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DYNATECH R/D COMPANY

LOW CAPITAL COST FUEL GAS PRODUCTION

- Final Report -

Contract Number DPE-5542-C-00-3050-00
Project Number 936-5542

Submitted to:

Science & Technology/EY
SA-18
AGENCY FOR INTERNATIONAL DEVELOPMENT
Washington, D.C. 20523

July 31, 1985

by:

Donald L. Wise
Alfred P. Leuschner
Ralph L. Wentworth

Dynatech Project Number AID-1
Dynatech Report Number 2360

a division of **DYNATECH CORPORATION**

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TABLE OF CONTENTS

Section		Page
	SUMMARY	iv
1	INTRODUCTION	1
2	FUEL GAS PRODUCTION THROUGH DIGESTION OF WASTE IN LANDFILLS	4
2.1	Anaerobic Digestion Principles	4
2.1.1	Temperature	6
2.1.2	pH, Alkalinity, and Volatile Acids	6
2.1.3	Nutrients	7
2.1.4	Toxic Substances	7
2.2	Applications of Anaerobic Digestion	7
2.3	Landfill Technology	9
3	ANALYSIS OF DIGESTER SYSTEMS	13
3.1	The Rate of Digestion	13
3.2	Example of Village Biogas Potential	27
3.2.1	Biogas Potential From Animal Manures	27
3.2.2	Biogas Potential From Agricultural Residues	28
3.2.3	Combined System	29
3.2.4	Impact on Village	30
3.2.5	System Size	30
4	DIGESTION EXPERIMENTS	32
4.1	Summary of Experiments	32
4.2	Experimental Results	35
4.3	Discussion of Results	38
5	LIST OF REFERENCES	41

LIST OF FIGURES

Figure		Page
3.1	Hole in Ground Anaerobic Digester (Cross Section)	14
3.2	Rate Constant as a Function of Temperature	17
3.3	Temperature Gradient In Soil After Step Change in Digester Temperature	19
3.4	Temperature Profile of Soil Surrounding Digester After Step Increase In Digester Temperature	19
3.5	Calculation of Maximum Heat Loss Rate for a Digester Maintaining Mesophilic Temperature as a Function of Digestion Rate Constant	23
3.6	Comparison of Conversion History of Digesters With and Without Preheating to Mesophilic Temperatures*	26

LIST OF TABLES

Table		Page
3.1	Logic for Program Calculations Digester Temperature History	21
3.2	Assumptions for Calculating Digester Temperature History	22
3.3	Volume to Surface Area Ratios of Digesters Built With 45° Sloping Trapezoidal Sides	25
4.1	Total Gas Generation Observed in the Batch Anaerobic Digestion of Seven Waste Materials	36

SUMMARY

It was proposed to the U.S. Agency for International Development to conduct a broad based project on a straightforward low capital cost anaerobic digestion system, including the direct participation of Co-Principal Investigators in ten countries. The concept to be experimentally evaluated was that of batch-type anaerobic digestion, following the advancing technology of controlled landfilling of municipal solid wastes. In addition to fuel gas production, this system was considered to also be useful for preparing organic wastes as soil conditioners.

Rather than explore large-scale batch digestion of municipal solid waste in developing countries, the objective of this project was to consider smaller village-type batch digesters. Moreover, it was proposed that the experimental evaluation include an array of solid wastes that would be indigenous to a village in developing country. These organic residues include agriculture residues, some "industrial" wastes (as might come from local food processing plants), as well as garbage and other forms of what may be considered municipal wastes. Thus, in one area of the world, one might consider the potential for improved utilization of cotton stalks, combined with all other local municipal and industrial organic wastes. In another part of the world, these local wastes might be combined with rice straw--all along with several types of animal manures.

The plan actually carried out was to enlist the support of ten well-respected research workers, each in different countries, as Co-Principal Investigators. These ten Co-Principal Investigators then carried out bench-scale experiments following the technology of controlled landfilling. Supportive to this experimental program was technical support from Dynatech in the form of discussions, project review, and engineering analysis.

