurate field studies were necessary.

A desk study by Roeser (1979) of two household plants in Honduras showed that the economic viability of the plants depended critically upon the relative time spent on dung and firewood collection. At low dung collection times, the largest plant (360 cubic feet) was viable. The smaller plant (180 cubic feet) was viable only when cooking rather than lighting was the end use adopted. However, in the absence of subsidized kerosene for lighting, use of biogas for lighting was viable at low dung collection and preparation times. He recommended further study before diffusing biogas, and drew attention to the importance of comparing the use of a biogas plant for cooking with the use of an improved stove. If the fuel efficient "Lorena" stove could reduce firewood collection time to one hour per day, use of biogas for cooking was not as profitable to the household as use of the stove.

Tarrant (1977) undertook a comprehensive evaluation of the use of a community plant for generation of electricity in Debarek, Ethiopia. He concluded, using three different measures of social worth, that the project was viable at current oil prices (the fuel used to value biogas), but that the project was not financially viable. However, the detailed figures provided on financial and social costs and benefits suggest that a subsidy to cover the financial deficit would still leave the project socially viable. He concluded that more detailed field evidence was required on three critical parameters: electricity demand projections, slurry transport costs, and the value of dung, to firm up the estimates presented.

Industrial and Commercial Feedlots

Developed countries using anaerobic digestion to treat industrial wastes include Israel, the United States, the Federal Republic of Germany and the Netherlands. In developing countries only a few large scale units are known to exist, although some laboratory work has been carried out in India, Brazil and China. The largest number are in China, and Stuckey (1982) obtained some tentative economic data during a recent study tour. The best documented case involved a distillery in Louzi County (130 kilometers from Chengdu, Sichuan Province), which treated 130 cubic meters per day of stillage with a 2,000 cubic meter thermophilic digester. The gas produced (3,000 cubic meters per day) was used to cook meals for 200 workers, fuel a boiler, run a bus and truck (using compressed gas), and generate electricity. The total capital cost of the digester and ancillary equipment was ¥188,000, and it was estimated that savings in coal (700 tons per annum) and electricity (500,000 kilowatt hours) amounted to ¥82,800 per year. The estimated payback period was less than three years.

Another unit (100 cubic meters) was installed in a leather tannery in Jiading County (20 kilometers from Shanghai) to treat the sludge generated, produce energy, and reduce the amount of solids to dispose of. The approximate capital cost of the unit was ¥60,000. However, the annual savings in energy and reduced sludge disposal costs are unknown.

Because of a lack of field data, no conclusions can be drawn about the economic viability of biogas in industrial applications; however, a number of important points can be made. First, since industries generate larger volumes of liquid and solid wastes than families and small villages, there are often substantial costs involved in handling and disposing of these wastes. However, if a biogas unit is installed, these disposal costs can be reduced, and the resulting savings can be used to offset the cost of the plant.

Second, since many industrial wastes are soluble and quite biodegradable, efficient new techniques such as the filter, ABR and UASB can be used to treat the waste at low capital costs per unit volume. In addition, economies of scale should also reduce the capital input per unit volume of waste treated.

Third, the biogas produced from treating industrial wastes anaerobically is a valuable commercial fuel, and can substitute for many of the fossil fuels currently being used in industries in developing countries.

Fourth, use of the effluent (liquid and solids) from a biogas plant led to a large number of income generating activities, including selling the slurry as a fertilizer/soil conditioner; raising fish or ducks; growing mushrooms or other crops; and drying the effluent to sell as a feed additive for animals. These uses may lead to an integrated resource recovery operation which could result in a net cash income.

Finally, factors which normally inhibit the adoption of biogas at the family or community level, such as lack of capital and technical expertise, would not normally present a problem for industrial biogas plants. Diffusion need only be limited by the financial viability of the biogas unit.

Experience in the use of anaerobic digestion to treat the manure generated in commercial feedlots in developing countries is also limited, although the one case of Maya Farms in the Philippines has been reasonably well documented.

Maya Farms is one of the pioneers of large scale biogas applications in the developing countries, and the technology forms an integral part of an intensive animal rearing farm located within Metropolitan Manila. Manure from 22,000 pigs is fed into a variety of batch and continuously fed digesters which produce a total of 66,000 cubic feet of biogas per day. The gas produced is used directly as a fuel in the processing plants, or substitutes for gasoline in a number of engines which drive a variety of equipment and machinery. In addition, some of the gas is used in motors to generate electricity which is used on site.

The slurry is separated into two fractions, liquid and solid, and the liquid is used to fertilize crops and feed fish ponds, while the solids are refed to pigs, cattle and ducks. These solids supply around 10 to 15% of the total feed requirements of the pigs and cattle, and 50% of the feed for the ducks.

Based on actual operating data from Maya Farms, Judan (1981) estimated the benefits from small (4 sows), medium (48 sows), and large (500 sows) farms using biogas units in the Philippines. In his analysis he calculated benefits in terms of savings on inputs of fuel, feed and fertilizer that would have been necessary in the absence of the biogas unit. For the small farm, 27% of the benefits came from fuel savings, 54% from animal feed savings, and 19% from the fertilizer saved. In the medium farm, the respective savings were 36, 52 and 12%, while in the large one they were 21, 79 and 0%, since no crops were fertilized. The most important benefit is derived from refeeding the slurry solids to the pigs.

These results are qualitatively consistent with Israeli experience in which feeding a 12% solids slurry from thermophilic digestion of dairy manures to fish ponds or beef feedlots provided most of the benefits (Marchaim, 1982).

Judan provides a summary statement of the investment and operating expenses of Maya Farms, and estimated payback periods of 39 months (small), 21 months (medium), and 30 months (large). This study provides a strong economic case for the development of integrated systems that efficiently utilize all the outputs from a biogas unit by substituting for purchased farm inputs. However, since this conclusion rests on the benefits accruing from refeeding the sludge solids to animals, caution should be exercised as there is still some controversy about the effects of refeeding. A recent review by Ward (1982) states that "most recent tests have indicated that the digester residues have a negative effect on the total digestable nutrients and metabolizable energy in the mixed feeds. Decreased (animal weight) gains of up to 20% per kg of feed consumed have been noted. Thus the cattle would have to be fed more and held longer to obtain equal final conditions with cattle not fed the effluent." This may offset any potential savings from refeeding with digester effluent.

One study evaluated experience with anaerobic digestion in industrialized countries with particular reference to its transferability to developing countries. Marchaim et al. (1981) describe a conceptual 200 cubic meter thermophilic digester system in Israel being fed cattle manure (15 to 18% total solids), where the biogas was used for heating and power generation, and the slurry to fertilize crops, feed fish, cultivate mushrooms, and as a partial feed for sheep and calves. Their positive economic analysis also depended on the income generated from the slurry in the form of feed. When no income was available from the slurry, the "break even" point (i.e., when the net present value of the whole operation is zero) occurred when the price of gasoline was US$1.22 per gallon. If all the slurry were sold as feed, then the plant would be economically viable at any gasoline price above US$0.23 per gallon. They claimed this analysis would be valid in similar situations in developing countries, e.g., a village cooperative in Gujarat, India; however, this claim should be regarded with some caution since the technology used (thermophilic, continuous mixing, high loading rates) is quite sophisticated, and may cause problems in developing countries.

PROBLEMS IN MEASUREMENT AND VALUATION

Inputs (Costs)

Construction

Plant costs have been specified in some detail by KVIC for the full range of sizes of the only design promoted on a large scale in India. Shadow prices have also been calculated by French (1979), Bhatia (1977) and Bhavani (1976) by valuing labor at a zero shadow wage, and steel and cement (40% of initial costs) with a 20% premium over market prices to reflect their real resource costs. It is this treatment of labor that is the most problematic. The total (KVIC estimated) construction costs of a plant are very high (Rs2332 for 2 cubic meters at 1975 market prices), and proponents of biogas plants reduce these costs in economic analyses by presuming that land for the site and labor used in construction have no opportunity cost. Except in the most densely settled villages, land can be treated at no cost since the quantities involved are so small. However, the assumption of a zero shadow wage of labor will be valid only when labor is completely idle because of the lack of work opportunities, not through choice. Lal (1974), in a detailed discussion of this issue, estimated for each Indian State non-zero shadow wage rates for both skilled and unskilled labor. It is unlikely that a shadow wage for unskilled labor of 70 to 80% of the market wage is typically correct, though it can be greater than 100% in the peak season.

Evidence on adoption behavior suggests that in practice the financial cost of construction materials in relation to farm cash incomes is the most important factor. To make these costs manageable, KVIC has organized large subsidies (varying between Rs1000 and Rs1950 for the 3 cubic meter plant) to farmers who have the collateral (five animals is a common figure). Since no farmer purchases a plant without a loan, it means in effect that at current construction costs they are only accessible to farmers who can provide this collateral. The one thing that practically all analysts agree upon is the urgent need to reduce costs if the program is going to have any opportunity to involve poorer households. The Indian design using steel gasholders has a higher initial capital cost than the Chinese designs: mainland or Taiwanese. Optimization of the design with respect to relative material costs, or substitution by one of these alternative designs, would result in cost reduction, and provide the possibility for more widespread adoption.

Organic Feedstocks

In India these consist primarily of cow dung. The correct social opportunity cost of dung is its value in the best alternative use, which is usually assumed to be as fertilizer. This simplifies the analysis because fertilizer is both an input and output of the system. Bhatia, for example, used a zero net social opportunity cost (what he calls the "economic" cost) because the costs and benefits largely offset each other, and only regarded any increments to fertilizer value as a benefit.

Bhavani (1976) introduced an extra stage in the process by giving a composite estimate based on two opportunity costs of dung: for fuel and for fertilizer. Her opportunity cost thus takes account of dung previously used as fuel and as fertilizer. She has taken their replacement costs using a calorifically equivalent amount of coal, and an NPK equivalent amount of imported fertilizer. These "efficiency or real resource costs" make dung in fertilizer use 2.6 times more expensive than dung in fuel use. In her social cost-benefit analysis, her three reference situations (with their benefit-cost ratios) were:

a. all dung used as fuel (1.898);

b. all dung used as manure (1.234); and

c. dung used one-third as fuel and two-thirds as manure (1.4556).

She concluded that "it is obvious that the whole economics of biogas plants depend on the proportion of cow dung which is used as fertiliser before the introduction of biogas plants," since the more dung was burned previously, the better the economics of the biogas plant become. Strictly speaking, the derivation of shadow prices requires that a scarce resource be given the value of its next best alternative use, so for Bhavani the technically correct approach (given her data) would be to value dung at imported fertilizer prices.

For financial analysis, one should use the price of dung as fertilizer and as cakes in proportion to those two uses of dung previously, since this is the true replacement cost to the farmer. In most analyses, e.g., Parikh's and KVIC's, this has meant that, unlike Bhavani's analysis, where dung was burned the financial returns to the farmer from biogas are lower than when it was composted. This is because the price of dung as cake for fuel is higher than dung as manure. For example, for dung inputs for a 3 cubic meter plant the KVIC annual values (Sathianathan, 1975) are Rs338 for fuel, and Rs165 for manure. The correct cost in a financial analysis for most farm households may in fact only be an imputed value of family labor time involved in collection of dung, rather than the market value of dung either in the form of cakes or manure, since these market values are never actually received except by larger farmers. This assumption does not improve the economics of biogas plants, rather the reverse, for it means that the replacement costs of the biogas plant output should be valued in the same way as the dung input. In practice, most Indian farm households are not able to afford the investment anyway, and for the few that can the assumption of a market value for dung is reasonable.

Labor Time Involved in Collection of Organic Materials and Water, Digester Operation and Maintenance

Since it is usually assumed that an equal amount of labor is required to collect dung for traditional uses (fuel or manure) as for the biogas plant, frequently no extra value is assigned in financial analysis for labor costs of dung collection. With the larger farmers who have biogas plants, cow dung is often collected only from the farmyard, and it is more convenient to aggregate this labor requirement with other labor uses. A constant water supply is a requirement which often restricts possible plant locations since many villages do not have adequate year round supplies. The other main tasks are mixing water and dung, feeding the plant, stirring, and spreading an equivalent amount of slurry from the plant onto the compost pit. In total these tasks have been variously estimated to require 7 to 10 minutes per cubic foot of plant capacity, 35 minutes per 100 cubic feet, 4 hours per 100 cubic feet, one hour per 60 cubic feet (Berger, 1976 for Nepal) and the time it takes to smoke a cigarette (for China, van Buren, 1979). Except at harvest time, or in small or poor families, it is unlikely that the small quantities of labor used have a significant opportunity cost. Often rich farm households, where the family members do not have to contribute physical labor, will have permanent farm servants who are not fully employed. In a social cost-benefit analysis, the labor to run the plant is more plausibly valued at zero in contrast to the labor used in construction.

Maintenance

Poor maintenance has been said to be the single most important cause of plant failure in the KVIC design, particularly the failure to paint the gas holder to avoid corrosion. The KVIC estimates of parts life have generally been overoptimistic and highly variable. Assumptions on plant life vary between 15 and 40 years. Depending on the discount rate, a life of more than 25 years has little impact upon benefit-cost ratios. According to a survey by Moulik et al. (1978), the major item of expense was the gas holder. Maintenance costs averaged Rs470 per year (before discounting) during the first eight years of operation of a 100 cubic feet plant, and increased by nearly Rs1500 when replacement of the holder became necessary. Since there is little substantive data available, KVIC estimates are generally adopted. Its estimate of Rs180 (Rs50 painting cost and Rs130 depreciation) is much lower than Moulik et al.'s (1978). In the studies by Parikh and Bhatia, even lower values were used.

Extension

An often neglected major input which should be incorporated into a social cost-benefit analysis is extension. Survey evidence suggests that access to technical assistance is a major determinant of plant performance, and yet social benefit-cost studies rarely consider this as a cost item. Program extension services are not social overhead capital, but are integral to the satisfactory performance of individual plants. They should appear as a cost item at least to the extent that literature, training programs and village level workers are involved. There is mounting evidence that the economics of plants, once constructed, are closely tied to the availability of extension services (Moulik et al., 1978; van Buren, 1979).

Outputs (Benefits)

As discussed in Chapter 2, the primary outputs of an anaerobic digester are biogas and slurry, which can be put to a variety of end uses. Depending on the quantity and quality of each, the type of fuel or other product considered relevant when discussing replacement costs and the end use, both economic and financial values can vary widely.

CONCLUSIONS

There is a dearth of substantive data on which to evaluate the economic viability of biogas in developing countries. This is particularly acute in the area of industrial and commercial feedlot applications, but less so with household and community level applications. However, in the latter two cases most of the data come from India, and are derived from theoretical design figures using the floating cover design with cattle dung as the primary feedstock. With such a narrow data base few, if any, conclusions can be drawn about the viability of biogas under other circumstances, for example, using different designs and feeds in different social and environmental milieus, and in varying areas of application.

In addition to a lack of substantive data, existing economic evaluations suffer from the lack of an agreement upon methodology. Common problem areas include: lack of data on the effect of technical parameters on plant performance; valuation of inputs; valuation of biogas in relation to substitutable fuels and end uses; valuation of slurry with regard to its use as a fertilizer/soil conditioner and animals feed; marginal utility of output; and valuation of secondary benefits. A consensus on methodology should be developed to allow economic data to be compared among various applications, under varying circumstances, and to enable rigorous economic comparisons between biogas and other renewable energy technologies, or with conventional energy sources.

The financial viability of biogas plants depends on whether outputs in the form of gas and slurry can substitute for fuels, fertilizers or feeds which were previously purchased with money. If so, the resulting cash savings can be used to repay the capital and maintenance costs, and the plant has a good chance of being financially viable. However, if the outputs do not generate a cash inflow, or reduce cash outflow, then plants lose financial viability. Finally, if broader social criteria such as SCBA are used to evaluate biogas, conclusions will be more favorable than a strictly financial analysis.

Household biogas units may not be universally financially viable in some countries such as India; in other countries, such as China, they will be viable due to cash savings in fuels and fertilizers. Social viability is difficult to evaluate because of problems in valuing secondary benefits.

The financial viability of community scale plants is limited by considerations similar to those for household units, although economies of scale will tend to make them a better prospect financially. However, it appears that the primary barriers to diffusion are not economic or technical, but rather social and organizational. Since the benefits from a community plant can be shared by poorer households that would not be able to afford the investment and operating cost of household units, community plants may be more socially viable than the smaller units.

The financial viability of biogas units in industry and commercial feedlots appears promising, although more data are needed on the cash benefits from animal refeeding and integrated resource recovery schemes.

CHAPTER EIGHT

A SURVEY OF BIOGAS PROGRAMS IN DEVELOPING COUNTRIES

The following survey, while not exhaustive, is representative.

NORTHERN AFRICA

There are not many biogas programs in this region. Those countries working with biogas are, in order of decreasing commitment: Egypt, Sudan, Burkina Faso, Algeria, Cameroon, Mali, Senegal, Liberia and Tunisia (El-Halwagi, 1982).

Egypt

In Egypt three organizations are working with biogas; the National Research Centre (NRC--Dr. M. M. El-Halwagi) in Dokki, Cairo; the Agricultural Research Centre (ARC--Dr. M. N. Alaa El-Din) at Giza; and the Faculty of Agriculture at Fayoum.

NRC has engineers, microbiologists, parasitologists and rural sociologists, and is partly financed by the United States Agency for International Development (USAID). It has three experimental fixed and floating cover digesters of eight to ten cubic meters at its laboratory, and has installed two fixed and three floating cover digesters in selected villages. Its primary goal is to provide gas for cooking and lighting. Several large demonstration units to be used to generate electricity for cattle raising and poultry rearing properties are also planned.

NRC is also negotiating with the National Organization for Resconstruction and Development of Egyptian Villages (ORDEV) to construct 1,000 demonstration units in 15 governorates with partial funding from USAID. This three year plan includes the establishment of a biogas training center at the NRC to train engineers, technicians and skilled labor to build 50 units the first year, under direct NRC supervision. Over the next two years it plans to construct, operate and follow up on 950 units with minimum NRC involvement (El-Halwagi, 1982).

Laboratory and field scale digester design, pathogen studies, fertilizer evaluation and sociological analysis are other NRC projects (El-Halwagi, 1979). Its approach has been to develop a technical understanding of biogas before going further. It is proceeding with limited implementation in both traditional and planned villages chosen by sociological fieldwork, and is monitoring these units to ensure they are both technically and socially successful. NRC considers itself a center of knowledge rather than an implementing agency.

ARC is partly funded by FAO, and primarily employs agronomists. Its main focus is family sized digesters to provide gas for cooking and lighting. Thirteen units have been installed to date, mostly eight to ten cubic meter fixed dome or floating cover designs. There is one 150 cubic meter bag digester on a chicken farm, and there are current plans for another 24 units, primarily for cattle and poultry manure (Alaa El-Din et al., 1982).

ARC has publicized biogas through newspapers, radio, TV and slide shows in villages. It also cooperates at the national level with other institutes (Alaa El-Din et al., 1982). It has been working on the digestibility of various agricultural residues and municipal wastes, the fertilizer effect of the slurry and the health effects of the effluent. In general ARC has been fairly active in promoting biogas technology, and has installed more units than NRC.

At the national level Egypt has a coordinating committee comprised of representatives from the government and various research institutes. Development of a cohesive national policy is pending (El-Halwagi--personal communication, 1982).

Other Countries

The Sudan conducted a joint project with the German Agency for Technical Cooperation (GTZ) on water hyacinth utilization from 1976 to 1981. Three designs were tested: floating cover, fixed dome and bag. The last design was found to be the best for both gas production and construction. The project terminated for lack of technical infrastructure, support, and public awareness. The Sudanese are now building technical expertise in their universities and research institutes.

In Burkina Faso the Inter-African Committee on Hydraulic Studies (CIEH) and the Institute for Tropical Agronomic Research (IRAT) are carrying out a joint study on batch fermentation of agricultural residues and cattle manure to produce fertilizer and biogas for irrigation pumps and motors (Thery, 1977). To date about 14 two to four cubic meter units have been built (Sola, 1979).

Algeria started work on biogas in 1938, and by 1956 the Agricultural Institute of Algeria was operating eight digesters with a total capacity of 300 cubic meters, using cattle manure. Recently (ECWA, 1981) the Ministry of Energy has expressed interest in reactivating this work.

Other programs in the region include a GTZ project in Cameroon, a USAID demonstration project in Mali, and a future pilot project under the United Nations Environmental Programme (UNEP) rural energy scheme in Senegal.

SUB-SAHARAN AFRICA

In general the extension of biogas technology in Sub-Saharan Africa is constrained by limited available resources. National coordination has not yet been developed. Implementation often outstrips technical research and development and follow up is inadequate, resulting in many failures. There is a general need to develop indigenous technical expertise along with stronger national institutions before widescale implementation is attempted.

Interest in biogas appears high. Some 400 units have been built in three countries, Kenya, Tanzania and Ethiopia.

Kenya

Kenya has between 150 and 200 units (Ward, 1981; King, 1978). Most research and development is being done by the Department of Agricultural Engineering, University of Nairobi (R. P. King), Egerton College (P. A. M. Misiko), and the Tunnel Co., Ltd. (T. Hutchinson). A loosely coordinated national committee of government and university representatives under the Department of Energy is responsible for dissemination of information on biogas.