At the conclusion of the project a Workshop was held (at the Museum of Science, in Boston, MA) in which all ten Co-Principal Investigators presented the results of their work. It was concluded that

this system for smaller scale batch digestion of combined organic residues does indeed appear to be generic. That is, with appropriate technical input, essentially any mixture of available organic wastes may be practically converted to fuel gas, while leaving a seemingly useful residue as a soil conditioner (no soil conditioning tests were proposed nor run).

It is recommended with the clearly defined success of this AID sponsored project, that work be continued to the demonstration phase. That is, steps should be taken to demonstrate a complete village size anaerobic digester system, as based on the encouraging results of this project.

In every respect continued work--at the level of on-site village demonstration--is merited.

Section 1

INTRODUCTION

There is broad recognition of the potential for energy generation from a variety of organic wastes through the process of anaerobic digestion. The process is in use world-wide to produce methane fuel gas from such waste materials as manures and municipal solid waste. Although the process is welcome and acceptable, lack of experience and technical information has hindered the broader application of this useful technology. In particular, it is recognized that many wastes suitable for conversion to fuel gas lie at hand in all parts of the world without utilization. Such wastes are commonly available in places where energy resources are not only costly, but often unaffordable. Thus, an incentive exists to get information about energy generation from wastes in the hands of those who can benefit from the knowledge.

Further incentive to develop technical information of this kind arises through the demonstration during the last decade that the cost of fuel gas generation from waste may be reduced significantly through so-called "controlled landfilling." This process (Augenstein and co-workers, 1976) overcomes certain cost and productivity problems encountered with conventional continuous stirred tank digesters. In controlled landfilling a suitable inoculum, nutrients, buffer, and moisture are added to waste placed in a low cost cavity, either natural or constructed, resulting in anaerobic digestion at a higher rate than with untreated waste. The main objectives of the controlled landfill concept for enhanced fuel gas production are: a) to increase the amount of energy produced in the digestion process, relative to the amount of energy required to run the process, b) to remove constraints on current digestion technology, enabling lower capital cost waste stabilization and fuel gas generation from waste, c) to allow digestion of waste to occur at much higher solids concentration, d) to permit waste to be digested with little or no preseparation of nonbiodegradable

materials, and e) to enable economic digestion by using longer retention times in a landfill. It was an intent of the work reported here to show that a number of waste materials broadly encountered around the world are suitable candidates for exploitation through the controlled landfilling process.

The advantages of the proposed system to an LDC include:

a) Energy recovery from many residues in the form of a useful and acceptable "biogas" fuel not otherwise recoverable;

b) A simple process -- as simple as landfilling of MSW;

c) Low capital cost -- costs associated with the labor of digging a large pit;

d) Utilization of all organic residues in a populous area -- this includes:

- all municipal wastes (solid wastes, garbage, sewages sludge);
- industrial residues such as those from food processing;
- agricultural residues such as wheat, rice, and barley straws as well as animal manures;

e) Waste "stabilization," i.e. waste treatment, especially valuable for sewage sludge.

The experiments reported here were carried out with the intention of demonstrating the applicability of anaerobic digestion to fuel gas production from a variety of wastes. It was expected that such a demonstration by widely distributed researchers working with different, but available wastes would be broadly helpful and stimulating to interested persons and agencies, world-wide. The digestibility of seven municipal and agricultural wastes in batch systems was determined by investigators on five continents. The participants of the reported study were as follows:

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   Instituto Centroamericano de Investigacion y Tecnologia Industrial
   Guatemala, C.A.

2. Kee Kean Chin
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3. M. Nabil Alaa El-Din
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4. Uri Marchaim
   Migal Laboratories
   Kiryat Shemona, Israel

5. Joan Mata
   Universitat de Barcelona
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6. V.V. Modi
   The Maharaja Sayajirao University of Baroda
   Baroda, India

7. William G. Padolina
   University of the Philippines at Los Banos
   Laguna, Philippines

8. Suhirman
   Lembaga Biologi Nasional
   Bogor, Indonesia

9. Javier B. Verastegui
   Instituto de Investigacion Tecnologica Industrial y de Normas Tecnica
   Lima, Peru

10. M.H. Wong
    The Chinese University of Hong Kong
    Shatin, NT, Hong Kong

In the following sections of this report the principles of fuel gas generation from wastes are summarized. The technology of gas production from landfills is reviewed with special emphasis on the process of controlled landfilling. Projections are presented to characterize the functioning of a landfill digester system in a field situation. The experimental results obtained by the cooperating investigators are presented.

Section 2

FUEL GAS PRODUCTION THROUGH DIGESTION OF WASTE IN LANDFILLS

The technical background on energy recovery from organic wastes, especially municipal solid wastes, but also agricultural residues and crops grown specifically for energy recovery is reviewed. Special emphasis is placed on fuel gas production from "controlled landfilling." Some of the problems and techniques of fuel gas production via this low capital cost batch digestion method are discussed.

2.1 Anaerobic Digestion Principles

The term "anaerobic digestion" refers to the ability of certain classes of microorganisms to grow on a number of different organic compounds in the absence of oxygen (hence the term anaerobic), converting them ultimately to the gases carbon dioxide and methane. This process is referred to traditionally as "anaerobic digestion." The technology of anaerobic digestion has long been utilized to dispose of waste materials, especially sewage sludge solids. Methane is generated in anaerobic digestion, and the usefulness of the gas was recognized as the sludge disposal process was developed in the nineteenth century. Since that time, anaerobic digestion has been utilized throughout the world to stabilize sewage solids, and often the gas produced has been used to provide heat and power for the treatment plant. During the twenty years after World War II, attention to the development of anaerobic digestion lagged as aerobic treatment and teritary sewage treatment processes were developed mainly due to their ability to treat sewage more completely and because of their relatively low costs. As energy costs have escalated rapidly during recent years, however, attention has been focused again on anaerobic digestion as a waste treatment process.

Further expansion of the technology occurred during the late 1960's as anaerobic digestion was viewed with renewed interest as a potential source of energy and as a waste disposal process for various types of

organic wastes, including municipal solid waste and agricultural residues. Dr. Clarence G. Golueke, Research Biologist at the University of California, Richmond Field Station, was the first of the more recent workers to study anaerobic digestion of solid waste. A five-year program under his direction examined the technical feasibility of digesting municipal wastes admixed with animal waste (Golueke and McGauhen 1970; Goleuke 1971). Further work at the University of Illinois under the direction of Dr. John T. Pfeffer demonstrated the feasibility of methane production from municipal solid waste, with limited additions of sewage sludge (Pfeffer 1974; Pfeffer and Liebman 1974).

In 1969, an intensive laboratory and engineering evaluation of fuel gas production from municipal solid waste was initiated at Dynatech R/D Company by Consolidated Natural Gas Service Company, Inc., Cleveland, Ohio. Laboratory experiments conducted at Dynatech reaffirmed the technical feasibility of utilizing the basic anaerobic digestion process to convert organic wastes to pipeline-quality fuel gas (Cooney and Wise 1975) and a detailed engineering analysis of fuel gas production from solid waste (Kispert, et al 1975) provided cost data.

The heart of the anaerobic digestion process is microbiological conversion of the organic constituents of waste to methane. The chemistry involved for any general waste carbohydrate material may be represented by the following generalized reaction:

$$C_nH_aO_b + (4n - a - 2b)/4\ H_2O \rightarrow (4n - a + 2b)/8\ CO_2 + (4n + a - 2b)/8\ CH_4 \qquad (2.1)$$

In the important case of conversion of cellulose to methane this becomes

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2. \qquad (2.2)$$

The yield is 0.41 m^3 (STP) CH_4/kg (6.5 ft^3/lb), equal volumes of methane and carbon dioxide being produced.