Tanzania

Lyamchai and Mushi (1982) estimated that 120 digesters had been installed in Tanzania by 1979, but 40% of them were no longer functioning. The primary design used was the mild steel floating cover, but problems were experienced with corrosion. A cheaper alternative design has been developed by the Arusha Appropriate Technology Group (AATG) using seven metal drums lashed together with wire. Some of the cost savings are offset by gas leaks around the floating drums.

Information dissemination is carried out by the Small Industries Development Organization (SIDO) and consists of showing demonstration plants to interested people. Pamphlets have been printed in Kiswahili describing plant size and giving construction details (Lyamchai and Mushi, 1982).

Ethiopia

Ethiopia is reported to have about 100 digesters, but few details are available. Megerson (1980) reported that the floating cover type is the most widely used, and that efforts have been concentrated on reducing the capital cost of digesters and manufacturing methane burning lamps and stoves from local materials.

LATIN AMERICA

[The following section is a summary of a short term study of biogas in Latin America commissioned by IRCWD (Umana, 1982).]

Although Brazil has managed to organize and implement a very successful biogas program, the remaining Latin American countries do not appear to have coherent national policies on biogas. Six countries, Mexico, Venezuela, Ecuador, Peru, Trinidad and Tobago, and Bolivia, which are net oil exporters, and Colombia, which produces some of its own petroleum needs, have limited incentive for developing renewable energy sources. An interregional organization, the Latin American Energy Commission (OLADE) attempted to promote biogas in Bolivia, Guyana, Haiti, Honduras, Jamaica and Nicaragua. Ten digesters of varying designs including batch, plug flow and fixed dome were to be built in each country. Only 50 digesters were built in two years, about half of which are reported to be working satisfactorily, at a cost of $800,000. While the program helped to make people aware of the new technology, additional development of administrative and technical infrastructures is needed.

Brazil

Brazil's program is only a few years old, but is very successful. During the period 1980-81, 1,600 digesters were built. The estimated total number of digesters in Brazil in 1982 was 2,300.

This national program was established in 1979, with the Brazilian Enterprise for Technical Assistance and Rural Extention (EMBRAPA) playing the lead role. EMBRAPA employs 25 State Biogas Managers located in the different states. State Managers operate through approximately 30,000 agricultural extension officers who are attached to the State Enterprise for Agricultural Extension (EMATER).

The Ministry of Agriculture has established a biomass unit to oversee all agroenergy programs; the unit coordinates policy with the Ministry of Mines and Energy, which is ultimately in charge of national energy policy. In addition to this government network, the Brazilian Enterprise for Agricultural Research (EMBRATER) and other institutes and universities carry out basic research in anaerobic digestion. The National Council for Technological Research (CNPQ) presently supports 110 research projects.

Adaptation and development of biogas focusses on small and medium scale farmers who want to modernize their life and become integrated with the mainstream of industrial society. The program emphasizes uses of gas other than cooking, including motors, pumps, refrigerators, electricity for radio and TV, etc. An effective educational campaign has been devised to reach the small scale farmer with simple cartoonlike publications and radio and TV programs. A recent national TV program generated 2,000 letters to EMBRAPA requesting more information and construction plans. EMPBRATER has held 128 courses to train approximately 2,000 technicians. A number of conferences and seminars have been held to exchange information between researchers and implementers.

The floating cover and fixed dome designs predominate, but two indigenously developed models, the Marinha and Macroenergetica, are becoming popular. The floating cover design has an average volume of 11.4 cubic meters, costs a reported $55 to $85 per cubic meter and represents over 70% of the existing units. The fixed dome model is smaller, 8.4 cubic meters, but considerably cheaper at $25 to $45 per cubic meter, and represents about 14% of the existing units. Due to its cost the fixed dome design is preferred for domestic applications, but the floating cover design is favored for its simple construction and controllable gas pressure. A large capital goods industry has sprung up to manufacture equipment to use the gas.

This program is well planned by a strong national organization, with good technical input and an integrated implementation program. In addition, the financial side has been well covered with approximately three million dollars available through EMBRATER to finance construction. Since the program has only been operating for a short time there has been little chance for substantial feedback, but continued gains in biogas technology can be anticipated.

Central America

Central America has approximately 110 digesters. There is active experimentation on the floating cover, fixed dome, a Guatemalan model, and two PVC plug flow digesters. The plug flow design is reported to cost about $30 per cubic meter, and units of 5 to 50 cubic meters have been built, but the lifetime and operational characteristics of this model have not yet been sufficiently tested. Research and development are being carried out at the Meso-American Centre for Studies of Appropriate Technology (CEMAT) in Guatemala, and at the Technological Institute (ITCR) and University of Costa Rica. Most support has come from bilateral aid organizations, USAID and the International Development Research Centre (IDRC) or regional programs (ICAITI, OLADE).

Mexico

There are an estimated 150 digesters in Mexico, mostly developed by research institutes such as the Instituto de Investigaciones Electricas (IIE) of Cuernavaca, and the Fundacion Ecodesarrollo Xochicalli (FEXAC). Due to plentiful petroleum reserves, national interest in biogas is limited to digesters used mainly for sanitation rather than energy.

Andean Countries

In the Andean region there is also little interest in digestion due to fossil fuel production. Some research is being done by the Central University and CADAFE in Venezuela, "Las Gaviotas" and the University of the Andes in Colombia, INE and ESPOL in Ecuador, and INTINTEC and the Technical University of Cajamarca in Peru. The last two institutes are working on the utilization of digester slurry as fertilizer on vegetables. There are approximately 120 digesters in this region.

South Oriental Countries

The South Oriental region, Argentina, Uruguay and Paraguay, has the least development in Latin America, due to the availability of cheap fossil fuels (mainly gas), and the large urban populations that characterize the region. Only 20 digesters are known to exist. However, there are a number of groups in Argentina which are carrying out basic research including the Instituto Nacional de Tecnologia Apropriada (INTA), CEFOBI at the University of Rosario, and PROIMI at the University of

Tucuman. These last two institutes are working on the digestion of water hyacinth and bagasse, respectively.

CHINA

[The following section is a summary of a short term study of biogas in China commissioned by IRCWD in May, 1982 (Chan U Sam, 1982).]

Biogas technology development in China began in the early 1920s. Progress was intermittent until 1972, at which time 1,300 digesters existed. Since then development has expanded rapidly, and by 1982 approximately seven million digesters had been built, a large percentage in Sichuan Province.

This rapid development has had strong government support. The government has established a well integrated program of expansion, financial support, biogas extension offices at all levels, meetings, training courses, and publicity on a vast scale through newspapers, radio and television. These activities are coordinated through the National Office for Biogas Development and Extension (NOBDE) in Beijing, and the State Office for Biogas Utilization and Expansion (SOBUE) in Sichuan Province.

The three main designs in use in rural areas are, in order of decreasing numbers, fixed dome, floating cover and bag. A cheap concrete floating cover design was developed in the last three years because of problems with the fixed dome. Recently the bag digester, made of red mud plastic, has been gaining wider acceptance due to its low cost, ease in handling, and excellent durability. Comparing these, the floating cover produces as much as 35%, and the above ground, solar heated bag produces 50 to 300% more gas than the fixed dome.

Laboratory studies have been carried out on treating industrial wastes with the anaerobic filter and UASB process. From this work a hybrid reactor, the partly filled anaerobic filter (PFAF), was developed which combined advantages of both types. Wastes from industries producing alcohol, meat, silk and paraffin have been treated in the laboratory using the above processes. Full scale thermophilic processes have been used successfully to treat alcohol wastes and nightsoil, using 1,360 to 4,000 cubic meter reactors.

A large number of institutes are involved in biogas research, including Chengdu Institute of Biology, Chengdu Research and Training Centre for Biogas Development and Extension, Beijing Institute of Solar Energy, Agricultural University of Zhejiang Province, Shanghai Institute of Industrial Microbiology, Sichuan Biogas Extension Office, and the Guangzhou Institute of Energy Conversion.

The basic government policy is to concentrate biogas development in areas with firewood shortages and with severe schistosomiasis. Emphasis has also been given to self sufficiency based on residential digesters for family cooking, lighting and nightsoil disposal requirements. The financial capacity of the family unit, aided by subsidies from the collective and the state, is relied on for the financing of family digesters. These subsidies vary from region to region. Families requiring further assistance receive additional subsidies or loans at 1.8% interest from the Agricultural Bank.

Over 400 small and large generators provide electricity for domestic and industrial use, and small two-wheeled tractors powered by biogas are quite common. Some large facilities generate enough gas to make it economic to compress for use in trucks and buses. Attempts have even been made to produce organic chemicals (CH_2Cl_2, $CHCl_3$, carbon tetrachloride) from the biogas. However, after some initial enthusiasm in the early 1970s, interest waned due to the complexity of the process, high capital investment, and its unprofitable nature.

In order to disseminate information on biogas to technologists, provincial and local officials, a comprehensive institutional infrastructure has been established under the State Leading Group on Biogas Construction, comprised of representatives from various departments of the State Council. The executive institution SOBUE holds annual meetings for directors and staffs of biogas implementation agencies and research institutions to discuss projects and coordinate activies in biogas. Meetings of technical panels on fermentation, digester construction, biogas utilization, digested slurry utilization and sanitation are also held once a year.

Significant research is appraised by experts to determine where it should be widely publicized. These appraisal conferences also provide opportunities to exchange detailed research experiences. In addition, meetings for directors of biogas offices in major provinces and cities are held every year to exchange experiences, discuss approaches to problem solving, and to develop programs for further research.

A great deal of effort has been expended in training biogas technicians. Government financed training courses, taking from 15 to 30 days, teach basic biogas theory. Several digesters are built during the course. Two or three people from an area are trained, then they return to their villages and train others.

During the 1970s, emphasis was directed to local adaptation and implementation of biogas generation. A large number of digesters were built. China's biogas program now promotes standardized designs in which promising ones like the bag digester are implemented. At the national level, problems and research advances are continually evaluated and fed back into the implementation program. In summary, China's program is sophisticated and integrates research and development, implementation, financing and extension within a cohesive national biogas policy.

SOUTHEAST ASIA

Most biogas activity in Southeast Asia is in the Republic of Korea; the Philippines; Taiwan, China; and Thailand, with by far the greatest number of digesters in Korea.

Federal Republic of Korea

In 1969 the government, through its Office of Rural Development (ORD), began a large scale implementation of biogas. By 1975 about 29,000 household units had been installed (Park and Park, 1981). The basic design consisted of a concrete lined cylinder with a wooden floating cover lined with plastic. In 1976, due to problems with cold weather operation, the government changed the emphasis from small digesters to village scale units with both heating and mixing. This was accomplished with a "bubble gun" mixer. Park et al. (1979) showed that in winter only 32% of the gas production was required for heating, and when solar collectors were used this dropped to only 16% (Park and Park, 1981). The present status of village scale implementation is not known.

Most research is done by the ORD. However, the Institute of Agricultural Engineering is experimenting with PVC bag and concrete fixed dome digesters (FAO, 1981), and the College of Agriculture at Suweon is working on a two stage digester of reinforced plastic insulated with paddy husk.

Philippines

In the Philippines, Maya Farms, an agroindustrial division of Liberty Flour Mills, pioneered use of biogas technology in 1972. In 1979 it was estimated that there were 240 digesters in the Philippines, of which 73% were operating (Galano et al., n.d.).

In September 1976 the Philippines established a nonconventional energy program with biogas as one of its components (Terrado, 1981). The program was primarily under the control of the Energy Development Board, which organized a regional and metropolitan program. Twelve demonstration digesters were built by technicians trained by Maya Farms personnel, on state farms owned by the Bureau of Animal Industry. Progress was constrained by lack of resources for adequate organization and maintenance.

Research is being conducted on optimum conditions for gas generation, rates of loading, dilution, mixing and retention, and variations in temperature by the National Institute of Science and Technology (NOST), the University of the Philippines at Los Banos, the Central Luzon State University, and Maya Farms.

Thailand

Biogas technology was introduced into Thailand in 1960 by the Department of Health in order to hygenically dispose of animal wastes. After the energy crisis in 1973 biogas became a major subject of interest for a number of government agencies and the public. In 1981 there were approximately 300 digesters in Thailand (FAO, 1981), mostly five cubic meter floating cover design, but Ratasuk et al. (1979) reported that 61% had fallen into disuse.

Gas is used for cooking and lighting. Some research has been carried out utilizing 1.5 cubic meter concrete water jars as digesters, and preliminary studies have been undertaken on fixed dome designs. The main institutes carrying out research are the Applied Scientific Research Corporation and the Asian Institute of Technology (AIT).

Taiwan, China

Taiwan has been involved in biogas since the mid 1970s. The bag digester made of red mud plastic was one of its major innovations. The primary digester feed in Taiwan is swine manure, and work has been carried out to grow algae for animal feed using the digester effluent. The number of digesters in Taiwan is estimated at over one thousand.

INDIAN SUBCONTINENT

This region is comprised of the following countries: India, Nepal, Sri Lanka, Pakistan and Bangladesh. There is substantial documentation on biogas, especially in India.

India

At this time there are approximately 100,000 digesters in India, very unevenly distributed among the states as each government places different emphasis on biogas (Moulik, 1982). Many of these have become inoperative because of limited resources for extension and support. The primary focus of the Indian program is to provide fuel for cooking and lighting in rural domestic situations, mainly using eight to ten cubic meter floating cover digesters. In recent years, in order to reduce the capital cost of units, a lot of work has been done on the fixed dome Janata (Public) digester. Singh and Singh (1978) claimed that installation costs could be reduced by changing to the Janata design. Other designs such as the bag and plug flow do not appear to have penetrated into India at all. Besides cooking and lighting, biogas has also been used quite extensively for pumping and power generation.

In 1975 an All-India Coordinated Biogas program was initiated by the Department of Science and Technology involving the following research institutes already working on some aspect of this technology: (1) the Khadi and Villages Industries Commission (KVIC), (2) the Indian Council on Agricultural Research Institute (ICAR), (3) the Planning Research and Action Division (PRAD) of the government of Uttar Pradesh, (4) the Structural Engineering Research Centre, (5) the Indian Institute of Management (IIM), (6) the National Environmental Engineering Research Institute (NEERI), and (7) the Department of Physics, Lucknow University (TATA, 1981, 1982). In addition, the New Delhi and Bangalore campuses of the Indian Institute of Technology are carrying out research.

Previously information flowed through the All India Committee on Biogas in New Delhi. In 1983 the Department of New Energy Sources (DNES) was created to coordinate and improve implementation of biogas policies, research and development, demonstration, extention and construction of household and community units throughout India. The new department and its advisory Commission for Additional Sources of Energy will eliminate earlier problems of coordination and communication.

Nepal

In Nepal there are approximately 1,200 digesters operating, mostly floating cover, but a few fixed dome. In addition there are three community scale plants. The biogas produced is used primarily for cooking and lighting, although in some cases it has been used to power irrigation pumps.

The primary research, development and implementation institutes in Nepal are the Development and Consulting Services (DCS) of the Butwal Technical Institute, the Energy Research and Development Group (ERDG) in Tribhuvan University, and the Gobar Gas Company, which is a private company set up by DCS to commercialize biogas. DCS is very effective in publishing all the information it has available, which is circulated quite widely.

Sri Lanka

In Sri Lanka there were approximately 150 digesters in 1981, and it was estimated that by the end of that year there would be close to 300 (Santerre, 1981). Of the digesters installed, approximately 45% were floating cover designs, while the remainder were fixed dome. Most of the digesters were family sized, and the gas produced was used for cooking and lighting. The primary institutes involved with biogas in Sri Lanka are the Ceylon Electricity Board, and the Industrial Development Board.

Pakistan

The Appropriate Technology Development Organization (ATDO--1980) estimated that 60 units had been installed in Pakistan, and that 50 more were under construction. Most of these were small, three to ten cubic meters, and primarily for family cooking and lighting. The main organizations working with biogas are ATDO in Islamabad, and the Energy Resources Cell of the Ministry of Petroleum and Natural Resources.

Bangladesh

Bangladesh has a few biogas units installed, mostly in research institutes such as the Bangladesh Agricultural University and the Bangladesh University of Engineering and Technology at Dacca.

APPENDIX I

FUNDAMENTAL CONSIDERATIONS IN ANAEROBIC DIGESTION

This Appendix augments Chapter 2, providing information on fundamental aspects of anaerobic digestion. Included are microbiology and biochemistry, environmental influences on the digestion process, biodegradability, and kinetic modeling. Although these subjects are addressed to a depth which should be adequate for most readers, the numerous references cited are sources of additional information.

MICROBIOLOGY AND BIOCHEMISTRY

The biological processes in anaerobic digestion are complex, natural phenomena which take place continuously throughout the world. It is important to understand the reactions involved in order to construct facilities which utilize to maximum benefit the forces of nature.

Catabolism

All living organisms require energy for cell maintenance and growth. In nonphotosynthetic organisms, this energy is derived from the oxidative degradation of substrate material such as carbohydrates or fatty acids. Degradation of complex organic compounds into simpler compounds with release of energy is known as catabolism. The energy released during oxidation of substrate is captured and stored in the cell in the form of ATP (adenosine triphosphate, the major energy storage compound in cells). To preserve electroneutrality, oxidation of the substrate must be accompanied by reduction of another compound, for example:

$$4CH_3CHOCOOH + 11O_2 \longrightarrow 12CO_2 + 10H_2O + \text{energy} \qquad (1)$$

$$\text{lactic acid} + \text{oxygen} \longrightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

In this case, the acid is oxidized to carbon dioxide while oxygen is reduced (by transfer of hydrogen) to form water.

The main catabolic processes by which energy can be derived are classified according to the type of compound which is reduced while the substrate is being oxidized. Respiration refers to a catabolic reaction in which an inorganic compound is reduced. The reaction shown above for lactic acid is an example of aerobic respiration in which oxygen is available to the organism and is ultimately reduced to water. This allows complete conversion of the organic carbon to carbon dioxide and results in the greatest possible release of energy from the substrate. In the absence of oxygen, some organisms can undergo catabolism by reducing inorganics such as nitrate, sulfate or carbon dioxide to form nitrogen, hydrogen sulfide, or methane, respectively.

In the absence of inorganic oxidants, catabolism can proceed by concomitant oxidation and reduction of the organic substrate itself. This process is termed fermentation, and is characterized by reduction of an organic (rather than inorganic) compound, for example:

$$C_6H_{12}O_6 \xrightarrow{\text{yeast}} 2CH_3CH_2OH + 2CO_2 + \text{energy}$$
$$\text{glucose} \longrightarrow \text{ethanol} + \text{carbon dioxide} + \text{energy} \qquad (2)$$

Here, two moles of carbon are oxidized to carbon dioxide while four moles of carbon are reduced to form ethanol. Since all the carbon in the glucose molecule cannot be completely converted to carbon dioxide, much of the energy available in the substrate compound remains untapped (i.e., substantial energy still resides in the ethanol product). Hence, fermentation reactions yield only a small amount of energy compared with aerobic respiration. For example, a cell growing under anaerobic conditions must degrade about 20 times more glucose than a cell growing under aerobic conditions, in order to obtain an equal amount of energy. Because cell growth requires energy, the growth rate of anaerobic organisms is very slow, and aerobes can easily out-compete anaerobes if oxygen is present.

The slow growth rate of anaerobic organisms has important implications for anaerobic digesters. First, it requires that digesters be designed and operated to retain the organisms in the system for long enough periods to maintain the large bacterial population needed for efficient substrate utilization. Second, low cell yield means that anaerobic systems have low requirements for nutrients (such as phosphorus and potassium) and produce little excess cell mass.

Anaerobic Degradation of Complex Substrates

The organics in digester feed materials such as manure or agricultural residues can be classified into three main components: carbohydrates, proteinaceous compounds, and lipids (fats). The carbohydrates normally occur in the form of complex lignocellulosic fibers, proteins are large molecules made up of amino acid (peptide) chains, and fats are glycerides mostly comprised of various straight-chain fatty acids. Thus digester feedstocks are composed of very complex organic matter which must be solubilized and broken down into smaller compounds in order to be assimilated by cells.

The first step in this degradation is enzymatic hydrolysis which occurs in the substrate solution (outside of the cells) by the action of exocellular enzymes produced by the cells. Hydrolysis results in formation of sugars from carbohydrates, amino acids from proteins, and fatty acids from lipids, as well as other products. The smaller compounds thus produced can be absorbed by the cells and undergo reactions to either derive energy or synthesize new cell material.

In the case of cellulose, three enzymes are utilized sequentially to degrade the carbohydrates to simple sugars such as glucose. Inside the cell, these sugars are degraded to pyruvate, a major intermediate product in cell metabolism from which numerous end products can be formed. The main end products are CO_2, H_2 and acetate. However, depending on culture conditions such as pH, temperature and partial pressure of hydrogen, different reaction pathways are available which can also lead to formation of reduced compounds such as propionate, butyrate, and lactate.

Similarly, the amino acids obtained from hydrolysis of proteins are degraded to form NH_3, CO_2, acetate, formate, and propionate. Inorganic nitrogen compounds can also be degraded, with urea converted to ammonia and nitrate reduced to N_2. The fatty acids formed from lipids are principally degraded to acetate and molecular hydrogen (H_2) end products, although reduced products such as propionate and butyrate can also result depending on conditions.

Catabolism of complex substrates proceeds initially by hydrolysis followed by degradation to form a relatively small variety of end products. These include CO_2, NH_3, H_2, formate, acetate, propionate, butyrate, lactate, succinate, and ethanol. This degree of catabolism is carried out by a certain group of organisms known as fermentative bacteria. Although these end products still contain a substantial amount of energy which could be utilized for cell metabolism, fermentative bacteria are incapable of their further degradation. Further catabolism is carried out by other groups of bacteria resulting in the ultimate end products of anaerobic digestion, methane and carbon dioxide.

The Microbial Stages of Anaerobic Digestion

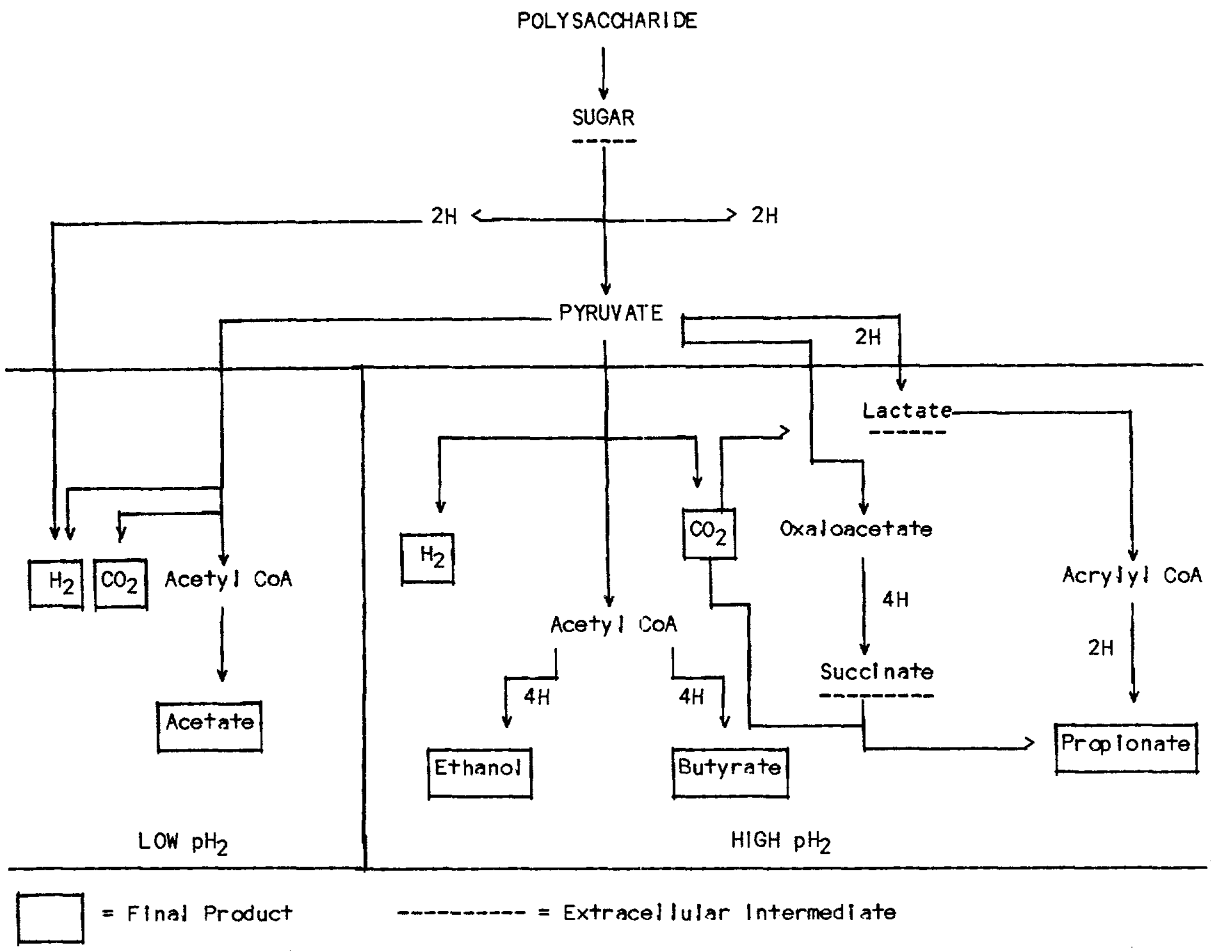
According to present theory, methane production in anaerobic systems occurs in stages from the activity of three main groups of bacteria: (1) fermentative (acid producing), (2) acetogenic (hydrogen producing), and (3) methanogenic (methane producing) bacteria. As discussed in the previous section, the fermentative bacteria are involved in the hydrolysis and breakdown of complex substrates into simple end products such as CO_2, H_2, and carboxylic acids. This occurs via two main catabolic pathways. In simplified form these are:

$$\text{substrate} \longrightarrow CO_2 + H_2 + \text{acetate} \qquad (3)$$

$$\text{substrate} \longrightarrow \text{propionate} + \text{butyrate} + \text{ethanol} \qquad (4)$$

The products from the first pathway above can be utilized directly by the third group of bacteria to produce methane. It has recently been discovered (Bryant et al., 1976), however, that reaction (3) is favored thermodynamically only at a low hydrogen partial pressure. At high hydrogen partial pressure the fermentative bacteria shift to alternate catabolic pathways (e.g., reaction 4) resulting in the formation of reduced organic compounds such as propionate, butyrate and ethanol. This is illustrated in Figure I.1.

Figure I.1. Simplified Scheme of the Pathways Involved in the Catabolism of Carbohydrates by Fermentative Bacteria and the General Trends in the Formation of the Major Endproducts at Low and High Partial Pressures of H_2. (After McInerney and Bryant, 1981.)



The second (acetogenic) group of bacteria utilizes the longer chain fatty acids (e.g., propionate and butyrate) which are produced in the fermentative stage. The acetogenic bacteria are so named because they produce acetate as well as hydrogen and CO_2. These products can be utilized directly by the methanogens to produce CH_4. Recent investigations (McInerney and Bryant, 1981) indicate the growth of the acetogens to be very sensitive to the partial pressure of hydrogen in the culture. Several species have been isolated which can only be grown in a co-culture with a hydrogen-utilizing bacterium, e.g., a methanogen (McInerney et al., 1979; Boone and Bryant, 1980). It appears that the acetogens are strongly dependent on the methanogenic bacteria to remove hydrogen as quickly as it is produced, otherwise the hydrogen partial pressure builds up and inhibits the breakdown of the substrate.

The methanogenic bacteria produce methane via two major pathways. About 70% of the methane produced in digestion of sewage sludge, for example, is formed by the splitting of acetate (Smith and Mah, 1978; Mountfort and Asher, 1978). The reaction is as follows:

$$CH_3COO^- + H_2O \longrightarrow CH_4 + HCO_3^- + \text{energy} \tag{5}$$

acetate + water -----> methane + bicarbonate + energy

Most of the remaining methane production is accomplished by bacteria which oxidize hydrogen and reduce bicarbonate (Gujer and Zehnder, 1982), as follows:

$$4H_2 + HCO_3^- + H^+ \longrightarrow CH_4 + 3H_2O + \text{energy} \tag{6}$$

hydrogen + bicarbonate + hydrogen ion -----> methane + water + energy

This second pathway is critical to the entire digestion process, since it is responsible for removing hydrogen and maintaining the low hydrogen partial pressure required for the production of acetate. If hydrogen partial pressure increases above a minimal level, for example, 0.0001 atmosphere (atm), the fermentative bacteria will shift to production of acids other than acetate, and conversion of these acids to acetate by the acetogens will initially cease. Since the primary pathway for methane production is by cleavage of acetate, a decreased rate of biogas production will result.

Since methanogenic bacteria are fragile and slow growing, it is important to maintain optimum environmental conditions such as temperature and pH and to recognize and correct unstable conditions. Although hydrogen partial pressure exerts a profound regulatory influence on the products of fermentation and the degradation of non-acetate acids, these effects occur at partial pressures which are so low as to be difficult to observe. Rather, an unbalanced reactor is often manifested in other ways such as decreasing pH levels due to the buildup of propionate and longer chain acids. Environmental conditions and their effects on digester performance are discussed in the next section.

Note also that the methanogenic bacteria are strict anaerobes. The presence of molecular oxygen is toxic to these organisms, and even the presence of inorganic sources of oxygen, for example nitrates, may inhibit their growth. Thus, successful digester operation requires that oxygen be excluded from the reaction vessel. This is important from a safety viewpoint as well, since introduction of air could result in an explosive gas mixture.

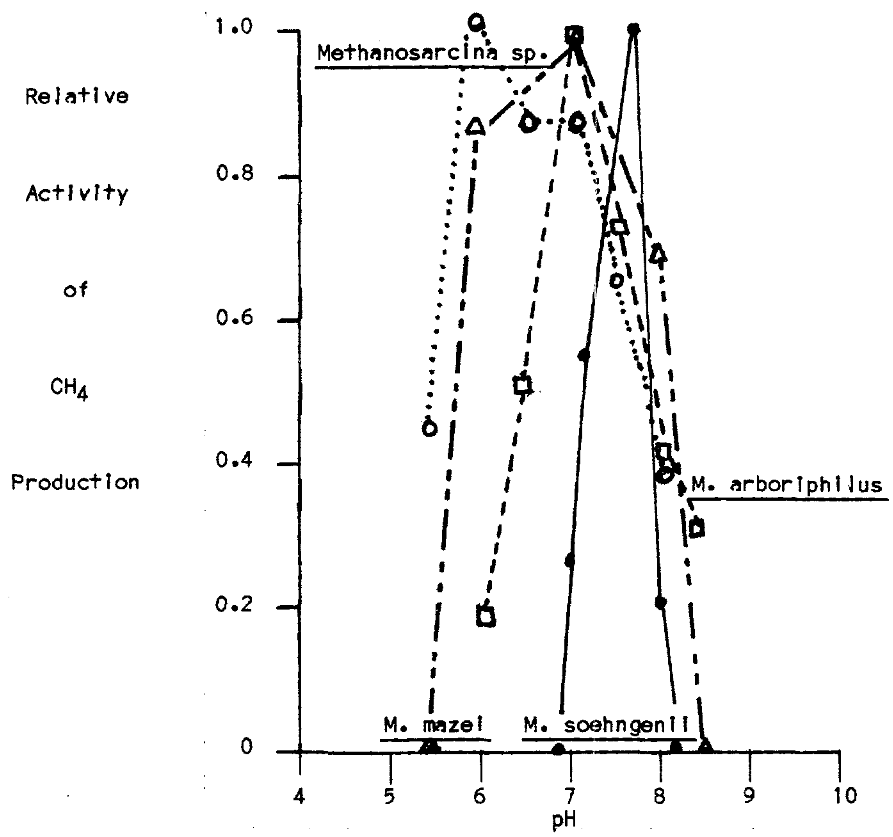
ENVIRONMENTAL FACTORS IN ANAEROBIC DIGESTION

As described above, efficient digester performance depends on maintaining healthy populations of three groups of bacteria which act together to convert substrate to methane. The hydrogen-removing methanogenic bacteria are particularly important since their inactivity can inhibit the activity of the other groups. The methanogens are also the slowest growing group and are generally the most sensitive to changes in the environmental conditions discussed below.

Digester pH

Methanogens generally exhibit a sharply defined pH range over which growth will occur, as shown in Figure I.2. The general optimum pH for digesters has been found to range from 6.8 to 7.2, in agreement with these data.

Figure I.2. Proton Activity Relationship for Methanogenesis. Activity of various pure strains of methane bacteria at different pH.



Reference: Zehnder et al. (1982).

The pH in the digester affects performance in several ways. Since CO_2 is a major component of biogas, and its solubility is substantially affected by pH, both the biogas composition and production rate are affected by changes in digester pH. Since methane is not highly soluble in water, its production rate is not altered by this effect. The digester pH can also affect performance by altering the solubility of any metal sulfides present, thus affecting the toxic influence of heavy metals.

Digester pH is governed by the interaction of the various acids and bases which are present in the reactor. Some of the chemical equilibrium reactions involved are:

$$CO_{2\,g} \rightleftharpoons CO_{2\,aq} \quad (7)$$

$$CO_{2(aq)} + H_2O \rightleftharpoons H_2CO_{3\,aq} \quad (8)$$

$$H_2CO_{3(aq)} \rightleftharpoons HCO_3^- + H^+ \quad (9)$$

$$HCO_3^- \rightleftharpoons CO_3^- + H^+ \quad (10)$$

$$Ca^{++} + 2HCO_3^- \rightleftharpoons CaCO_3 + CO_2 + H_2O \quad (11)$$

$$H_2O \rightleftharpoons H^+ + OH^- \quad (12)$$

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^- \quad (13)$$

$$CH_3COOH \rightleftharpoons CH_3COO^- + H^+ \quad (14)$$

$$H_2S \rightleftharpoons HS^- + H^+ \quad (15)$$

$$H_3PO_4 \rightleftharpoons H_2PO_4^- + H^+ \quad (16)$$

$$H_2PO_4^- \rightleftharpoons HPO_4^- + H^+ \quad (17)$$

$$HPO_4^- \rightleftharpoons PO_4^- + H^+ \quad (18)$$

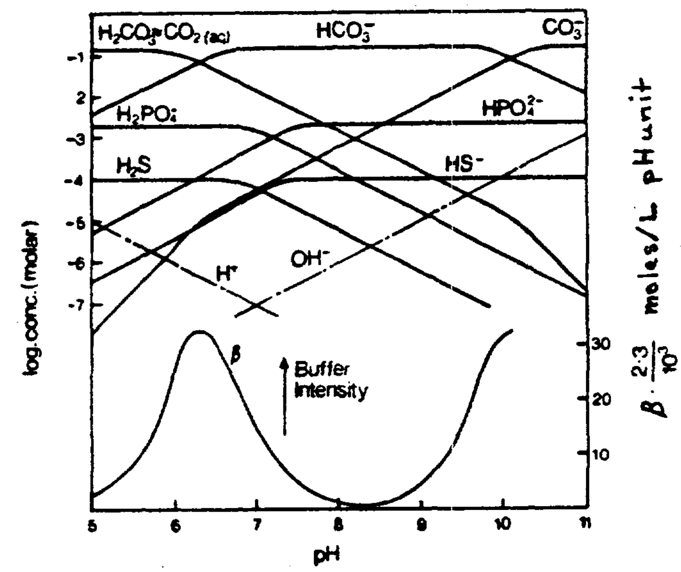
Equations (7) through (12) describe the aqueous carbonate/bicarbonate buffer system which occurs in natural water systems in equilibrium with CO_2. Equations (13) through (15) depict equilibria which result from the typical digester products ammonia, acetate and hydrogen sulfide. Equations (16) to (18) usually apply to a limited extent since phosphorus is a major nutrient requirement.

The high substrate concentrations typically employed in digesters result in high ionic strength, and accurate equilibrium pH calculations and measurements should include activity coefficient corrections. The reader interested in detailed acid-base equilibria calculations should consult an advanced text in water chemistry (e.g., Stumm and Morgan, 1970).

Figure I.3 demonstrates that buffer intensity rises sharply as the pH is decreased from 8 to approximately 6.3, with typical digester conditions. The presence of bicarbonate helps prevent adverse effects to microorganisms (methanogens) which would result from low pH caused by excessive production of volatile fatty acids during digestion.

Although bicarbonates provide buffering capacity, upsets in digester operation can lead to exhaustion of this buffer and shifts in pH which are large enough to degrade performance. For example, if the feed rate is suddenly increased sharply, the microorganisms would respond with increased growth. Since the fermentative bacteria grow faster than the methanogens, they are able to catabolize substrate and form acetate and other acids faster than these can be utilized by the methanogenic group, and acids will accumulate. If the buildup in volatile acids exceeds the buffer capacity of the solution, then the pH will drop below the optimum

Figure I.3. Logarithmic Equilibrium Diagram of the Distribution of the Main Solute, Inorganic, pH-buffering Species in the Supernatant of Digested Sewage Sludge.



Reference: Zehnder <u>et al.</u> (1982).

range for metabolism and the growth rate of the methanogens will be severely inhibited. When this happens the digester is said to be "unbalanced" because the population of acid-using bacteria has not kept pace with the growth of the acid-forming bacteria.

Other upsets in operation, such as a sudden temperature drop or introduction of a toxin, can also lead to an unbalanced condition and be manifested as a low pH condition. Once the digester becomes unbalanced, the condition must be corrected by operational changes; left to its own, the microbial system tends to sustain the undesirable condition since the acid-forming bacteria continue to reproduce faster than the methanogens at low pH.

Toxicity Effects in Digesters

Just as the presence of nutrients can stimulate digestion, so can digestion be inhibited by toxic levels of various substances. While toxicity is not often a problem in digesters operating on natural substrates, problems can often occur in treating industrial wastes. The penalty paid when a digester fails due to toxicity can be severe, sometimes requiring the digester to be emptied, its contents to be disposed of, and the unit to be restarted.

The first and most sensitive indicator of toxicity is methane production, since decreased methane yield often occurs long before there is a buildup of acids. An increase in volatile acids is also an indicator, but this can be misleading since toxic effects on fermentative bacteria may not result in buildup of acids, and in other cases stable operation can be attained even with volatile acid concentrations as high as 4000 mg/L (Kroecker et al., 1979). Better judgments can be made if both indicators, methane production and volatile acid concentration, are monitored.

Toxicity is measured in terms of the toxicity threshold, which for digesters is defined as the concentration of a substance at which there is a significant reduction in the rate of methane production from a balanced population, as compared with a control culture to which the substance has not been added. Measurement is most economically conducted using a batch bioassay technique, as developed by Owen et al. (1979). In this procedure, anaerobic seed, buffered nutrient media and the toxicant of interest are incubated in a stoppered serum bottle; a known amount of acetate and propionate is added and the methane production is monitored by means of a glass syringe. Inhibition is measured by comparing the methane production with toxicant present to that of a control in which toxicant is absent.

Researchers have documented a number of factors which affect toxicity and which make it difficult to obtain reproducible toxicity threshold values. For example, continuous digesters can show a marked resistance to toxic substances compared with batch systems (Stuckey et al. 1978). This is due to the phenomenon of acclimation, which represents an adjustment of the population (e.g., a rearrangement of its metabolic resources) to the adverse effects of a given toxicant. Acclimation can be achieved in continuous digesters by slowly increasing the concentration of the toxic substrate, as opposed to "shocking" the population by a sudden increase in concentration (Kugelman and Chin, 1971). Because of this phenomenon, batch bioassay data will normally give conservative threshold values when applied to the design of continuous systems.

Toxicity threshold values are also affected by antagonistic or synergistic effects. Antagonism is a reduction of the toxic effect of one substance by the presence of another. Synergism refers to cases in which the net toxicity of two substances is greater than the sum of the effects of each substance when acting independently. Other factors which influence toxicity include the microbial composition of the culture used in the bioassay test, the type of reactor (e.g., attached growth systems such as anaerobic filters appear more resilient) system pH, and adsorption of toxicant by the solids present in the digester (Kugelman and McCarty, 1965).

Many substances have been shown to be toxic or inhibitory to anaerobic digestion. Some of these, e.g., Ni, Na, Ca, K, and Mg, are stimulatory at very low concentrations but toxic at higher levels. It is also useful to note that, since Na and Ca are inhibitory at high concentrations, toxic effects can be caused by overcorrecting a low pH problem by adding too much chemical. From an exhaustive review of the literature, Stuckey (1983) classified a number of elements and compounds according to their threshold toxicities in anaerobic digestion. High threshold concentrations were reported for sulfide, calcium, magnesium, potassium, sodium and ammonia, and moderate threshold concentrations for heavy metals (Cd, Cr, Cu, Fe, Hg, Ni, Zn, etc.). In contrast, low threshold concentrations of aromatic, fatty, or propionec acids and of synthetic detergents were reported. The most toxic substances included antibiotics, acetylene, amines, azides, 2-bromethane, cyanides, and hydrogen ion.

Ammonia toxicity can result when feedstocks containing a high protein content are digested, causing deamination of protein constituents. An equilibrium is established between free ammonia (NH_3) and ammonium ion (NH_4^+) depending on the pH of the digester slurry:

$$NH_4^+ \rightleftharpoons NH_3 + H^+ \qquad (19)$$

Since free ammonia is much more toxic than ammonium ion, ammonia toxicity thresholds are very sensitive to pH. Free ammonia levels should be maintained below 80 mg/L while ammonium ion can generally be tolerated up to 1500 mg/L as N. With acclimation, stable operation has been demonstrated for ammoniacal nitrogen concentration up to 8000 mg/L (van Velsen, 1979). Cation antagonism has also been shown to reduce ammonia toxicity, with effects noted for sodium concentrations as low as 0.002 moles/L (Kugelman and Chin, 1971).

Although high concentrations of volatile acids such as acetate, propionate or butyrate are associated with toxicity effects, evaluations are complicated by the decrease in pH which results from a buildup in volatile acids in the digester. Recent experimental evidence suggests that relatively large concentrations of these compounds (e.g., 6000 mg/L or more) can be present without inhibiting digestion, provided that the digester pH is neutral so the acids are almost completely dissociated (McCarty, 1964b; Khan and Mes-Hartree, 1981; Hobson and Shaw, 1976).

The toxicity of certain heavy metals is shown in Table I.1. The soluble fraction is the toxic form, and toxic effects are thus affected by solubilities. Many heavy metals form insoluble sulfides and hydroxides. Thus the presence of sulfate and other sulfur forms in the feed can reduce the toxic effects of Cd, Ni, Pb, Zn, and Cu, during digestion. Small rises in pH (e.g., 0.3 pH units) can result in large (30 to 50%) decreases in concentrations of metals such as Ni, Zn, and Cu due to hydroxide precipitation. The solubilities of metal sulfides increase with temperature, and therefore in some cases higher operating temperatures may produce a slight heavy metal toxicity and not result in the increased methane production rates which would normally be expected.