For other substrates, the proportions of methane and carbon dioxide produced may be different. For example, the conversion of proteins yields a gas with 75 percent methane, and the conversion of fats yields a gas with 70 percent methane (Konstandt 1976). Thus, the conversion of a complex organic substrate will yield a gas which is typically 50 to 60 percent methane and 40 to 50 percent carbon dioxide.

Environmental conditions which affect the rate and yield obtained in anaerobic digestion include temperature, pH, alkalinity, volatile acid concentrations, nutrients, and toxic substances. Due especially to the sensitivity and slow growth of the microorganisms responsible for generation of the methane, these environmental parameters must be controlled with specific ranges for adequate digestion to occur.

2.1.1 Temperature

Three specific temperature ranges have been defined for anaerobic fermentation, psychrophilic (10 to 20°C), mesophilic (30 to 40°C), and thermophilic (50 to 60°C). In a landfill digester, the temperature cannot be controlled as it can be in conventional stirred tank digester. However, due to the exothermic nature of the anaerobic reactions, these the contents of a fermenting landfill generally will exhibit higher temperatures than the surrounding atmosphere. The digestion process may occur more slowly in the psychrophilic range rather than in the more rapid mesophilic or thermophilic ranges, but it does not cease.

2.1.2 pH, Alkalinity, and Volatile Acids

These three environmental parameters are interdependent. For stable anaerobic digestion to occur the system pH should be between 6.6 and 7.6, with an optimum range of 7.0 to 7.2 (McCarty 1964). Volatile acids, an intermediary product in the fermentation process, can increase in concentration if a system imbalance occurs due to other environmental factors

which inhibit the growth of the methane formers. In such a situation, volatile acid concentrations will increase and the pH will drop, thus further aggravating the situation until methanogenesis ceases. However, this problem can be avoided if buffer is added to keep the pH near neutral.

2.1.3 Nutrients

A variety of organic and inorganic nutrient substances are required for adequate digestion to occur. Among these are carbon, nitrogen, phosphorus, sulfur, vitamins, and trace minerals (Loehr 1966). Agricultural residues and municipal solid waste may be deficient in one or many of these nutrients and require supplementation. Of specific concern is the ratio of carbon to nitrogen to phosphorus-(C:N:P); a ratio of 100:5:1 will be adequate in most cases (Sanders and Bloodgood 1963; van den Berg and Lentz 1977; Lane 1979).

2.1.4 Toxic Substances

Numerous substances, if present in a high enough concentration will cause inhibitory or toxicity problems. Those of major concern include sulfides (>200 mg/ℓ), soluble heavy metals (>1.0 mg/ℓ), alkaline earth metals such as sodium (5,000 - 8,000 mg/ℓ), potassium (4,000 - 10,000 mg/ℓ), calcium (2,000 - 6,000 mg/ℓ), and magnesium (1,200 - 3,500 mg/ℓ), and ammonia (1,700 - 4,000 mg/ℓ) (EPA 1974).

With agricultural and municipal residues, these substances should not cause significant problems with the possible exception of localized areas within the digester. Most of these substances only become soluble (and therefore toxic) at low pH, and through adequate buffering the pH will remain near neutral.

2.2 Applications of Anaerobic Digestion

The application of these and more detailed principles to practical fuel gas generation and waste disposal is summarized by Wentworth,

Ashare, and Wise (1979). As pointed out in that review anaerobic digestion technology may be approached at different levels of detail. In the most general approach the engineering design of digesters proceeds on the basis of conventional process description -- rate, yield, etc. At the next level of detail, the extracellular chemistry of the digester is taken into account. At the fundamental level the detailed metabolism of the microorganisms of concern is the basis for design and application. Contributions to the technology are available from each of these levels although the knowledge of the fundamental microbiology is not yet sufficiently understood to provide the sole basis for digester design and operation. The present state-of-the-art finds expression in a variety of digestion schemes. Perhaps most familiar is the stirred tank reactor, in which a slurry or solution of the substrate to be digested is maintained at constant environmental conditions in the presence of suitable anaerobic flora. The extension of this process is the plug flow reactor, in which successive volumes of the digesting medium pass unmixed as "plugs" through the digester, thereby achieving greater conversion. Both stirred tank and plug flow reactors may be enhanced by recycled active mass of microorganisms. In recent years very useful digester schemes have been developed involving the immobilization of microorganisms and the passage of matter to be digested past these active surfaces. In contrast to these fluid systems are high solids content digesters. Here the substrate is immobile and the active microorganisms are present on the substrate or in the reduced proportion of fluid medium present.