Heavy metals are known to be absorbed by biomass, being actively transported to the cell wall interior (Hayes and Theis, 1978). This effect, coupled with solubility phenomena, normally results in relatively low soluble concentrations of heavy metals in digester slurry. Hence, allowable feed concentrations can be much greater than the threshold values, as seen by comparing Tables I.1 and I.2.

Table I.1. Concentration of Soluble Heavy Metals Exhibiting 50% Inhibition of Anaerobic Digesters (after Stuckey, 1983).

Cation	Approximate Concentration in mg/l
Fe^{++}	1^{-10}
Zn^{++}	10^{-4}
Cd^{++}	10^{-7}
Cu^{+}	10^{-12}
Cu^{++}	10^{-16}

Table I.2. Highest Dose of Metal that Will Allow Satisfactory Anaerobic Digestion of Sludge (continuous dosage).

Metal	Concentration in Influent Sewage, mg/liter	
	Primary Sludge Digestion	Combined Sludge Digestion
Chromium (VI)	50	50*
Copper	10	5
Nickel	40	10*
Zinc	10	10

*Higher dose not studied.

Reference: Adapted from Kugelman and Chin (1971).

Methods which can be used to control toxicity are:

a. Remove toxic substances from the feed (or keep them out);

b. Dilute the feed to below the toxic threshold value;

c. Add chemicals to form a non-toxic complex or insoluble precipitate; and/or

d. Add an antagonistic substance.

The first two methods may be straightforward in some cases but impractical in others. The third method has been demonstrated using ferrous sulfate addition. Since iron is the most soluble of the heavy metal sulfides, its presence causes the precipitation of other metals. Potential toxicity due to soluble iron is kept in check if sufficient alkalinity is present, since iron carbonate will precipitate (Lawrence and McCarty, 1964; Mosey, 1976; Grady and Lim, 1980). An example of the fourth method is the reduction of sodium toxicity by addition of potassium and calcium chlorides (McCarty, 1964a).

The Influence of C/N Ratio on Digestion

Nitrogen requirements are best evaluated based on the net rate of biomass production in the digester. This is because the amount of nitrogen required as a nutrient is governed mainly by the quantity of protoplasm (or cells) produced, and because the N content of anaerobic cells is approximately a fixed percentage of the total cell mass. Thus, the higher the overall cell yield, the higher is the nitrogen requirement. Evaluation of net cell yield, in turn, involves the effects of the feedstock biodegradability and reactor residence time.

Of the total carbon in the feed material, much but not all is usually degradable; the relatively nondegradable portion (e.g., lignin) passes through the digester essentially unchanged and requires no nitrogen. The fraction of the degradable carbon which is actually degraded is determined by the hydraulic residence time and other operating conditions such as temperature and pH. Only part of the carbon which is actually degraded is synthesized into cell mass, since much of it is converted into gaseous products (i.e., CH_4 and CO_2). This last factor is largely a function of the mean cell residence time, θ_c, since net cell yield is reduced at long θ_c due to endogenous respiration and cell lysis. Thus it is evident that the amount of nitrogen required per quantity of carbon in the feed (i.e., the optimum feed C/N ratio) can vary considerably for different digester feeds, designs and operating conditions.

Actual feedstocks have widely varying C/N ratios. Stuckey (1983) assembled C/N ratio information from a variety of sources (Barnett, 1978; BORDA, 1980; Chynoweth, et al., 1978; Fry, 1975; Hills, 1979; NAS, 1977; Polprasert, 1982; UNEP, 1981; van Brakel, 1980; Wolverton and McDonald, 1978). Reported C/N ratios varied from about 1 for human or animal urine to from 5 to 10 for human feces, 7 to 15 for poultry or swine manure, 15 to 30 for sheep, and 20 to 35 for cattle and horses. Ratios for forage, grasses, hay, and water hyacinth were from about 10 to 30 and for straw and plant stalks from 30 to 150. Raw and rotted sawdust were about 500 and 200, respectively. Household garbage varied from 20 to 35. Optimum C/N ratios can be determined for specific cases by assessing the factors discussed above. For feedstocks with non-optimum C/N ratios, adjustment of the ratio may improve performance or may even be essential for successful operation. For example, the C/N ratio of a feed could be empirically adjusted upwards by mixing it with a carbohydrate-rich material (e.g., straw added to nightsoil). In other cases, dilution with water may be a practical way to alleviate NH_3 toxicity which would otherwise result from a feed having a low C/N ratio.

BIODEGRADABILITY OF DIGESTER FEEDSTOCK

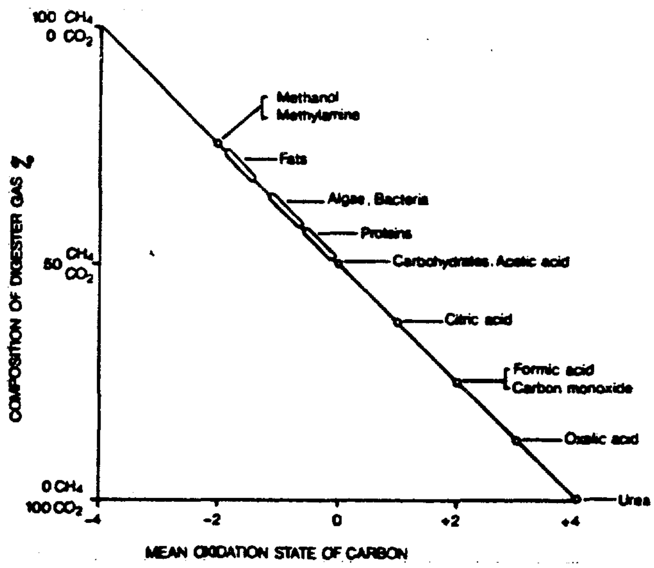
Biodegradability and Gas Production

Methane, of course, is one of the major products of interest in digester operation. The quality of the biogas depends on the relative amounts of CH_4 and CO_2 ultimately produced. The methane content obtainable from a given feedstock material can be estimated if the average chemical composition of the feed is known. Suppose, for example, that the feed to a digester contained only carbohydrates with an average composition of $C_6H_{10}O_5$. Assuming complete conversion to CO_2 and CH_4, the digestion process would be described by the following balanced reaction:

$$C_6H_{10}O_5 + H_2O \longrightarrow 3CO_2 + 3CH_4.$$

This results in a gas composition of about 50% methane. This result is typical for carbohydrate feedstocks, and similar results can also be derived for complex feedstocks containing carbohydrates, proteins, and lipids, as shown in Figure I.4. The calculation described above is oversimplified, however, and should be corrected for effects such as less than complete conversion of feed to gaseous end products, diversion of substrate into cell growth, and solubility of CO_2 in substrate.

Figure I.4. Composition of Biogas Depending on Mean Oxidation State of Carbon in the Substrate, Assuming Total Mineralization.



Reference: Zehnder (1982).

A more complete approach that accounts for these factors was developed by McCarty (1974):

$$C_nH_aO_bN_c + H_2O \longrightarrow CH_4 + CO_2 + C_5H_7O_2N + NH_4^+ + HCO_3^- \tag{21}$$

where the $C_5H_7O_2N$ product is the average chemical composition of anaerobic cells as determined empirically. Bicarbonate ion is formed as needed to balance the positive charge from ammonium ion production. Balancing equation (21) gives

$$\begin{aligned} &C_nH_aO_bN_c + (2n + c - b - \frac{9sd}{20} - \frac{ed}{4})H_2O = \\ &\frac{de}{8} CH_4 + (c - \frac{sd}{20})HCO_3^- + \frac{sd}{20} + C_5H_7O_2N + (c - \frac{sd}{20})NH_4^+ + \\ &(n - c - \frac{sd}{5} - \frac{de}{8})CO_2 \end{aligned} \tag{22}$$

where $d = 4n + a - 2b - 3c$, and $s + e = 1$. The value s represents the fraction of degradable substrate converted to cells, while e is the portion converted to CO_2 and CH_4 (i.e., energy). The value of s is given by:

$$S = a_e \frac{(1 + R_c b\theta_c)}{(1 + b\theta_c)} \qquad (23)$$

where a_e = maximum s value (for $\theta_c = 0$);

b = endogenous decay coefficient, time $^{-1}$;

θ_c = solids residence time; and

R_c = the refractory portion of cells formed during decay (= 0.2).

Values of a_e, taken from McCarty (1972), are given in Table I.3.

Table I.3. Values for a_e and Y in Equation 23 for Methane Fermentation of Various Waste Components.

Waste Component	Chemical Formula	a_e	Y gm cells per gm COD consumed
Carbohydrate	$C_6H_{10}O_5$	0.28	0.20
Protein	$C_{16}H_{24}O_5N_4$	0.08	0.056
Fatty Acids	$C_{16}H_{32}O_2$	0.06	0.042
Domestic Sludge	$C_{10}H_{19}O_3N$	0.11	0.077
Ethanol	C_2H_6O	0.11	0.077
Methanol	CH_4O	0.15	0.11
Benzoic Acid	$C_7H_6O_2$	0.11	0.077

Reference: Adapted from McCarty (1972).

In equation (22), it is assumed that substrate is converted completely to the products shown; that is, residual quantities of intermediate products such as acetate are neglected. This assumption would be reasonable for a well-operating digester with a long residence time. In addition, equation (22) neglects the effects of digester temperature, pressure and pH, which affect the bicarbonate and ammonium ion concentrations.

The empirical formula for the feed, $C_nH_aO_bN_c$, refers to the average chemical composition of the biodegradable fraction. This formula can be calculated from analytical values of the volatile weight of organics, the COD, the organic nitrogen and the organic carbon content of the feed, as shown by McCarty (1972). Since it is difficult to separate the degradable fraction from the refractory fraction, it is convenient (although not strictly accurate) to assume the chemical composition of both fractions to be the same. Under this assumption, equation (22) shows that one mole of feed would produce (1-R)(de/8) moles of methane, where R is the fraction of the feed which is refractory. Thus equation (22) can be used to provide useful estimates of gas production and composition; however, the factors which limit its accuracy should be kept in mind.

Another method of estimating biogas production is by means of a material balance. This can be done by measuring the chemical oxygen demand (COD) of all the streams (including biogas) which enter and exit the digester. COD is determined analytically by addition of a strong chemical oxidant such as dichromate ion to a sample, and is a measure of the equivalent oxygen required by the sample to oxidize its constituents to compounds such as CO_2 and H_2O (Standard Methods, 1978).

Of the products in the gas phase, carbon dioxide has zero COD since it is fully oxidized. The COD of methane can be calculated from the stoichiometry of its oxidation reaction:

$$CH_4 + 2O_2 \longrightarrow CO_2 + H_2O \qquad (24)$$

From this we can see that one mole of methane requires two moles of oxygen and thus has a COD of 2 x 32g = 64g. Since one mole of gas occupies approximately 22.4 liters at standard conditions (ideal gas law), one liter of methane (at STP) is equivalent to 64/22.4 = 2.86g of COD.

For an anaerobic process with no oxygen present, COD is a conservative parameter. That is, the sum of all COD inputs to a digester is equal to the sum of all its COD outputs. This means that the COD removed from the feed (i.e., influent COD minus effluent COD) is equal to the COD of the biogas. Hence, removal of one gram of COD from the feed results in one gram of gaseous COD, or 1/2.86 = 0.35 liters of methane at STP. Applied to a continuous flow digester at steady state conditions, the volumetric methane production rate is:

$$V = 0.35\ (S_i - S_o)\ Q \qquad (25)$$

where S_i = influent COD, g/L;

S_o = effluent COD, g/L;

Q = influent flow rate, L/d; and

V = methane production rate (at STP), L/d.

Equation (25) accounts for the biodegradability of the feed through the term S_o, which includes the refractory fraction of the feed. S_o also accounts for residual levels of degradable organics which are in the effluent due to incomplete conversion. In using equation (25), S_i and S_o are measured analytically for a feedstock of interest.

As COD can be correlated with the volatile solids (VS) content of a sample, VS analyses can be used in predicting gas production. However, the relationship between COD and VS is empirical, varying considerably from sample to sample. For example, the COD/VS ratio for a carbohydrate is about 1.1 whereas that for a lipid is about 2.9 and that for a protein is about 1.5 (McCarty, 1972). Thus, care should be exercised when predicting gas production on the basis of VS values.

Factors Affecting Biodegradability

Biodegradability is usually measured as either percent COD removal or percent VS destruction, and varies considerably for different feedstocks (see Table I.4). Biodegradability should be normalized in terms of digester residence time (θ), since a typical digestion may achieve 80% degradation in 15 days, 90% in 30 days, and 95% in 120 days.

Table I.4. Biodegradability of Various Digester Feeds

Substrate	θc days	T °C	%COD destroyed	%VS destroyed	Comments
Broiler Chicken litter	10	60	13	20	high lignin content age for one year
Peat (Minnesota)	60	35		11.1	
	56	55		16.7	
Swine manure	15	35	58	60	14% protein ration
Diary Bull manure	15	32 .5	11.27	26.7	10% TS feed
Swine manure	15	32 .5	54.6	60.9	"
Poultry manure	15	32 .5	78.1	67.8	"
	28	31	45.3	-	
Meatworks effluent 140	15.1	26	-	44.3	
Yeast waste	-	30	67.1	62.6	
Cattle manure	80	-	-	28.1	
Kelp 159	12	35	57.7	45.1	
Dairy manure + barley straw	25	35	30.2	28.9	80% alfalfa, 15% barley, 80% manure, 20% straw
Hyacinth-Bermuda grass-MSW-sludge blend (25% each)	12	35	40.3	39.2	
Beef Cattle manure (varying feed)					constant through temp.
9 % corn silage, 88% corn		30 .6	72.5	-	range = biodeg. at
91.5% corn silage, 0% corn			52.1	-	infinite detention
40.0% corn silage, 53.4% corn			55		67.1
7% corn silage, 87.6% corn		55	73.5	-	
6-8 weeks old feed lot		55	60.0	-	
Municipal refuse	15	35	45.6	36.2	12.5% sewage solids added
Corn stover (Illinois)	40	35	64.8		batch
(Missouri)	40	35	59.1		batch
Wheat straw	120	35		55.4	batch
Corn stalks	120	35		77.2	batch
Corn leaves	120	35		71.8	batch
Cattails	120	35		59.3	batch
Treated kelp	120	35		62.0	batch
Water hyacinth	120	35		58.8	batch
Corn meal	90	35		84.9	batch
Newsprint	90	35		28.1	batch
Elephant manure	120	35		52.5	batch
Chicken manure	120	35		75.6	batch
Swine manure	120	35		72.7	batch
Dairy cow manure R_1	120	35		58.8	batch
Dairy cow manure R_2	120	35		57.5	batch
Dairy cow manure R_3	120	35		52.8	batch
Diary cow manure	120	35		52.8	batch

Source: Adapted from Stuckey, 1983.

Most of the common digester feedstocks contain a considerable portion of plant material, either added directly as crop residues or indirectly as animal manures. Many of the constituents of plant matter are highly biodegradable, as shown in Table I.5. Lignin, however, is essentially 100% refractory and is believed to inhibit the biodegradability of the carbohydrates with which it is linked. For example, lignified cells may physically entrap nutrients or may block access to cellulosic fibers (van Soest, 1979). Since lignin is a major component of plants responsible for providing structural support to plant cell walls, it has a great effect on the overall biodegradability of typical digester feeds.

Table I.5. Anaerobic Biodegradability of Plant Constituents (after van Soest, 1979).

Substance	Biodegradability
lignin	virtually refractory; inhibits degradation of associated carbohydrates
carbohydrates	most soluble forms highly degradable
proteins, amino acids, nucleic acids	highly degradable
pectin	highly degradable
cellulose	crystalline form (ordered) highly degradable; amorphous form (non-ordered) less degradable
hemicellulose	acid soluble and relatively degradable in pure form; insoluble in native state (bonded with lignin)

The effect of lignin is demonstrated by many of the substances listed in Table I.4. Peat has a high lignin content because the non-lignin fractions are extensively degraded in the natural environment, and it shows a highly refractive content. On the other hand, cornmeal has a low lignin content, having a low percentage of cell wall material, and exhibits high degradability. The reported values for degradability of cattle manure vary from about 30 to 70%; this can be explained as follows:

a. the high protein rations used in developed countries have low lignin content and the resulting manures show high degradability;

b. cattle in developing countries are mostly fed agricultural residues with a high content of lignocellulosics resulting in more refractory manures; and

c. better degradability has been found for fresher manures (Hashimoto et al., 1981).

Another factor which appears to influence biodegradability is the amenability of the substrate to solubilization. Hemicelluloses, for example, are acid soluble and relatively degradable in their pure form, but are insoluble and less degradable in their native state (in which they are bonded with lignin, van Soest, 1979). In addition, many soluble industrial wastes are highly degradable (75% or more, McCarty et al., 1972; McMorrow et al., 1970; Hiatt et al., 1973; Arora et al., 1975), while insoluble sludges and animal wastes are only 40 to 60% degradable (Hobson and Shaw, 1973).

Analytical Measurement of Biodegradability

In most cases, experimental determination of biodegradability is preferable to use of literature values, due to the numerous variables which affect biodegradability. Operation of a continuous flow digester at a long detention time yields the best data, but is time consuming and expensive. Use of less expensive methods (e.g., batch incubations) reduces cost and allows assessment of more variables (such as C/N ratio, temperature, pretreatment, etc.).

Owen et al. (1979) developed an incubation technique using glass serum bottles to measure the biodegradability of a substrate. Detailed experimental techniques are given in the paper, but in principle the assay is as follows. The serum bottle (250 ml) is flushed with a 70% N_2, 30% CO_2 gas mixture and a known amount (with respect to COD) of the substrate is placed into the bottle together with an anaerobic seed and buffered nutrient media. A rubber serum cap is inserted into the top of the bottle to seal it, and the bottle is incubated at the temperature of interest. From time to time, the gas volume produced in the bottle is measured by means of a wetted glass syringe inserted through the rubber cap. Each time the volume is measured, the gas composition (%CO_2, N_2, CH_4) is determined by a gas chromatograph. As discussed previously, the amount of methane produced can be directly related to the removal of COD from the substrate, and hence the degradation of substrate can be determined as a function of reaction time.

To determine the refractory portion (R) of the substrate, it is assumed that the degradable portion is completely converted to CH_4 and CO_2 products as the reaction time approaches infinity (Morris et al., 1977). Extrapolation of the data to infinite reaction time gives R, since any substrate COD remaining is refractory.

This batch bioassay method is very flexible since a large number of bottles can be set up at one time, and it is inexpensive since it only requires glassware and a few chemicals. In developing countries where gas chromatography equipment may not be available, older and simpler methods might be used such as CO_2 absorption in hydroxide and ignition of methane.

Care should be exercised in reporting and comparing biodegradability data since the term is used loosely in the literature and confusion can result. This is best illustrated by an example. Suppose a solution of glucose containing 100 mg/L COD is to be digested. Digestion would typically convert 80 mg/L COD of this COD to methane and 20 mg/L to biological cells. Although glucose is 100% biodegradable, COD measurements of the influent and effluent would show only an 80% reduction.

Pretreatment Methods to Increase Biodegradability

Since most common digester feeds are only 40 to 60% degradable, substantial increases in gas yield could be achieved if the substrate could be rendered 100% biodegradable. This is particularly true for feeds which contain a large amount of refractory lignocellulosics such as agricultural residues. There are three main methods for increasing biodegradability which are briefly discussed below.

Physical-chemical methods involve reaction with an acid or alkali at ambient or elevated temperature (100 to 200°C). Various researchers have demonstrated improvements in biodegradability of 100% or more using heat or chemical treatments on feedstocks such as cornstalks, municipal solid waste, activated sludge, rice straw, and sugar cane bagasse (Buswell and Hatfield, 1936; Gossett, 1976; Owen, 1979; Stuckey, 1980; Robbins et al., 1979; Han and Callihan, 1974; McFarlane and Pfeffer, 1981). Nonetheless, these methods do not appear to be economical due to the high cost of chemicals or heating equipment involved.

Physical methods include cutting, grinding or shredding of the feedstock to increase surface area for enzymatic attack. Available data (Nelson et al., 1939; Ghosh and Klass, 1979; Buswell and Hatfield, 1936; Wolverton et al., 1975; Colberg et al., 1980) in this area are contradictory, but it appears that substantial positive effects require reduction to a very small particle size (e.g., to a flour form). More studies are needed to better define the potential of this technique.

Biological pretreatment methods include aerobic composting and feeding to animals followed by dung collection. While the latter method is obviously a widespread practice, composting appears to be common mainly in China (UNEP, 1981). Compost piles are prepared by cutting crop residues into small pieces and mixing these with limewater and excreta. Composting can reduce scum formation and increase gas yield, but it also consumes some of the organic substrate in the composting process itself; hence the composting time should be adjusted to maximize gas yields. This method appears promising since it is simple to carry out, but further work should be performed to quantify the benefits and optimize the parameters involved.

KINETIC MODELS

Monod Model

For a bacterial culture under conditions in which an essential nutrient (or substrate) is present in limited amounts, Monod (1949) showed that the growth rate can be described by the following hyperbolic function:

$$\mu = \mu_m \frac{S}{K_s+S} \qquad (26)$$

where S = essential nutrient (or substrate) concentration, mass/unit volume;

μ = specific growth rate, time^{-1};

μ_m = maximum specific growth rate, time^{-t} (at large S); and

K_s = "half-rate" coefficient (i.e., concentration of S at which the rate is one-half the maximum, or $\mu = 1/2\ \mu_m$), mass/unit volume.

Assuming the limiting nutrient to be the biodegradable fraction of the feedstock (i.e., the energy source), the following relationships can be derived for the ideal case of a completely mixed digester without solids recycle (McCarty, 1974):

$$r_{su} = -\frac{dS_d}{dt} = -\frac{kS_dX}{K_s + S_d} = \frac{S_d^o - S_d}{\theta_c} \quad (27)$$

$$S_d = \frac{K_s(1 + b\theta_c)}{\theta_c(Yk - b) - 1} \quad (28a)$$

$$\frac{1}{\theta_c} = \frac{kYS_d}{K_s + S_d} - b \quad (28b)$$

$$S_T = S_r^o + \frac{K_s(1 + b\theta_c)}{\theta_c(Yk - b) - 1} + \frac{1.42Y(S_d^o - S_d)(1 + 0.2b\theta_c)}{(1 + b\theta_c)} \quad (29)$$

$$v = \frac{0.35(S_T^o - S_T)}{\theta} \quad (30)$$

where r_{su} = substance utilization rate, mass/unit volume.time;

S_d = concentration of biodegradable substrate in the effluent, mass/unit volume;

S_d^o = concentration of biodegradable substrate in the influent, mass/unit volume;

S_T = concentration of total substrate in the effluent, mass/unit volume;

S_T^o = concentration of total substrate in the influent, mass/unit volume;

S_r^o = concentration of refractory substrate in the influent, mass/unit volume;

t = time;

k = μ_m/Y = maximum utilization rate coefficient, mass of substrate consumed per time per mass of microorganisms;

Y = maximimum yield coefficient, mass of cells formed per mass of substrate consumed;

X = concentration in the reactor of microorganisms utilizing substrate, mass/unit volume;

b = endogenous decay coefficient, $time^{-1}$;

θ = hydraulic detention time, time;

θ_c = mean cell (solids) residence time, time;

γ_v = volumetric gas production rate, volume of methane per time per volume of reactor.

Substrate concentrations S_d, S_T^o, etc., are often expressed in terms of chemical oxygen demand (COD), g/L. Note that equation (30) is valid only for S_T expressed as g/L of oxygen demand (see equation 25).

These relationships describe key performance parameters (i.e., degree of feedstock degradation, rate of gas production) in terms of kinetic coefficients (b, Y, k, K_s) and the design parameter, θ_c. For a given feedstock composition and digester temperature, the kinetic coefficients are fixed, and the model predicts S_d and γ_v to be functions of only one variable, θc. This provides an underlying justification for the design approach described in the previous section based on use of θc as the key design variable.

The results of the Monod model can be used to determine an optimum value of θ_c which minimizes effluent concentration (or maximizes gas production rate), by simply plotting S_T (or γ_v) versus θc for a given feed composition and operating temperature. Also equation (28b) can be used to predict the minimum θ_c^m (at which washout will occur), since S_d equals S_d^o at this condition.

First-Order Model

In many cases, the substrate utilization rate can be adequately described by a simple first-order rate expression:

$$\frac{dS_d}{dt} = -k_1 S_d \qquad (31)$$

where k_1, the first order rate coefficient ($time^{-1}$), is a function of temperature.

Integration of equation (31) gives:

$$\ln S_d - \ln S_d^o = K_1 t \qquad (32)$$

so k_1 can be determined using batch reactor data from a plot of ln S_d versus t. Applying equation (31) to a completely mixed digester without solids recycle gives:

$$S_d = \frac{S_d^o}{k_1 \theta + 1} \qquad (33)$$

Thus, k_1 can be calculated readily using influent and effluent concentration data from a digester operating at steady state conditions.

Contois Model

It is often observed that as the feed substrate concentration is increased, the bacterial growth rate decreases, presumably due to mass transfer limitations. Contois (1959) proposed a modified form of the Monod expression to account for this effect:

$$\mu = \frac{\mu_m S_d}{B S_d^o + S_d} \qquad (34)$$

where B is a kinetic coefficient. Chen and Hashimoto (1978) applied this model to the digestion of cattle manure for a completely mixed reactor without solids recycle, and derived the following:

$$S_d = \frac{K S_d^o}{\theta\, u_m - 1 + K} \qquad (35)$$

$$\gamma_v = \frac{B_o S_T^o}{\theta} \left[1 - \frac{K}{\theta\, \mu_m - 1 + K} \right] \qquad (36)$$

where K = a kinetic coefficient, dimensionless

B_o = ultimate methane yield coefficient (for infinite θ), volume of methane produced per unit mass of substrate in the feed

θ = hydraulic residence time (= θ_c in this case)

For specific conditions of feedstock composition and digester temperature, the kinetic coefficients (μ_m and K) and the gas yield coefficient (B_o) have fixed values, and S_d and γ_v are then determined solely by θ_c. This is the same conclusion as reached above for the Monod model, and supports the use of θ_c as a key design parameter.

Determination of Kinetic Coefficients

In order to use kinetic models, one must evaluate the various coefficients. It is also important to evaluate which model is most appropriate to use. Since none is perfect, one model may give a closer fit to a particular data set than another, depending on the type of feed material, the operating conditions and the residence time of the reactor. Also, a simpler model is easier to use and may be more appropriate for certain digester types or where only limited data are available.

The rate coefficient for the first-order model can be readily determined from either batch or continuous digester data using either equation (32) or equation (33). Two kinetic coefficients must be evaluated for the Contois model, μ_m and K. With data obtained from a series of digester experiments having different residence times, these coefficients can be determined from a plot of θ vs $(S_d^o - S_d)/S_d$, since equation (35) can be rearranged as follows:

$$\theta = \frac{1}{\mu_m} + \frac{K}{\mu_m}\frac{(S_d - S_d^o)}{S_d} \qquad (37)$$

Thus, the slope of the plot would give K/μ_m and the intercept would equal $1/\mu_m$. The gas yield coefficient, B_o, must also be determined from experimental data. This can be done by measuring gas production as a function of θ and extrapolating to estimate the methane yield at very large θ, or by batch incubation tests. It is important to run these experiments at constant conditions, since the coefficients are functions of the type of feed and the operating temperature, pH, etc. A new set of coefficients must be evaluated for each temperature of interest.

Four kinetic coefficients must be evaluated at each temperature in order to use the Monod model. This is determined from laboratory data in the following example problem for a soluble feedstock.

Given

Assume the following data for pure acetate feedstock obtained at steady state conditions from a bench scale digester at 20°C using a continuous complete-mix reactor without recycle of solids.

Unit Number	S_d^o mg COD/L	S_d mg COD/L	$\theta = \theta_c$ d	X mg VSS/L
1	10,000	8,450	10	50
2	10,000	4,590	12	190
3	10,000	2,500	16	240
4	10,000	1,750	20	250
5	10,000	1,380	24	250
6	10,000	1,080	30	240

Required

Determine the values of the coefficients Y, b, k and K_s. Estimate the gas production rate for a feed concentration of 15,000 mg/L (as COD) and a mean cell residence time of twice the minimum value.

Solution

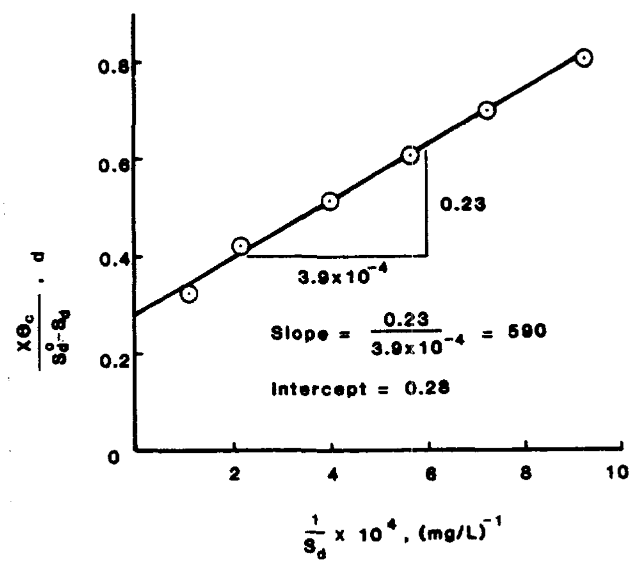
1. Divide equation (27) by X and take its inverse to obtain:

$$\frac{X\theta_c}{S_d^o - S_d} = \frac{K_s}{k}\frac{1}{S_d} + \frac{1}{k}$$

The values of K_s and K in this equation can be derived from a linear plot of $X\theta_c/(S_d^o - S_d)$ versus $(1/S_d)$, with the y-intercept equal to (1/k) and the slope equal to (K_s/k).

Compute the terms and plot the data:

Unit Number	$\frac{X\theta_c}{S_d^o - S_d}$	$\frac{1}{S_d}$
1	0.323	0.000118
2	0.421	0.000218
3	0.512	0.000400
4	0.606	0.000571
5	0.696	0.000724
6	0.807	0.000926



The y-intercept equals (1/k):

$1/k = 0.28$ mg VSS·d/mg COD

$k = 3.6$ mg COD/mg VSS·d

The slope equals (K_s/k):

$K_s/k \;=\; 590$ mg COD d/L

$K_s \;=\; (3.6)(590) \;=\; 2120$ mg COD/L

2. Rearrangement of equation (27) gives:

$$\frac{kS_d}{K_s + S_d} = \frac{S_d^o - S_d}{X\theta_c}$$

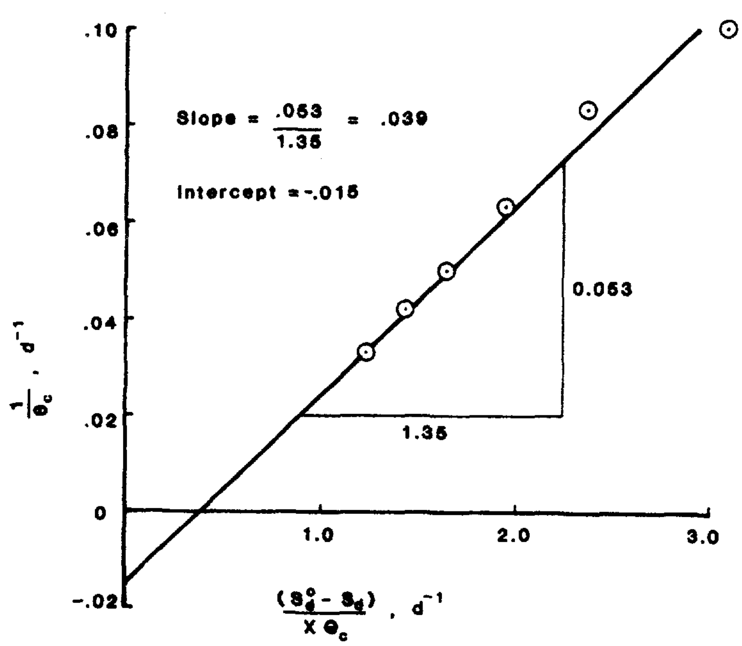
Substitution of this expression into equation (28b) yields:

$$\frac{1}{\theta_c} = \frac{Y(S_d^o - S_d)}{X\theta_c} \quad -b$$

Using this equation, a plot of $(1/\theta_c)$ versus the term $(S_d^o - S_d)/X\theta_c$ should result in a straight line with a slope equal to Y and a y intercept equal to (-b).

Compute the terms and plot the data:

Unit Number	$\frac{1}{\theta_c}$	$\frac{S_d^o - S_d}{X\theta_c}$
1	0.100	3.100
2	0.083	2.375
3	0.063	1.953
4	0.050	1.650
5	0.042	1.437
6	0.033	1.239



The y-intercept equals (-b):

$b = -(-0.015) = 0.015\ d^{-1}$

The slope equals Y:

Y = 0.039 mg VSS/mg COD utilized

3. Compute θ_c^m for a feed concentration of 15,000 mg/L by setting S_d equal to S_d^o in equation (28b):

$$\frac{1}{\theta_c^m} = \frac{kYS_d^o}{K_s + S_d^o} - b = \frac{(3.6)(.039)(15,000)}{(2120 + 15,000)} - 0.015 = 0.108$$

$$\theta_c^m = 9.25\ d$$

4. Calculate the effluent concentration using equation (28a), with $\theta_c = 2\theta_c^m = 18.5$ d:

$$S_d = \frac{Ks(1 + b\theta_c)}{\theta_c(Yk - b) - 1} = \frac{(2120)[1 + .015(18.5)]}{18.5[.039(3.6) - .015] - 1} = 2050 \text{ mg COD/L}$$

5. Estimate the gas production rate using equation (30):

$$v = \frac{0.35(S_T^o - S_T)}{\theta}$$

where $\theta = \theta_c = 2\ \theta_c^m = 18.5$ d and $S_T = S_d$, because acetate is 100% degradable.

Thus,

$$v = \frac{0.35(15 - 2.05)}{18.5} = 0.245 \text{ L methane/L reactor volume} \cdot \text{d}$$

Note that the units of S_T to use in equation (30) are g COD/L.

As defined in the Monod model, X is the concentration of anaerobic bacterial mass which is utilizing substrate in the digester. In the above example, the value of X was taken as equal to the volatile solids content of the insolubles present in the digester. This is a reasonable assumption for such cases in which the feed contains no insoluble matter and thus all the solids in the digester can be presumed to be active anaerobic bacterial matter. For most biogas feedstocks of interest, however, a substantial quantity of insoluble matter is introduced with the feed, and it is difficult to determine what portion of the solids in the digester constitute anaerobic bacterial mass. This means that X cannot be determined readily for most cases of practical interest, and thus the relations derived from the Monod model (equations 27 through 30) are most useful for soluble feedstocks (e.g., industrial wastewater). Digesters with insoluble feeds are designed based on substrate-limited conditions, as assumed in the Monod model, but because X is difficult to measure, θ_c is often used directly as a design parameter rather than relationships such as given in equations (27) through (30).

Application of Kinetic Models to Design of Various Digester Types

The discussions above have been directed mainly towards the sizing of continuous flow digesters without solids recycle. This section briefly discusses examples of design approaches which can be used to size other types of anaerobic systems.

For batch reactions, the first-order model is typically used. For digestion of tropical vegetable material (e.g., grass, coffee husks), Boshoff (1967) used a formula similar to equation 32:

$$y = G(1 - e^{-k_1 t}) \qquad (38)$$

where y = quantity of gas produced in time t;

G = quantity of gas produce at t = infinity; and

k_1 = first-order rate coefficient, $time^{-1}$.

Once G and k_1 are evaluated (for a given feed and temperature), equation (38) can be used to calculate the time required in the reactor to produce a desired amount of gas.

The performance of a plug flow reactor is approximately equal to that obtained by several completely mixed reactors in series, as shown by Jewell et al. (1980) using a first-order kinetic model. For n reactors in series, it can be shown from equation (33) that the substrate concentration in the final reactor is given by:

$$S_d^n = \frac{S_d^o}{\left(1 + \frac{k_1 \theta}{n}\right)^n} \qquad (39)$$

where S_d^n = biodegradable substrate concentation in effluent from the n^{th} (final) reactor, mass/unit volume;

n = number of reactors in series; and

θ_n = hydraulic residence time of the reactor series ($= \theta_1 + \theta_2 + . . . + \theta_n = \theta_c$).

A plug flow reactor is more closely approximated if n is very large ($n \rightarrow \infty$), in which case:

$$\lim_{n \rightarrow} \left[1 + \frac{k_1 \theta_n}{n}\right]^n = \exp(k_1 \theta) \qquad (40)$$

and

$$S_d^n = S_d^o \exp(-k_1\theta) \quad (41)$$

This expression is of the same form as the result given above for a batch reactor (equation 38).

The factors affecting the kinetics of waste removal in an anaerobic filter are complex but can be described using a first-order model (equation 31)(Young, 1968).

Due to vertical mixing with gas production, the kinetic behavior in a filter lies between that of a plug flow reactor and that of a completely mixed reactor. Filter performance data appear to be better described by the completely mixed reactor model, equation (33).

Here θ is equal to the filter void volume divided by the flow rate of the feed stream. Values for k_1, evaluated for many feedstocks and filters, are approximately 0.45 $hour^{-1}$ (McCarty, 1974), which for a detention time of 10 hours would give a removal efficiency of the biodegradable fraction of 82%. However, for plastic media, k_1 tended to be lower, with values around 0.1 $hour^{-1}$. The value of k_1 is determined experimentally and is dependent on such factors as surface area of the media, biofilm depth, mass transfer, and the kinetics of the reaction within the biofilm. Unfortunately, no method yet exists to evaluate k_1 from a fundamental viewpoint, although recent work on aerobic biofilm kinetics (Rittman and McCarty, 1980) may be used eventually to predict anaerobic filter performance.

The performance of the contact process can be described by equations expressed in terms of the solids residence time, θ_c, such as equation (28b). Solids are retained in the contact system by use of a clarifier and solids recycle stream, and thus the solids residence time (θc) can be greatly increased compared to the hydraulic residence time (θ). Hence the reactor size (which depends on θ rather than θ_c) can be substantially reduced compared with the volume of a digester without solids recycle.

Finally, for the ABR and UASB reactors, the kinetics appear to lie between those for suspended growth (e.g., completely mixed) and fixed film (e.g., anaerobic filter) systems. Since the fundamentals of fixed films are still poorly understood, design of these processes would probably require laboratory or pilot scale experimentation, with assessment of performance based on loading rates and on θc.

Factors Influencing the Sizing of Anaerobic Digesters

In the foregoing discussion, the solids residence time has been given as a key variable affecting digester performance. It is important to consider other factors as well in sizing digesters. Suppose a digester is to be sized to achieve the maximum methane production rate per unit of reactor volume, and that the Contois model has been found to be applicable. From equation (36), the volumetric gas production rate is a function of:

a. B_o, the ultimate biodegradability (i.e., the yield of methane per gram of volatile solids added as θ approaches infinity);

b. S_t^o, the feed substrate concentration, mass/unit volume;

c. θ, the residence time; and

d. K and μ_m, kinetic constants

The ultimate biodegradability, B_o, is a function of the chemical structure and compostion of the feed (e.g., glucose is 100% degradable whereas lignin is virtually refractory). Pretreatment methods can be used to increase B_o.

At low concentration (e.g., up to about 3.5%VS), γ_v increases linearly with increased S_T^o. At higher concentrations, increases in S_T^o have less effect, apparently due to mass transfer limitations. This phenomenon is best expressed in terms of the loading rate, S_T^o/θ. At low loading rates (e.g., up to 1 kg VS per m^3 of reactor per day) and constant conditions, methane yield per kg of VS is constant (i.e., independent of loading). At some higher loading rate, the methane yield per kg of VS will fall off. This critical loading rate depends on feed properties, and is much higher for soluble substrates than for insoluble feeds.

The kinetic coefficients also strongly affect γ_v. These are in turn affected by the temperature of the system and by the presence of toxicants. Decreased μ_m and increased K_s occur in the presence of toxicants. Increased temperature results in increased values of μ_m; typical corrections are:

$$\mu_m = 0.13T - 0.129 \tag{42}$$

where T is in degrees Celsius (Hashimoto <u>et al.</u>, 1981), and:

$$\frac{\mu_T}{\mu_{20}} = k_T \exp(T - 20) \tag{43}$$

where T = temperature, °C;

μ_T = specific growth rate at temperature T, time $^{-1}$;

μ_{20} = specific growth rate at 20°C, time^{-1}; and

k_T = temperature-activity coefficient, dimensionless.

APPENDIX II

GLOSSARY

Acid-forming Bacteria--The group of bacteria in a digester that produce volatile acids as one of the by-products of their metabolism.

Active Volume--The actual volume available in a digester for bacterial action. It is calculated by subtracting the volume occupied by grit and scum from the volume of the digester occupied by sludge.

Aerobic--In the presence of free oxygen.

Aerobic Bacteria--Bacteria which live and reproduce only in an environment containing oxygen which is available for their respiration, such as atmospheric oxygen or oxygen dissolved in water.

Alkaline--The condition in which there is present a sufficient amount of alkali substances to result in a pH above 7.0.

Anaerobic--Without the presence of free oxygen.

Anaerobic Bacteria--Bacteria that live and reproduce in an environment containing no free or dissolved oxygen.

Anaerobic Contact Process--An anaerobic digestion process in which the microorganisms are separated from the effluent slurry by sedimentation or other means and returned to the digester to increase the rate of stabilization.

Anaerobic Digester--A reactor that is constructed to bring about the degradation of organic matter by anaerobic bacteria.

Anaerobic Digestion--The degradation and stabilization of organic materials brought about by the action of anaerobic bacteria with the production of biogas (biomethanation). The process is slightly exothermic (heat-producing).

Batch-Feed Digester--A digester which retains all the feedstock added in a single charge. Discharge of the entire batch occurs at the end of the retention time.

Benefits--Tangible benefits of a biogas system are those that are easily quantifiable and have a monetary value. Such benefits include the value of the gas and the fertilizer produced. Intangible benefits are those that are not so easily quantified or related to a monetary value. Examples include the value of an improvement in environmental sanitation.

Biofeed--Solids recovered from digested sludge and processed into feed material.

Biogas--A mixture of gases, predominantly methane and carbon dioxide, produced by anareobic fermentation.

Biogas Plant--A facility used to process organic matter to produce biogas and sludge; it consists mainly of a digester and gasholder.