Practical digestion systems based on all the variants of this technology have been applied to a wide variety of substrates, including sewage, industrial wastewaters, animal manures, agricultural residues, municipal waste, and plant matter raised specifically for digestion. Examples and case histories are provided in the proceedings of recent symposia (Stafford, Wheatley and Hughes (1980); Hughes et. al. (1982); Anon. (1983)) and monographs (Hobson, Bousfield and Summers (1981); Jewell (1975); Wise (1981)). Of special utility in producing fuel gas from municipal and agricultural wastes is the landfill, that is, a relatively inexpensive, natural

or constructed, digester consisting of a pit filled with matter undergoing digestion at high solids content. The usefulness of the landfill is enhanced by managing the buffer content, the presence of nutrients, and the moisture content and distribution in the so-called "controlled landfill."

2.3 Landfill Technology

It has long been known that methane gas is produced in landfills, however only recently have landfills been viewed as methane producers whose energy is economically harvestable. Subsequently, the art of landfill design has evolved to the point where consideration is being given to designing landfills with energy recovery in mind. Applying landfill gas recovery concepts for energy production from agricultural residues in LDCs hold many significant advantages:

1. Landfill construction is not capital intensive. In the construction of a landfill, the soil is used to contain the residue. This eliminates the need for expensive digesters constructed from steel or concrete. By lining the bottom and top of a landfill with a material such as compacted clay anaerobic conditions are maintained. In addition, the liner serves as a barrier to liquid migration to the groundwater and migration of methane gas to the atmosphere.

2. Landfills require no residue pretreatment. Conventional digestion systems all require some form of residue pretreatment. Initially, the residue must undergo particle size reduction via grinding or chopping. Second, the residue must be slurried so that it could be pumped into and out of a digester. Landfilling of the residue requires no pretreatment of this nature.

3. Landfills are labor intensive, low technology systems. The construction of a landfill requires manpower for placement and covering of residues. Once the residue is in place only minimal attention is required to keep the system operating, and no sophisticated technology is needed to

maintain gas production, or recover the gas. In comparison, conventional digestion, or the production of other energy forms (such as alcohols) from agricultural residues require a higher degree of technical sophistication.

4. No residue disposal is required. With other energy recovery systems the residue after fermentation requires some form of liquid/solid separation and solids disposal. In a landfill the residue is already in place, requiring no further disposal.

Controlled landfilling (Augenstein et. al. 1976, 1976/1977) is the managed, batch anaerobic digestion of waste to enhance fuel gas production. In controlled landfilling there is added to the waste a suitable inoculum, nutrients, buffer, and moisture which allow the microbial action of anaerobic fermentation to proceed at a substantially higher rate than in untreated substrate. In this practice, high stabilization rates like those obtained in continuous stirred tank reactor is combined with the lower capital and operating costs of landfilling.

Inoculum may be provided initially by the addition of substance or the residue from a working digester. At a location near a sewage treatment plant, sewage sludge can provide excellent inoculum. Residue from another fuel gas-generating digester may serve, as well. In the event a regional plan is put in place to establish a number of landfill digestion systems the establishment of a central digester may be warranted for the generation of seed.