Buffer Capacity--A measure of the capacity of water or wastewater for offering a resistance to changes in pH.

Calorific Value--The amount of heat that can be obtained from a fuel, usually expressed in terms of calories per unit weight (volume) of the fuel.

Catabolism--Destructive metabolism involving the production of energy and resulting in the breakdown of complex materials within the organism.

Carbon/Nitrogen Ratio (C/N Ratio)--The ratio of organic carbon to that of total nitrogen.

Coliform--A rod-shaped bacterium found in intestinal tracts of most animals, which is often used as an indicator to detect fecal contamination.

Composting--Controlled decomposition of organic matter under aerobic conditions by which material is transformed to humus. The process is exothermic resulting in a rise in temperature.

Continuous-Feed Digester--A digester which is regularly charged with small amounts of fresh slurry at short intervals; the freshly charged slurry automatically displaces an equal volume of effluent and the process continues without interruption.

Degradation--The breakdown of substances by chemical, physical, and/or biological action.

Denitrification--Anaerobic reduction of nitrogen compounds, such as nitrates, to elemental nitrogen.

Detention Time--The theoretical period of residence in a given volume or unit. It is normally calculated by dividing the active volume of the unit by the rate of flow of the liquid through it.

Dewatering--The process of removing water from the effluent slurry of a digester by evaporation or filtration.

Digester--The unit in which anaerobic digestion takes place, which may be constructed so as to store the biogas produced by anaerobic digestion.

Digester Slurry--Mixture of fermented organic matter and water.

Digestion--The controlled decomposition of organic substances, normally under anaerobic conditions.

Effluent--The sludge or spent slurry from a continuous-fed digester.

Enzyme--A complex organic substance (protein) produced by living cells and having the property of accelerating transformations such as digestion processes.

Facultative--The ability of microorganisms to live under either aerobic or anaerobic conditions.

Floating Gasholder--A biogas container consisting of an inverted open-top tank floating over a pool of liquid such as digester slurry; it rises when it fills with biogas and sinks as the gas is depleted. The weight of the floating cover controls the pressure of the gas which is discharged from the gasholder.

Gasholder--A separate appurtenance that receives and stores the gas produced in a digester.

Grit--Heavy mineral matter often present in digester feedstock such as sand, gravel, and cinders, which accumulates in the bottom of the digester.

Humus--The end product of a composting or digestion process.

Hydraulic Retention Time--The average time that a liquid stays in a reactor before it is discharged. It is equal to the active volume of the reactor divided by the flow rate of the liquid entering it. It is usually expressed in days but may be as short as hours.

Inactivation--The process by which parasite eggs, pathogenic bacteria and viruses are rendered inactive and hence unable to propagate.

Inoculant, Inoculum--Any material, such as previously digested feedstock, that is added to a newly started digester to hasten the degradation of organic matter and the production of methane.

Inorganic Matter--Material in solution or suspension, such as sand, salt, iron, calcium, and other minerals, which are not degraded by microorganisms.

Manure--Animal excreta, normally fecal matter from livestock.

Manure Slurry--The mixture of manure and water coming from livestock pens.

Mesophilic--Within a moderate temperature range, normally 30-40°C.

Metabolism--The biochemical changes in living cells by which energy is provided for vital processes and activities, and new material is synthesized (catabolism + anabolism).

Methane (CH_4)--A colorless, odorless, flammable gas and the main constituent of natural gas, coal gas and biogas.

Methane Forming Bacteria--The group of bacteria in a digester that uses acetate and H_2 as energy sources and produces methane.

Night Soil--Human feces and urine collected by buckets or vacuum trucks.

Organic Matter--Materials which come from animal or vegetable sources. Organic matter generally can be degraded by bacteria and other microorganisms.

Pathogen--Disease-causing organism.

Plug Flow--Movement without mixing in the axial (longitudinal) direction in a digester. The opposite of complete-mixing in digesters.

Retention Time--The number of days that organic matter or bacteria remain in the digester. See also Detention Time.

Sludge--The slurry of settled particles resulting from the process of sedimentation.

Sludge Digestion--A process by which organic matter in sludge is gasified, liquified, mineralized, or converted to a more stable form, usually by anaerobic organisms.

Specific Volume--Daily volume of biogas produced per unit volume of digester.

Supernatant--Liquid removed from settled sludge. Supernatant commonly refers to the liquid between the sludge in the lower portion and the scum on the surface of an anaerobic digester.

Suspended Solids--Solids that are in suspension in water or other liquids.

Thermophilic--Of a relatively high temperature, normally in the range of 50-80°C.

Toxicity--A condition that will inhibit or destroy the growth or function of an organism.

Total Solids--The sum of dissolved and suspended constituents in a sample, usually stated in milligrams per liter.

Volatile Acids--Short chain (C_1 - C_2) fatty acids which are produced by acid forming bacteria. They are soluble in water, can be steam-distilled at atmospheric pressure, and are commonly reported as equivalent to acetic acid (moles/L of acid x 60 = mg/L of acetic acid).

Volatile Solids--The solids that volatilize and therefore are lost on ignition of a sample of dry solids at 550°C. Representing the organic matter in the sample, the volatile solids are expressed as a percentage of the total solids.

REFERENCES

Alaa El-Din, M.N., El-Shimi, S.M., Mahmou, M.H., Abd. El-Aziz, I.M., Ali, B.E., Mohamed, M.E., and Anton, G.G. (1982). Progress report on the activities of the FAO/MOA project TCP/EGY 0003 (MI): Biogas for rural population. Dept. of Agricultural Microbiology, Institute of Soils and Water Research, Agricultural Research Center, Giza, Egypt.

Alicbusan, R.V., Abad, E.J., Silverio, M., and Arceo, T.L. (n.d.). Economic and net-energy analysis of biogas systems. National Institute of Science and Technology, Manila, Philippines.

Alpern, R. (1981). Landfill gas potential of Angeles City refuse. M.S. thesis, Department of Civil Engineering, University of Southern California, Los Angeles.

Alviar, C.J., Baoy, G.T., Calangi, D.B., Castillo, A.C., Averion, M.O., Elefano, S.C., Santos, R.S., Benet, R., and Hocon, R. (1980). Cow manure biogas production and utilization in an integrated farm system at the Alabang dairy project. Paper presented at the 47th Annual Convention of the Philippines Veterinary Medical Association, February.

American Chemical Society (1972). Solid Waste II. Washington, D.C., U.S.A.

Anderson, G.K., Donnelly, T., and McKeown, K.J. (1982). "Identification and control of inhibition in the anaerobic treatment of industrial wastewaters." Process Biochemistry, 17 (4) 28-32.

Arora, H.C., Chattopadhya, S.N., and Routh, T. (1975). "Treatment of vegetable tanning effluent by the anaerobic contact filter process." Water Poll. Contr. (G.B.), 74 (5) 584.

Arora, H.C., and Chattopadhya (1980). "Anaerobic contact filter process: a suitable method for the treatment of vegetable tanning effluents," Water Poll. Contr. (G.B.), 79 (5) 501-6.

Augenstein, D.C., Wise D.L., and Wentworth, R.L. (1976). "Fuel gas recovery from controlled landfilling of municipal wastes," Resource Recovery & Conservation, 2, 103.

Azusa Land Reclamation Co. (1982) Report to Government Refuse Collection & Disposal Assn., Inc., Washington, D.C.

Bachmann, A., Beard, V.L., and McCarty, P.L. (1982). Comparison of fixed-film reactors with a modified sludge blanket reactor. Proceedings of the 1st International Conference on Fixed-Film Biological Processes, Kings Island, Ohio, April.

Bahadur, S., and Agarwal, S.C. (n.d.). Community biogas plant at Fateh Singh Ka Purwa--an evaluation. Planning Research and Action Division (PRAD), State Planning Institute, Lucknow, India.

Barker, H.A. (1956). Bacterial fermentations. CIBA Lectures in Microbial Biochemistry, Institute of Microbiology, Rutgers, New Jersey, USA.

Barnett, A. (1978). "Biogas technology: A social and economic assessment." In Barnett, A., Pyle, L., and Subramanian, S.K., Biogas Technology in the Third World: A Multidisciplinary Review, International Development Research Center, Ottawa, Canada.

Baron, J.L., Eberhard, R.C., Phillips, L.C., Shadel, S.L., and Yoshiaka, G.A. (1981). "Landfill Methane Utilization Technology Workbook" U.S. Dept. of Energy Report No. CPE-8101, Johns Hopkins University Applied Physics Laboratory, Baltimore, Maryland, 1981.

Berger, R.L. (1976). Economics of gobar gas. Division of Consulting Services, United Mission to Nepal, Butwal, Nepal.

Bhatia, R. (1977). Economic appraisal of biogas units in India: framework for social benefit cost analysis. Economic and Political Weekly, Bombay, India.

Bhatia, R., and Niamir, M. (1979). Renewable energy sources: the community biogas plant. Presented at a seminar in the Department of Applied Sciences, Harvard University, Cambridge, Mass., November.

Bhatia, R. (1980). Energy and rural development--an analytical framework for socio-economic assessment, technology and policy alternatives. Working document for participants at the Research Implementation Workshop on Energy and Rural Development, Chiang-Mai, Thailand, February, East West Center, Honolulu, Hawaii, U.S.A.

Bhavani, S. (1976). "Biogas for fuel and fertilizers in rural India - a social cost-benefit analysis." Indian Journal of Agric. Econ., 31 (3) 219-31.

Boersma, L., Gasper, E., Oldfield, J.E., and Cheeke, P.R. (1981). Methods For the recovery of nutrients and energy from swine manure. 2. Protein." Neth. J. Agric. Sci., 29, 99-112.

Boone, D.R., and Bryant, M.P., (1980). "Propionate-degrading bacterium Syntrophobacter wolinii, sp. nov., gen. nov. from methanogenic ecosystems." Appl. Environ Microbio., 40, 626-32.

BORDA Biogas Manual (1980). Biogas manual for the realization of biogas programmes, Bremen, FRG, 1-116.

Boshoff, W.H. (1965). "Methane gas production by batch and continuous fermentation." Tropical Science, 3, 155-65.

Boshoff, W.H. (1967). "Reaction velocity constants for batch methane fermentation on farms, notably in the tropics." J. Agric. Sci. Camb., 68, 347-9.

Brown, J.W., Pfeffer, J.T., and Liebman, J.C. (1976). Biological conversion of organic refuse to methane, U.S. Energy Research & Development Administration Report COO/2917-3, University of Illinois, Urbana, Illinois, 1976.

Bryant, M.P., Wolin, E.A., Wolin, M.J., and Wolfe, R.S. (1967). "Methanobacilus omeliamskii, a symbiotic association of two species of bacteria." Arch. Mikrobiol., 59, 20.

Buivid, M.D., Wise, D.L., Blanchet, M. J., Remedios, E.C., Jenkins, B.M., Boyd, W.F., and Pacey, J.G. (1981). "Fuel Gas Enhancement by Controlled Landfilling of Municipal Solid Wastes," Resource Recovery & Conservation, 6, 3.

Buswell, A.M. and Hatfield, W.D. (eds.) (1936). Anaerobic Fermentations, State of Illinois, Dept. of Registration and Education, Div. of the State Water Survey, Urbana, Illinois, Bulletin No. 32, 1-193.

Buswell, A.M., and Neave, S.L. (1930). Laboratory Studies of Sludge Digestion. State of Illinois, Dept. of Registration and Education, Div. of the State Water Survey, Urbana, Illinois, Bulletin No. 30, 1-84.

Chan, G.L. (1973). Integrated rural development. In a workshop organized by the Dept. of Agriculture, Papua, New Guinea, Port Moresby, Papua New Guinea, July.

Chan, G.L. (1975). Socio-economic aspects of various biogas systems. Economic and Social Commission for Asia and the Pacific, Workshop on Biogas Technology and Utilization, October, Manila, Philippines.

Chan, U Sam (1982). State of the art review on the integrated use of anaerobic processes in China. Internal report prepared for IRCWD, September.

Chavadej, S. (1980). Anaerobic filter for biogas production. Thai Institute of Scientific and Technological Research, Bangkok, Thailand, January.

Chen, Y.R., and Hashimoto, A.G. (1978). "Kinetics of methane fermentation." Biotech. and Bioeng. Symp., No. 8 269-82.

Chen, Y.R., et al. (1980). "Effect of temperature on methane fermentation kinetics of beef-cattle manure." Biotech. and Bioeng. Symp., No. 10, 325-39.

Chynoweta, D.P., et al. (1978). Biomethanation of giant brown kelp, macrocystitis pyrifera. Symposium papers on Energy from Biomass and Wastes, August, Washington, D.C., 229-51.

Cointreau, S.J., Gunnerson, C.G., Huls J.M., and Seldman, N.N. (1984). Recycling from Municipal Refuse, World Bank Technical Paper No. 30, Washington, D.C.

Colberg, P.J., Baugh, K., Everhart, T., Bachmann, A., Harrison, D., Young, Y.L., and McCarty, P.L. (1980). Heat treatment of organics for increasing anaerobic biodegradability. Civil Eng. Dept. Technical Report No. 253, Stanford University, Stanford, CA, USA.

Contois, D.E. (1959). "Kinetics of bacterial growth: relationship between population density and specific growth rate of continuous cultures." J. Gen. Microbiol., 21, 40-50.

Converse, J.C., Evans, G.W., Verhoven, C.R., Gibbon, W., and Gibbon, M. (1977). Performance of a large size anaerobic digester for poultry manure. ASAE Paper No. 77-0451, ASAE, St. Joseph, MI 49085.

Cooney, C.L. and Wise, D.L (1975). "Thermophilic Anaerobic Digestion of Solid Wastes for Fuel Gas Production," Biotechnology & Bioengineering, 17, 1119.

de Lucia, R.J., and Bhatia, R. (1980). Economics of renewable energy technologies in the rural third world. Meta Systems, Cambridge, Mass., USA, October.

Department of Non-Conventional Energy Sources (DNES), Annual Report 1982-83. Ministry of Energy, Government of India, New Delhi.

ECWA (1981). New and renewable energy in the Arab world. United Nations Economic Commission for Western Asia, Beirut, January.

El-Halwagi, M.M. (1979). The development and application of biogas technology in rural areas of Egypt, first progress report of applied science and technology. Project No. 263-0016, National Research Centre, Dokki, Cairo, Egypt, March.

El-Halwagi, M.M. (1982). The state of the art of anaerobic digestion in the Arab speaking countries and West Africa. Internal report prepared for IRCWD, June.

EMCON (1981). State of the art of methane gas enhancement in landfills, report for U.S. Dept. of Energy, EMCON Associates, San Jose, California, June, 1981.

Engineering Science, Inc. (1964). Azusa Experimental Fill--Study 5, Table III, Engineering Science, Inc., Berkeley, California.

ESCAP (1980). Guidebook on biogas develoment, Energy Resources Development Series, No. 21.

ESCAP (1981). Renewable sources of energy. ECDC-TCDC, Vol. II, BIOGAS.

Fair, G.M., and Moore, E.W. (1932). "Heat and energy relations in the digestion of sewage solids-III. Effect of temperature of incubation upon the course of digestion." Sewage Works J., 4 (4) 589-600.

Fair, G.M., and Moore, E.W. (1934). "Time and rate of sludge digestion; and their variation with temperature." Sewage Works J., 6 (1) 3-13.

Fair, G.M., and Moore, E.W. (1937). "Observations on the digestion of a sewage sludge over a wide range of temperatures." Sewage Works J., 9 (1) 3-5.

FAO (1981). The development and use of biogas technology in rural areas of Asia. Project Field Document No. 10. Improving Soil Fertility Through Recycling. FAO/UNDP Regional Project RAS/75/004. UN Food and Agriculture Organization, Rome.

Farquhar, G.J., Clement, B.N., and Constable, T.N. (1982). "An Investigation of Gas Production, Extraction & Utilization at a Canadian Landfill," Veröffentlichungen des Instituts für Stadtbauwesen Technische Universität Braunschweig, Gas- und Wasserhaushaft von Mülldeponien, Braunchsweig, FRG.

Feachem, R., Bradley, D.J. Garelick, H., and Mora, D.D. (1983). Sanitation and disease: health aspects of excreta and waste water management, J. Wiley and Sons, Chichester, U.K.

Fischer, J.R., Iannotti, E.L., Porter, J.H., and Garcia, A. (1979). "Producing methane gas from swine manure in a pilot-size digester." Trans. ASAE, 22, 370.

Franzius, V. (1982), "Utilization of landfill gas in Federal Republic of Germany BMFT Projects," edited by K. Thome-Kozmiensky, Recycling International-Recovery of Energy and Materials from Residues and Wastes, E. Freitag, Berlin, 1982.

French, D. (1979). The economics of renewable energy systems for developing countries, Washington DC, USA.

Fry, L.J. (1975). Practical building of methane power plants for rural energy independence, D.A. Knox, Andover, Hamsphire, USA.

Galano, R.I., de los Santos, A.G., Alicbusan, R., Belarmino, P.A., and Caron, G.M. (n.d.). Biogas technology: social and economic evaluation. De LaSalle University, Manila, Philippines.

Garber, W.F. (1954). Pilot-scale studies of thermophilic digestion at Los Angeles. Sewage and Ind. Wastes, 26, 1202.

Garber, W.F., O'Hara, G.T., Colbaugh, J.E., and Raksit, S.K. (1975). Thermophilic digestion at the Hyperion treatment plant. J. Water Poll. Cont. Fed., 47 (5) 950-61.

Garber, W.F. (1977). Certain aspects of anaerobic digestion of wastewater solids in the thermophilic range at the Hyperion treatment plant. Prog. Wat. Tech., 8, 401-6.

Ghate, B.P. (1979). Biogas, A pilot plant to investigate a decentralised energy system: Planning Research and Action Division, Planning Dept., State Planning Institute, Uttar Pradesh, India.

Ghosh, S., and Klass, D.L. (1979). The production of substitute natural gas and recyclables from municipal solid waste. Recyc. Berl., 79, (2) 789-94.

Gittinger, J.P. (1972). Economic Analysis of Agricultural Projects, The Johns Hopkins Press, Baltimore and London.

Golueke, C.G. (1958). "Temperature effects on anaerobic digestion of raw sewage sludge." Sewage and Ind. Wastes, 30 (10) 1225-32.

Golueke, C.G., Ed. (1971). Comprehensive studies of solid waste management, Report to the U.S. Environmental Protection Agency, University of California, Berkeley, California.

Gosling, D. (1980). Renewable energy resources in Thailand and the Philippines. Dept. of Theology, University of Hull, Hull, U.K.

Gossett, J.M. (1976). Heat treatment of refuse for increasing anaerobic biodegradability. Ph.D. Thesis, Civil Eng. Dept., Stanford University, California, USA.

Grady, C.P.L. and Lim, H.C. (1980). Biological Wastewater Treatment, Theory and Application, Marcel Dekker, Inc., New York and Basel, 883-6.

GRCDA (Government Refuse Collection and Disposal Assn.) (1983). Project Summary, Landfill Gas Control and Utilization Projects. GRCDA, P.O. Box 7219, Silver Spring, Md. 20910, USA.

Gujer, W., and Zehnder, A.J.B. (1982). Conversion processes in anaerobic digestion. Presented at the IAWPR Specialized Seminar on Anaerobic Treatment of Wastewater in Fixed-Film Reactors, Copenhagen, Denmark, June.

Halvadakis, C.P. (1983) Methanogenesis in solid waste landfill bioreactors, Ph.D. Dissertation, Stanford University, Palo Alto, California, USA.

Hamilton Standard (1980). Methane generation from cattle residue at a dirt feedlot. U.S. Dept. of Energy Report DOE/ET/20039-20, Hamilton Standard, Windsor Locks, Connecticut, USA.

Hamilton Standard (1981). Full scale experimental anaerobic fermentation facility: final report for design, construction & operation. U.S. Dept. of Energy Report DOE/ET/20009-T1. Hamilton Standard, Windsor Locks. Connecticut, USA.

Han, Y.W. and Calliban, C.D. (1974). Cellulose fermentation: effect of substrate pretreatment on microbial growth. Appl. Microbial, 27 (1), 159-65.

Hao, P.L.C., Yu, A.P., and Tang, H.S. (1980). Design and development of a red-mud plastic digester. Union Industrial Research Laboratories, Industrial technology Research Institute, Hsinchu, Taiwan.

Harris, J.M., Shirley, R.L., and Palmer, A.Z. (1982). Nutritive value of methane fermentation residue in diets fed to feedlot steers. J. Animal Science, 55 (6) 1293-1302.

Hart, S.A. (1963). "Digestion tests of livestock wastes." J. Wat. Poll. Cont. Fed., 35 (6) 748-59.

Hashimoto, A.G., Chen Y.R., and Varel, V.H. (1981a). Anaerobic fermentation of beef cattle manure, final report. SERI (Solar Energy Res. Inst.), Colorado, USA, January, SERI/TR-98372-1, 1-67.

Hashimoto, A.G., Varel, V.H., and Chen, Y.R. (1981b). "Ultimate methane yield from beef cattle manure: Effect of temperature, ration constituents, antibiotics and manure age." Agric. Wastes, 3 (4) 241-56.

Hayes, T.D., Jewell, W.J., Dell'Orto, S., Fanfoni, K.J., Leuschner, A.P., and Sherridan, D.R. (1979). "Anaerobic digestion of cattle manure." In Anaerobic Digestion, Stafford, D.A., Wheatley, B.I., and Hughes, D.E. (eds), Applied Science, London, UK.

Hayes, T.D., and Theis, T.L. (1978). "The distribution of heavy metals in anaerobic digestion." J.Wat. Poll. Cont. Fed., 50 (1) 61-72.

Hiatt, W.C., Carr, A.D., and Andres, J.F. (1973). "Anaerobic digestion of rum distillery wastes." Proc. 28th Conf. on Industrial Wastes, Purdue University, 966.

Hills, D.J. (1979). Effects of carbon:nitrogen ratio on anaerobic digestion of dairy manure, Agric. Wastes, 1, 267-78.

Hobson, P.N., and Shaw, B.G. (1973). "The anerobic digestion of waste from an intensive pig unit." Water Res., 7, 437-49.

Hobson, P.N., and Shaw, B.G. (1976). "Inhibition of methane production by Methanobacterium formicicum." Water Res., 10, 849-52.

Hong, C.M., Koh, M.T., Chow, T.Y., Tsai, P.H., and Chung, K.T. (1979). Utilization of hog wastes in Taiwan through anerobic fermentation. Food and Fertilizer Technology Center, Taipei, City, Taiwan, Extension Bulletin No. 131, October (FFTC EB 131).

Hu Bing-hong (1982). State of application and economic benefits from biogas and solar energy utilized in Xinbu Brigade of Leliu Commune. Science and Technology Commission, Shunde County, Guangdong, China, mimeo.

Huser, B.A., Wuhrmann, K., and Zehnder, A.J.B. (1982). Methanothrix soehngenii, gen. nov. sp. nov., a new acetotrophic non-hydrogen-oxidizing methane bacterium. Arch. Microbiol., 132, 1-9.

Hutchinson, T.H. (1972)."Methane farming in Kenya."Comp. Sci.,13,Nov.,30-1.

ICAR (1976). The economics of cow dung gas plants, Indian Council of Agricultural Research, New Delhi, India.

Idnani, M.A., and Varadarajan, S. (1974). Preparation of fuel gas and manure by anaerobic fermentation of organic materials. Indian Council of Agricultural Research, Technical Bull. No. 46, New Delhi, India.

Jewell, W.J., Davis, H.R., Gunkel, W.W., Lathwell, D.J., Martin, J.H., McCarty, T.R., Morris, G.R., Price, D.R., and Williams, D.W. (1976). Report prepared for the U.S. Energy Research and Development Administration, Report No. TIB 27164.

Jewell, W.J., Dell'Orto, S., Fanfoni, K.J., Fast, S.J., Jackson, D.A., Kabrick, R.M., and Gottung, E.J.(1981).Crop residue conversion to biogas by dry fermentation. Presented at 1981 Winter Mtg., ASAE, Chicago, USA, Dec.

Jewell, W.J., Dell'Orto, S., Fanfoni, K.J., Hayes, T.D., Lensehner, A.P., and Sherman, D.F. (1980). Anaerobic fermentation of agricultural residue: Potential for improvement and implementation. U.S. Dept. of Energy, Project No. DE-AC02-76ET20051, April, Vol. II, Final Report, 1-599.

Judan, A.A. (1981). Biogas works at Maya farms: its socio-economic aspects. Maya Farms Bio-energy Consultants, Liberty Flour Mills, mimeo.

Kabaara, A.M. (1969). Effect of methane sludge on soil properties. Kenya Coffee, monthly bulletin, December.

Khan, A.W., and Mes-Hartree, M. (1981). "Metabolics of acetate and hydrogen by a mixed population of anaerobes capable of converting cellulose to methane." J. Applic. Bacteriology, 50, 283-8.

King, R.P. (1978). The development of biogas-slurry plants and systems in Kenya. Prepared for ITDG (London), Dept. of Agric. Eng., Nairobi University, Nairobi, Kenya, June.

Kispert, R.G., Sedek, S.G., and Wise, D.L.(1975),"An Economic Evaluation of Fuel Gas Production from Solid Wastes," Res. Recov. and Cons., 1, 95-109.

Kispert, R.G., Sedek, S.G., and Wise, D.L. (1976), "An Evaluation of methane production from Solid Wastes," Resource Recovery and Conservation, Vol. 1, pp. 245-255.

Kladivko, E.J., and Nelson, D.W. (1979). Changes in Soil properties from application of anaerobic sludge. J. Wat. Poll. Cont. Fed, 51, 325-32.

Kroecker, E.J., Schulte, D.D., Sparling, A.B., and Lapp, H.M. (1979). Anaerobic treatment process stability. J.W.P.C.F., 51 (4) 718-27.

Kugelman, I.J., and Chin, K.K. (1971). "Toxicity synergism and antagonism in anaerobic waste treatment processes." In Anaerobic Biological Treatment Processes, Adv. in Chem., Series 105, Pohland, F.G. (ed.) American Chem. Soc., Washington DC, USA, 55.

Kugelman, I.J., and McCarty, P.L. (1965). "Cation toxicity and stimulation in anaerobic waste treatment." I Slug feed studies. J. Wat. Poll. Cont. Fed., 37, 97-115.

Lal, D. (1974). Study on social process for evaluating public investment projects. Tech. working papers Nos. 1-15. Planning Commission, Project Appraisal Division, New Delhi, India.

Lauer, D.A., Bouldin, D.R., and Klausner, S.D. (1976). Ammonia volatilization from dairy manure spread on the soil surface." J.Env.Qual.,5,134-41.

Lawrence, A.W., and McCarty, P.L. (1964). "The effect of sulfides on anaerobic treatment." Proc. 19th Ind. Waste Conference, Purdue University.

Leckie, J.D., Pacey, J.G., and Halvadkis, C.P. (1979), "Landfill management with moisture control," Proc. Amer. Soc. of Civil Eng., 107, EE2, 337-55.

Lettinga, G., Van der Geest, A.Th., Habma, S., and Van der Laan, J. (1979). Anaerobic treatment of methanolic wastes. Wat. Res., 13, 725-37.

Lettinga, G., Van Velsen, A.F.M., Habma, S.W., De Zeeuw, W.,and Klapwijk,A. (1980). Use of the upflow sludge blanket (USB) reactor concept for biological wastewater treatment, especially for anaerobic treatment. Biotech and Bioeng., 22, 699-734.

Lichtman, R. (1983). Biogas systems in India. VITA, Washington, D.C., USA.

Lyamchai, A.A., and Mushi, S.J.S. (1982). Outline of biogas technology development in Tanzania. Paper presented at the UNESCO/UNIDO Workshop on Biogas Technology in Africa, Arusha, Tanzania, February.

Mahin, D.B. (1982). Biogas in developing countries. Bioenergy System Report to USAID, Washington, DC.

Malina Jr., J.F. (1961). The effect of temperature of high-rate digestion of activated sludge. Proceedings, 16th Industrial Waste Conference, Purdue, 232-50.

Maramba, F.D. (1978). Biogas and waste recycling. The Philippine experience. Maya Farms Division, Liberty Flour Mills, Inc., Metro Manila, Philippines.

Marchaim, U., Prochenski, D., Perach, Z., Lombrozo, E., Dvoskin, D., and Criden, J. (1981). The Israeli anaerobic digestion process--"NEFAH": utilization of agricultural wastes to produce energy, animal and fish food supplements and industrial products. A paper presented at the Second International Symposium of Anaerobic Digestion, 6-11 September, Travermunde, Germany.

Marchaim, U., and Criden, J. (1981). "Research and development in the utilization of agricultural wastes in Israel for energy, feedstock fodder, and industrial products." In Fuel Gas Production from Biomass, Vol. I. Wise, D.L. (ed.), CRC Press, Boca Raton, Florida, USA, 95-120.

Marchaim, U. (1982). Personal communication.

Mazumdar, R. (1982). Review of the literature on the promotion of biogas systems (pilot ed.). Tata Energy Res. Inst., Doc. Center, Bombay, India.

McCarty, P.L. (1964a). "Anaerobic waste treatment fundamentals, Parts one to four." Public Works, September-December.

McCarty, P.L. (1964b). "The methane fermentation." In Principles and Aplications in Aquatic Microbiology, Heukelekian, H., and Dondero, N.C. (eds.), John Wiley & Sons, New York, 314.

McCarty, P.L. (1972). Stoichiometry of biological reactions. Presented at the International Conference Towards a Unified Concept of Biological Waste Treatment Design, Atlanta, Georgia, October.

McCarty, P.L. (1974). Anaerobic processes. Presented at the Birmingham Short Course on Design Aspects of Biological Treatment, IAWPR, Birmingham UK, September.

McCarty, P.L., Hann, D.J., McDermott, G.N., and Weaver, P.J. (1972). "Treatability of oily wastewaters from food processing and soap manufacturing." Proc. 27th Conference on Industrial Wastes, Purdue University.

McFarlane, P.N., and Pfeffer, J.T. (1981). Biological conversion of biomass to methane; first subcontract report, 1 Jan. 1980 to 31 March 1981, SERI, Colorado, USA, SERI/TR-98357-1; July, 1-163.

McGarry, M.G., and Stainforth, M.G. (eds.) (1978). Compost, fertilizer, and biogas production from human and farm wastes in the People's Republic of China. Pub. IDRC-TS8e, International Development Research Center, Ottawa, Canada.

McInerney, M.J., Bryant, M.P., and Pfennig, N. (1979). "Anaerobic bacterium that degrades fatty acids in syntrophic association with methanogens." Arch. Microbiol.,122, 129-35.

McInerney, M.J., and Bryant, M.P. (1981). "Review of methane fermentation fundamentals." Fuel Gas Production from Biomass, Vol. I, Wise, D.L. (ed.), CRC Press, Boca Raton FL, USA, 19-46

McMorrow, M.J., Burbank Jr., N.C., Young, R.H.F., Lau, L.S., and Klemmer, H.W. (1970). "Anaerobic digestion of pineapple mill wates." Proc. 25th International Conference on Industrial Wastes, Purdue University, 575.

Megerson, B. (1980). Introduction and popularization of biogas technology --The Ethiopian attempt and experience. ARSI Rural Development Project, Addis Ababa, Ethiopia.

Meta Systems (1981). Waste streams and integrated resource recovery systems in developing countries. Consultancy report for AID. Holworthy St., Mass. 01238, USA.

Mooij, H.P., and Streit, M. (1982). "ASEF Solid Wastes to Methane Gas, Pompano Beach, Florida, REFCON Technical Studies Report," U.S. Dept. of Energy, Waste Management Inc., Oak Brook, Ill., Feb. 1982.

Monod, J. (1949). "The growth of bacterial cultures." Ann. Rev. of Microbiol., 3, 371-94.

Morris, G.R., Jewell, W.J., and Loehr, R.C. (1977). Anaerobic fermentation of animal wastes: A kinetic design evaluation. Proc. 32nd Industrial Waste Conf., Purdue University, Lafayette, Ind., USA, 1-12.

Mosey, B.S. (1976). Assessment of the maximum concentration of heavy metals in crude sewage which will not inhibit the anaerobic digstion of sludge. Wat. Poll. Cont.(G.B.), 75.

Mosey, F.E., Swanwick, J,D., and Hughes, D.A. (1971). "Factors affecting the availability of heavy metals to inhibit anaerobic digestion." Wat. Poll. Control (G.B.), 668-80.

Moulik, T.K. (1982). Biogas energy in India. Academic Book Center, Ahmedabad, India.

Moulik, T.K., and Srivastava, U.K. (1975). Biogas plants at the village level: problems and prospects in Gujarat. Center for Management in Agriculture, Indian Institute of Management, Ahmedabad, India.

Moulik, T.K., Srivastava, U.K., and Shingi, D.M. (1978). Bio-gas system in India, a socio-economic evaluation. Center for Management in Agriculture, Indian Institute of Management, Ahmedabad, India.

Mountfort, D.O., and Ashner, R.A. (1978). "Changes in proportion of acetate and carbon dioxide used as methane precursors during the anaerobic digestion of bovine waste." Appl. Env. Microbiol., 36, 648-54.

Mukherjee, S.K., and Arya, A. (1980). Comparative analysis of social cost-benefit studies of biogas plants. Presented at the Energy and Rural Development Research Implementation Workshop, Chiang Mai, Thailand.

Mullan, J.D., Wyosnick, D.R., Gilleo, and Sheaffer, J.R. (1984). A preliminary analysis of several working anaerobic digestion systems. World Bank data.

NAS (1977). Methane generation from human, animal, and agricultural wastes. National Academy of Science, Washington, D.C.

National Office for Biogas Development and Extension (1982). Biogas in China. Report at the technical consultation among developing countries on large-scale biogas technology. Beijing, People's Republic of China.

Nelson, G.H., Straka, R.P., and Levine, M. (1939). "Effect of temperature of digestion, chemical composition, and size of particles on production of fuel gas from farm wastes." J. Agric. Research, 58, 273-87, Washington, D.C., USA.

Nian-Guo, Li (1982). Is the Xinbu system economically feasible? Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Beijing.

Odum, H.T. (1971). Environment, power and society. Wiley Intersci., New York.

Odum, H.T., and Odum, E.C. (1971). Energy Basis for Man and Nature. McGraw-Hill, New York.

O'Rourke, J.T.(1968). Kinetics of anaerobic waste treatment at reduced temperatures. Ph.D. Thesis, Civil Eng. Dept., Stanford Univ., Calif., USA.

Owen, W.F., Stuckey, D.C., Healy Jr., J.B. Young, L.Y., and McCarty, P.L. (1979). "Bioassay for monitoring biochemical methane potential and anaerobic toxicity." Water Res. 13 (6), 485.

Pacey, J.G. (1982), Controlled landfill demonstration project--discussion of the first year of operation, Veröffentlichungen des Instituts für Stadtbauwesen, Technische Universität Braunschweig, Gas- und Wasserhaushaft von Mülldeponien, Brauwnsweig, FRG.

Pang, A. (1978). Economics of gobar gas. Development and Consulting Services, United Mission to Nepal, Butwal, Nepal.

Parikh, K.S. (1963). Benefit-cost analysis of bio-gas plants in India. M.Sc. Thesis, Massachusetts Institute of Technology.

Parikh, K.S. (1976). Energy, Second India Studies. Macmillan Company of India Ltd., Delhi, India.

Park, Y.D., and Park, N.J. (1981). A study of feasibility on the village scale biogas plants through a farm demonstration trial during the winter season. Research Reports of the Office of Rural Development, Suweon, Korea, 23, November.

Park, Y.D., Park, J.J., and Lim, J.H. (1979). A study of capability on PVC-bag type biogas generator. Research Reports of the Office of Rural Development, Suweon, Korea, 23, November.

Pfeffer, J.T. (1974) Reclamation of energy from organic wastes, final report to U.S. Environmental Protection Agency, University of Illinois, Urbana, Illinois.

Pfeffer, J.T. (1974). "Temperature effects on anaerobic fermentation of domestic refuse." Biotech. and Bioeng., XVI, 771-87.

Picken, D.J., and Soliman, H.A. (1981). "The use of anaerobic digester gas as an engine fuel." J. Agric. Eng. Res., 26, 1-7.

Pohland, F.G. (1975). "Accelerated solid waste stabilization leachate treatment by leachate recycle through sanitary landfills," Progress in Water Technology, 7 (1).

Pohland, F.G. (1980). Leachate recycle as landfill management option," J. Environ. Eng. Div., Proc. Amer. Soc. of Civ. Eng., 80, EE6, December.

Polprasert, C., Kanok-Nukulchai, W., and Rajput, V.S. (1982). A ferro-cement digester: Biogas and biomass production. J.Ferrocem.,12 (1):25-34.

Pradham, R.S.(n.d.) Status of biogas plants in Nepal.CEDA, Kattmandu, Nepal.

Prasad, C.R., Prasad, K.K., and Reddy, A.K.N. (1974). Biogas plants: Prospects, problems and tasks." Economic and Political Weekly, 9 (32-4).

Prasith-rathsint, S., Chupikoolchai, S., Arthornthurasook, T., Sukruyapongse, P. (1979). The social and economic evaluation of biogas technology in rural Thailand. IDRC Project File No. 3-p-77-0076-04-02.

Prior, R.L., and Hashimoto, A.G. (1981). "Potential for fermented cattle residue as a feed ingredient for livestock." In Fuel gas production from biomass, Vol. II, Wise, D.L. (ed.), CRS Press, Boca Raton, Florida, USA, 215-38.

Pyle, D.L. (n.d.) A preliminary assessment of the economics of biogas in Kenya. Mimeo, Imperial College, London, U.K.

Qurishi, F.S. (1978). Biogas technology: evaluation of socio-economic effects on the life of a rural family. Paper presented at the Economic and Social Commission for Asia and the Pacific, Expert Group Meeting on Biogas Development, 20-6 June, Bangkok, Thailand.

Rahman, M. (1976). A preliminary report on the Academy biogas generator. Bangladesh Academy for Rural Development, Kotbari, Camilla.

Rajabapaiah, P., Ramanayya, K.V., Mohan, S.R., and Reddy, A.K.N. (1979). "Studies in biogas technology: Part I, performance of a conventional biogas plant." Proc. Indian Academy Sci., C2, Part 3, 357-63.

Ratusuk, S., Chantramonklasri, N., Srimuni, R., Ploypatarapunyo, P., Chavadej, S., Sailamai, S., and Sunthonsan, W. (1979). Final report on pre-feasibility study of the biogas technology application in rural areas of Thailand. Environment and Development Research Dept., Applied Scientific Research Corporation of Thailand, submitted to IDRC, Canada.

Ravindranath, N.H., Nagaraju, S.M., Somashekar, H.I., Channeswarappa, A., Balakrishna, M., Balachandran, B.N., and Reddy, A.K.N. (1980). An Indian village agricultural ecosystem--case study of Ungra Village, part I: main observations. Proceedings of Energy from Biomass conference, Brighton, November, 45-73.

Reddy, A.K.N., and Subramanian, D.K. (1979). "The design of rural energy centers." Proc. Indian Acad. Sci., X2, 395-416.

Rittman, R.E., and McCarty, P.L. (1980). "Model of steady state biofilm kinetics." Biotech. and Bioeng., 22, 2343.

Robbins, J.E., Arnold, M.T., and Lacher, S.L. (1979). Methane production from cattle waste and de-lignified straw. Infection and Immunity, 38 (1), 175-7.

Roeser, R.W. (1979). Cost-benefit analysis of biogas production in Pespire, Honduras. The Fletcher School, Tufts U. AID Contr. 522-T-411, Apr.

Roth, L.A., and Lentz, C.P. (1977). Anaerobic digestion of rum stillage." Canadian Institute Food Science Technol. J., 10 (2) 105-8.

Rottenberger, G. (1982). Personal communication.

Sanghi, A.K. (1979). Biogas in rural India: a perspective. Bureau of the Budget, Office of Planning, Springfield, Illinois, USA.

Santerre, M.T. (1981). Anevaluation of biogas; windmill; and other rural energy technologies in Sri Lanka. Tech. memo TM-81-2, East-West Centre, Honolulu, Hawaii.

Santerre, M.T., and Smith, K.R. (1980). Application of the FLEAT approach to rural household and community anaerobic digestion systems. Report PR-80-5, East-West Centre, Honolulu, Hawaii.

Sathianathan, M.A. (1975). Biogas: achievements and challenges. Association of Voluntary Agencies for Rural Development, New Delhi, India.

Schllenbach, S. (1980). Imperial Valley biogas project, operations and methane production from cattle manure, October 1978 to November 1979. In Symposium Papers: Energy from Biomass and Wastes, IV, IGT, Chicago, Ill., USA.

Schmid, L.A. (1975). "Feedlot Waste to Useful Energy." Proc. Am. Soc. Civil Engrs., EE5, 101, EE5, 787.

Schmid, L.A., and Lipper, R.Z. (1969). Swine wastes, characterization and anaerobic digestion. Proc. Conf. on Agric. Waste Mgt., Cornell Univ., Ithaca, N.Y., 50-7.

Schroepfer, G.J., Fullen, W.J., Johnson, A.S., Ziemke, N.T., and Anderson, J.J. (1955). "The anaerobic contact process as applied to packinghouse wastes." Sewage and Ind. Wastes, 27 (4), 460-86.

Sharma, Y.N. (1980). Biogas development and application in India. Presented at the Workshop on Low Cost Energy for Water Pumping, Botswana, November, mimeo.

Shelef, G., Kimchie, S., and Grynberg, H. (1980). "High-rate thermophilic anaerobic digestion of agricultural wastes." Biotech. and Bioeng. Symp. No. 10, 341-51.

Sheridan, M. (1981). Peasant innovation and diffusion of agricultural technology in China. Cornell Univ. Center for Intl Studies.

Shian, S., Chang, M. Ye, Y., and Chang, W. (1979). "The construction of simple biogas digesters in the Province of Szechwan, China." Agric. Wastes, 4, 247-58.

Simpson, D.E. (1971). "Investigations on a pilot-plants contact digester for the treatment of a dilute urban waste." Water Research, 5, 523-32.

Singh, R.B., and Singh, K.K. (1978). Janata biogas plants: Preliminary report on design and cost. Planning Res. and Action Div., State Planning Div., Uttar Pradesh, India.

Sirohi, A.S. (1977). Cost-benefit analysis of biogas plants in India. Workshop on Biogas Systems, Mgt. Dev. Inst., New Delhi, India.

Smith, M.R., and Mah, R.A. (1978). "Growth and methanogenesis by Methanosarcins strain 227 on acetate and methanol." Appl. Environ. Microbiol., 36, 870.

Sola, G. (1979). Contribution of the biogas research team working in Upper Volta. Presented at the UNEP-China Training Seminar.

Solly, R.K. (1980). Integrated biogas systems in Fiji and the South Pacific. Khadigramodyog, December, 156-63.

Speece, R.E., and McCarty, P.L. (1962). Nutrient requirements and biological solids accumulation in anaerobic digestion. Paper presented at the 1st International Conference on Water Pollution Research, London, UK, September.

Squire, L., and van der Tak, H.G. (1975). Economic Analysis of Projects. The John Hopkins University Press, Baltimore and London.

Srinivasan, H.R. (1978). Design aspects of KVIC biogas plants. Paper submitted to Export Group Meeting on Biogas Development, Bangkok, June. KVIC, Bombay, India, 1-21.

Standard Methods for the Examination of Water and Wastewater (1975), 14th ed., American Public Health Association.

Stuckey, D.C. (1980). Thermochemical pretreatment of nitrogenous organics to increase methane yields. Ph.D. thesis, Stanford U., Calif., USA.

Stuckey, D.C. (1982). Biogas in China: a back-to-office report on a study tour of China. IRCWD, Dubendorf, Switzerland, December.

Stuckey, D.C. (1983). Biogas in developing countries. Unpublished report. International Reference Center for Waste Disposal. Swiss Federal Technical Institute (EAWAG), Duebendorf, Switzerland.

Stuckey, D.C., Parkin, G.F., Owen, W.F., and McCarty, P.L. (1978). Comparative evaluation of anaerobic toxicity by batch and semi-continuous assays. J.W.P.C.F., 52 (4), 720-9.

Stumm, W., and Morgan, J.J. (1970). Aquatic Chemistry, An Introduction Emphasizing Chemical Equilibrium in Natural Waters, Wiley Intersci., N.Y.

Subramanian, D.K., Rajabapaiah, P., and Reddy, A.K.N. (1979). "Studies in biogas technology." Part II--optimization of plant dimensions. Proc. Indian Acad. Science, C2 (3), 365-75.

Tabasaran, Oktay (1981). Production of methane from municipal sanitary landfills and its utilization, presented at NATO Advanced Studies Institute, Bogazici University, Istanbul, Turkey, June.

Tarrant, J. (1977). Waste not, want not. Biogas fuel for rural electrification in Debarek, Ethiopia. Mimeo.

TATA Energy Research Institute (1982). Biogas handbook. Pilot Edition. Bombay, India. March.

TATA Energy Research Institute. (1981) Renewable energy research in India, Bombay, India. August.

Terrado, E.M. (1981). "Biogas development: the Philippines." In Biomass Energy Projects: Planning and Management, Goodman, L.J., and Love, R.M. (eds.), Pergamon Press, New York.

Theis, T.L., and Hayes, T.D. (1979). "Chemistry of heavy metals in anaerobic digestion." Chemistry of Wastewater Technology, Chapter 23, Ann Arbor Science, Ann Arbor, Mich. USA, 403-19.

Thery, D. (1977). "Biogas: a program for Sahelian countries." Ecodevelopment News, October, 33-5.

Thongkaimook, A. (1982). Economic analysis of some biogas technologies in the Tropics. M.Sc. Thesis, Asian Institute of Technology, Bangkok, Thailand.

Tyner, W.E., and Adams, J. (1977). "Rural electrification in India: biogas versus large-scale power." Asian Survey, 17 (8) 724-34.

Umana, A. (1982). State of the art review of anaerobic processes in Latin America. Internal Report prepared for IRCWD, August.

UNEP (1981). Biogas fertilizer system. Technical Report on a Training Seminar in China. United Nations Environmental Programme, Nairobi, Kenya.

USEPA (1979). Sludge Treatment and Disposal. United States Environmental Protection Agency. Washington, D.C.

van Brakel, J. (1980). The Ignis Fatuus of Biogas Small-Scale Anaerobic Digesters ("Biogas Plants"): A Critical Review of the Pre-1970 Literature, Delft University Press.

van Buren, A. (ed.) (1979). A Chinese Biogas Manual--Popularizing Technology in the Countryside, trans. Cook, M., Interm. Tech. Publ. Ltd., July.

Van Soest, P.J. (1979). Forages Fiber and the Rumen, Freeman, San Francisco, Calif., USA.

Van Velsen, A.F.M. (1979). "Adaptation of methanogenic sludge to high ammonia-nitrogen concentrations." Water Res., 13 (10), 995.

Veit, M.A. (1982). Personal communication.

Veit, M.A. and Zulaut (1982). Brazil landfill gas potential. World Bank data.

Walter, H. Harnickell, E., and Mueller-Dambois (1975). Climate-diagram Maps. Springer-Verlag, Berlin.

Ward, R.F. (1981). Digesters for the third world. Presented at a Second International Symposium on Anaerobic Digestion. Travemunde, FRG.

Ward, R.F. (1982). The refeeding of digested cattle manure. World Bank data. Washington, D.C.

Ward, R.F. (1984). Engineering design of biogas units for developing countries. Intl. Conf. on Biogas Tech. Transfer and Diffusion, Cairo, Nov.

Wise, D.L., Kispert, R.G., Langton, E.W. (1981), "A Review of Bioconversion of Systems for Energy Recovery from Municipal Solid Wastes, Part II--Fuel Gas Production," Resources and Conservation, 6, 117-136.

Wise, D.L., Kispert, R.G. (1981), "A Review of Bioconversion of Systems for Energy Recovery from Municipal Solid Wastes, Part III--Economic Evaluation," Resources and Conservation, 6, 137-142.

Wise, D.L. Personal Communication, 1983.

Wolverton, B.C., McDonald, R.C., and Gordon, J. (1975). Bio-conversion of water hyacinths into methane gas; Part I. National Space Technology Laboratories, Report no. TM X-72725, 1-13.

Wolverton, B.C., and McDonald, R.C. (1978). Nutritional composition of water hyacinths grown on domestic sewage. NASA/ERL Rep. No. 173, Washington, D.C., USA.

Xinsheng, M., Ruchen, C., Nian-guo, L., Chengchun, H., and Shearer, W. (1980). "The Xinbu system: an integrated rural production system." Development Forum, 8 (9) November.

Yawalkar, K.S., and Agrawal, I.P. (n.d.). Manures and fertilizers. Agro-horticultural Publishing House, Nagpur, India.

Young, J.C. (1968). The anaerobic filter for waste treatment. Ph.D. Thesis, Civil Eng. Dept., Stanford University, Stanford, Calif., USA.

Young, J.C. and McCarty, P.L. (1969). "The anaerobic filter for waste treatment." J. Wat. Poll. Cont. Fed., 41 (5), R 160-73.

Zehnder, A.J.B., and Wuhrmann, K. (1977). Arch. Microbiol., 111, 199.

Zehnder, A.J.B., Ingvorsen, K., and Marti, T. (1982). Microbiology of methane bacteria. Presented at the 2nd Intl. Symp. on Anaerobic Digestion. Travemunde, FRG, September, 1-26.

INTEGRATED RESOURCE RECOVERY PROJECT

UNDP/World Bank GLO/80/004

Recycling from Municipal Refuse (Technical Paper No. 30), 1984. S. Cointreau et al.

Remanufacturing (Technical Paper No. 31), 1984. R.T. Lund, MIT.

Aquaculture (Technical Paper No. 36), 1985. P. Edwards.

Municipal Waste Processing in Europe (Technical Paper No. 37),1985. J.G. Abert.

FORTHCOMING PUBLICATIONS:

Health Effects of Wastewater Irrigation and Their Control in Developing Countries, 1986. H. Shuval et al.

Co-Composting of Domestic Solids and Human Waste, 1986. L. Obeng.

Ultimate Waste Disposal to the Ocean, 1986. C.G. Gunnerson.

RURAL WATER SUPPLY HANDPUMPS PROJECT

UNDP/World Bank INT/81/026

Rural Water Supply Handpumps Project Report No. 3: Laboratory Testing of Handpumps for Developing Countries, Final Technical Report, 1984. Consumers' Association Testing and Research Laboratories.

Rural Water Supply Handpumps Project Report No. 4: Progress Report on Field and Laboratory Testing (Technical Paper No. 29), 1984. S. Arlosoroff et al.

Rural Water Supply Handpumps Project Report No. 5: Proceedings of Workshop
Ministry of Machine Building Industry, United Nations Development Programme, World Bank Workshop on the State of the Art and Application of Handpumps and Water Supply and Sanitation.
Changsha, Peoples Republic of China
August 15-21, 1984.

INFORMATION AND TRAINING FOR LOW COST WATER SUPPLY AND SANITATION PROJECT

UNDP/World Bank INT/82/002

Water Supply and Sanitation Project Preparation Handbook, 1983.

Volume 1: Guidelines (Technical Paper No. 12). Brian Grover.

Volume 2: Case Studies--Identification Report for Port City, Immediate Improvement Project for Port City, Pre-Feasibility Report for Farmville, Pre-Feasibility Report for Port City (Technical Paper No. 13). Brian Grover, Nicholas Burnett, Michael McGarry.

Volume 3: Case Study--Feasibility Report for Port City (Technical Paper No. 14). Brian Grover, Nicholas Burnett, Michael McGarry.

Low Cost Sanitation Publications (TAG)

Ten working papers and technical notes on different aspects of low cost sanitation, latrines construction and others.

The World Bank
Publications Order Form

SEND TO: **YOUR LOCAL DISTRIBUTOR** OR TO **WORLD BANK PUBLICATIONS**
(See the other side of this form.)
P.O. BOX 37525
WASHINGTON, D.C. 20013 U.S.A.

Date ______________________

Name ______________________

Title ______________________

Firm ______________________

Address ______________________

City __________ State ______ Postal Code __________

Country __________ Telephone (______) __________

Purchaser Reference No. ______________________

Ship to: (Enter if different from purchaser)

Name ______________________

Title ______________________

Firm ______________________

Address ______________________

City __________ State ______ Postal Code __________

Country __________ Telephone (______) __________

Check your method of payment.
Enclosed is my ☐ Check ☐ International Money Order ☐ Unesco Coupons ☐ International Postal Coupon.
Make payable to World Bank Publications for U.S. dollars unless you are ordering from your local distributor.

Charge my ☐ VISA ☐ MasterCard ☐ American Express ☐ Choice. (Credit cards accepted only for orders addressed to World Bank Publications.)

______________________ Credit Card Account Number

______________________ Expiration Date

______________________ Signature

☐ Invoice me and please reference my Purchase Order No. ______________.

Please ship me the items listed below.

Stock Number	Author/ Title	Customer Internal Routing Code	Quantity	Unit Price	Total Amount $

All prices subject to change. Prices may vary by country. Allow 6-8 weeks for delivery.

Subtotal Cost $______

Total copies ______ Air mail surcharge if desired ($2.00 each) $______

Postage and handling for more than two complimentary items ($2.00 each) $______

Total $______

Thank you for your order.

IBRD-0053

DISTRIBUTORS OF WORLD BANK PUBLICATIONS

ALGERIA
Office des Publications Universitaires
1, place centrale de Ben-Aknoun
Algiers

ARGENTINA
Carlos Hirsch, SRL
Galeria Guemes
Florida 165, 4th Floor-Ofc. 453/465
1333 Buenos Aires

AUSTRALIA, PAPUA NEW GUINEA, FIJI SOLOMON ISLANDS, AND VANUATU
Info-Line
Overseas Document Delivery
Box 506, GPO
Sydney, NSW 2001

AUSTRIA
Gerold and Co.
A-1011 Wien
Graben 31

BAHRAIN
MEMRB
P.O. Box 22103
Manama Town 317

BANGLADESH
Micro Industries Development Assistance Society (MIDAS)
G.P.O. Box 800
Dhaka

BELGIUM
Publications des Nations Unies
Av. du Roi 202
1060 Brussels

BRAZIL
Publicacoes Tecnicas Internacionais Ltda.
Rua Peixoto Gomide, 209
01409 Sao Paulo, SP

CANADA
Le Diffuseur
C.P. 85, 1501 Ampere Street
Boucherville, Quebec
J4B 5E6

CHILE
Editorial Renacimiento
Miraflores 354
Santiago

COLOMBIA
Enlace Ltda.
Apartado Aero 34270
Bogota D.E.
Apartado Aereo 4430
Cali, Valle

COSTA RICA
Libreria Trejos
Calle 11-13
Av. Fernandez Guell
San Jose

CYPRUS
MEMRB
P.O. Box 2098
Nicosia

DENMARK
SamfundsLitteratur
Rosenoerns Alle 11
DK-1970 Copenhagen V

EGYPT, ARAB REPUBLIC OF
Al Ahram
Galaa Street
Cairo

FINLAND
Akateeminen Kirjakauppa
P.O. Box 128
SF-00101
Helsinki 10

FRANCE
World Bank Publications
66, avenue d'Iena
75116 Paris

GERMANY, FEDERAL REPUBLIC OF
UNO-Verlag
D-5300 Bonn 1
Simrockstrasse 23

GREECE
MEMRB
24, Ippodamou Street
Athens-11635

HONG KONG, MACAU
Asia 2000 Ltd.
6 Fl., 146 Prince Edward Road, W,
Kowloon
Hong Kong

HUNGARY
Kultura
H-1011 Budapest
Fioi Utca 32

INDIA
UBS Publishers' Distributors Ltd.
Post Box 7015
New Delhi 110002
10 First Main Road
Gandhi Nagar
Bangalore 560009
Apeejay Chambers, P.O. Box 736
5 Wallace Street
Bombay 400001
8/1-B, Chowringhee Lane
Calcutta 700016
7/188, 1(CA), Swarup Nagar
Kampu 208002
Sivaganga Road
Nungambakkam
Madras 600034

INDONESIA
Pt. Indira Limited
Jl. Sam Ratulangi 37
Jakarta Pusat
P.O. Box 181

IRELAND
TDC Publishers
12 North Frederick Street
Dublin 1

ISRAEL
Jerusalem Post
Jerusalem Post Building
P.O. Box 81
Romema Jerusalem 91000

ITALY
Licosa Commissionaria Sansoni SPA
Via Lamarmora 45
Casella Postale 552
50121 Florence

IVORY COAST
Centre d'Edition et de Diffusion Africaines (CEDA)
04 B.P. 541
Abidjan 04 Plateau

JAPAN
Eastern Book Service
37-3, Hongo 3-Chome, Bunkyo-ku 113
Tokyo

JORDAN
MEMRB
P.O. Box 3143
Jabal
Amman

KENYA
Africa Book Service (E.A.) Ltd.
P. O. Box 45245
Nairobi

KOREA, REPUBLIC OF
Pan Korea Book Corporation
P. O. Box 101, Kwangwhamun
Seoul

KUWAIT
MEMRB
P.O. Box 5465

MALAYSIA
University of Malaya Cooperative Bookshop, Limited
P. O. Box 1127, Jalan Pantai Baru
Kuala Lumpur

MEXICO
INFOTEC
San Lorenzo 153-11, Col. del Valle
Deleg. Benito Juarez
03100 Mexico City

MOROCCO
MEMRB
2 Rue Moliere Racine
Casablanca

NETHERLANDS
Medical Books Europe, BV (MBE)
Noorderwal 38,
7241 BL Lochem

NEW ZEALAND
R. Hill and Son, Ltd.
Private Bag
New Market
Auckland

NIGERIA
University Press Limited
Three Crowns Building Jericho
Private Mail Bag 5095
Ibadan

NORWAY
Tanum Karl Johan, A.S.
P. O. Box 1177 Sentrum
Oslo 1

PAKISTAN
Mirza Book Agency
65, Shahrah-e-Quaid-e-Azam
P.O. Box No. 729
Lahore 3

PANAMA
Ediciones Libreria Cultural Panamena, S.A.
Av. 7, Espana 16
Panama Zone 1

PERU
Editorial Desarrollo SA
Apartado 3824
Lima

PHILIPPINES
National Book Store
701 Rizal Avenue
Metro Manila

PORTUGAL
Livraria Portugal
Rua Do Carmo 70-74
1200 Lisbon

SAUDI ARABIA
Jarir Book Store
P. O. Box 3196
Riyadh 11471

SINGAPORE, TAIWAN, BURMA
Information Publications Private, Ltd.
02-06 1st Fl., Pei-Fu Industrial Bldg., 24 New Industrial Road
Singapore

SOUTH AFRICA
Oxford University Press Southern Africa
P.O. Box 1141
Cape Town 8000

SPAIN
Mundi-Prensa Libros, S.A.
Castello 37
28001 Madrid

SRI LANKA AND THE MALDIVES
Lake House Bookshop
P.O. Box 244
100, Sir Chittampalam A. Gardiner Mawatha
Colombo 2

SWEDEN
For single titles:
ABCE Fritzes Kungl. Hovbokhandel
Attn: Mr. Eide Segerback
Regeringsgatan 12, Box 16356
S-103 27 Stockholm
For subscription orders:
Wennergren-Williams AB
Box 30004
S-104 25 Stockholm

SWITZERLAND
Librairie Payot
6 Rue Grenus
Case postal 381
CH 1211 Geneva 11

TANZANIA
Oxford University Press
P. O. Box 5299
Dar es Salaam

THAILAND
Central Department Store
306 Silom Road
Bangkok

TRINIDAD & TOBAGO
Systematics Studies Unit
55 Eastern Main Road
Curepe
Trinidad, West Indies

TUNISIA
Societe Tunisienne de Diffusion
5 Avenue de Carthage
Tunis

TURKEY
Haset Kitapevi A.S.
469, Istiklal Caddesi
Beyoglu-Istanbul

UGANDA
Uganda Bookshop
P.O. Box 7145
Kampala

UNITED ARAB EMIRATES
MEMRB
P. O. Box 6097
Sharjah

UNITED KINGDOM AND NORTHERN IRELAND
Microinfo Ltd.
P. O. Box 3
Alton, Hampshire GU 34 2PG
England

VENEZUELA
Libreria del Este
Aptdo. 60.337
Caracas 1060-A

WESTERN SAMOA
Wesley Bookshop
P.O. Box 207
Apia

ZIMBABWE
Textbook Sales Pvt. Ltd.
Box 3799
Harare

No. 25. Industrialization in Sub-Saharan Africa: Strategies and Performance

No. 26. Small Enterprise Development: Economic Issues from African Experience

No. 27. Farming Systems in Africa: The Great Lakes Highlands of Zaire, Rwanda, and Burundi (also available in French as 27F)

No. 28. Technical Assistance and Aid Agency Staff: Alternative Techniques for Greater Effectiveness

No. 29. Handpumps Testing and Development: Progress Report on Field and Laboratory Testing

No. 30. Recycling from Municipal Refuse: A State-of-the-Art Review and Annotated Bibliography

No. 31. Remanufacturing: The Experience of the United States and Implications for Developing Countries

No. 32. World Refinery Industry: Need for Restructuring

No. 33. Guidelines for Calculating Financial and Economic Rates of Return for DFC Projects

No. 34. Energy Efficiency in the Pulp and Paper Industry with Emphasis on Developing Countries

No. 35. Potential for Energy Efficiency in the Fertilizer Industry

No. 36. Aquaculture: A Component of Low Cost Sanitation Technology

No. 37. Municipal Waste Processing in Europe: A Status Report on Selected Materials and Energy Recovery Projects

No. 38. Bulk Shipping and Terminal Logistics

No. 39. Cocoa Production: Present Constraints and Priorities for Research

No. 40. Irrigation Design and Management: Experience in Thailand

No. 41. Fuel Peat in Developing Countries

No. 42. Administrative and Operational Procedures for Programs for Sites and Services and Area Upgrading

No. 43. Farming Systems Research: A Review

No. 44. Animal Health Services in Sub-Saharan Africa: Alternative Approaches

No. 45. The International Road Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements

No. 46. Guidelines for Conducting and Calibrating Road Roughness Measurements

No. 47. Guidelines for Evaluating the Management Information Systems of Industrial Enterprises

No. 48. Handpumps Testing and Development: Proceedings of a Workshop in China

The World Bank

Headquarters
1818 H Street, N.W.
Washington, D.C. 20433, U.S.A.

Telephone: (202) 477-1234
Telex: WUI 64145 WORLDBANK
RCA 248423 WORLDBK
Cable Address: INTBAFRAD
WASHINGTONDC

European Office
66, avenue d'Iéna
75116 Paris, France

Telephone: (1) 47.23.54.21
Telex: 842-620628

Tokyo Office
Kokusai Building
1-1 Marunouchi 3-chome
Chiyoda-ku, Tokyo 100, Japan

Telephone: (03) 214-5001
Telex: 781-26838

UNDP

New York
United Nations Development Programme
1 United Nations Plaza
New York, New York 10017

Telephone: (212) 754-1234
Telex: 125980 (domestic)
232-422 (overseas)
Cable Address: UNDEVPRO
NEW YORK

Geneva Office
Palais des Nations
CH-1211 Geneva 10
Switzerland

Telephone: 98-84-00
DBHTelephone: DDH98-58-50
Telex: (UNDP) 28.96.20 or (UN) 28.96.96
Cable Address: UNDEVPRO
GENEVA (SWITZERLAND)

Tokyo Office
Shin Aoyama Building
Room 2255
1-1, Minami-Aoyama 1-Chome
Minato-Ku
Tokyo 107, Japan

Telephone: 03-475-1619/20
Telex: J28 334
AB TKOPI J28 334
Cable Address: UNDEVPRO
TOKYO (JAPAN)

ISSN 0253-7494
ISBN 0-8213-0752-5