Enhancement of microbial activity can be achieved by recycling leachate through the decomposing refuse. The leachate which accumulates along an impermeable barrier, such as a clay substratum, is collected and recycled within the refuse. A laboratory study of this technique (Pohland, 1975) was carried out with simulated landfills constructed of corrugated steel sections of pipe 91.4 cm (36 inches) in diameter and joined to form a column 4.3 m (14 ft) deep were used for experimentation. A conical concrete bottom with a 3.8 cm (1.5 inch) drain was formed in each simulated fill to

seal the bottom of the pipe section and allow for drainage of leachate. The fill receiving recirculated leachate was pumped back through a distributor unit buried between the top of the compacted shredded refuse and the soil cover and allowed to percolate through the refuse. Refuse removed from the fill after 11 weeks indicated that decomposition had proceeded at a more rapid pace in the fill receiving recycled leachate than in the control fill where the leachate was wasted. Carbon reduction and volatile solids reduction was greater in the experimental fill than in the control.

Nutrients also may be furnished through the addition of inoculum as described. In the case where sewage sludge is available for application to municipal solid waste it has been observed that the proportion of sewage sludge generated to that of municipal waste generated is such that the sludge can furnish the correct quantity of nutrient required to support digestion of the waste. Agricultural wastes, e.g., animal manure, offer a potential source of nutrients. Finally, conventional chemical fertilizer may be utilized. Pretreatment with calcium carbonate can provide a superior buffering system within a controlled landfill. A feature of anaerobic digestion is that carbon dioxide production by microorganisms is invariably present during both acid and methane formation stages. When an excess calcium carbonate (beyond that which can dissolve in the aqueous phase at any organic acid level) is introduced into the digestion system carbon dioxide is given off. Organic acid anion formation is balanced by calcium cations going into solution, and pH drop is small enough for methane production to proceed. In the reverse situation, when acid anions are consumed and converted to methane, carbon dioxide generated as a consequence of the digestion process dictates precipitation of calcium carbonate/bicarbonate by solubility product relations. Calcium cations are removed from the aqueous phase, the pH rise is small, and digestion continues.

Laboratory studies by Augenstein et. al. (1976) have demonstrated the feasibility of controlling pH by pretreating shredded municipal refuse with calcium carbonate. A total of 27 liters of sewage sludge (pH = 5.25; 4% total solids concentration) was mixed with 1200 grams $CaCO_3$ for pH

adjustment to 6.3 and held overnight; 8 liters of digester effluent from a laboratory digester operating on municipal solid waste were then mixed thoroughly with the neutralized sludge to provide an inoculum of microorganisms, and that mixture was mixed with 18.1 kilograms of shredded municipal refuse using a rotary blade mixer. Digestion of the material in an unstirred digester at 37°C resulted in a conversion of fuel gas up to 0.128 m^3/kg dry sludge/waste solids. This value is to be compared with a methane yield of 0.095 m^3/kg dry sludge/waste solids obtained from the same solid waste source in a continuous stirred tank with a 25-day retention time.

A comprehensive evaluation of all these factors as well as moisture was made by Buivid et. al. (1981). In this parametric study, the effects of moisture, nutrient/innoculum addition, compaction, particle size, reduction, pH buffer addition, temperature and leachate recycle were assessed. The conclusions which can be drawn from these data can be summarized as follows: 1) conventional landfilling will yield methane production rates of 0.03 to 0.15 ft^3 CH_4/dry lb of municipal solid waste (MSW) in 12 months, whereas under controlled conditions this rate was shown to increase to 2.30 ft^3 CH_4/dry lb of MSW in three months; 2) the addition of moisture alone did not significantly increase methane production rates; however, moisture addition in combination with buffer, nutrients and microbial innoculum did; 3) addition of calcium carbonate at 1% by weight of total moisture was found to be sufficient to maintain an optimal pH; 4) size reduction of the MSW hinders moisture movement through MSW and decreases methane production; 5) mesophilic temperatures (37°C) were found to be optimal for methane production; 6) compaction of MSW in conjunction with incorporation of sewage sludge and buffer increases the volumetric production of methane although compaction may limit the benefits of leachate recycle; and lastly, 7) leachate recycle provided only minimal improvements in methane production when used in conjunction with incorporation of sewage sludge and buffer with the MSW.

A further concept for the digestion of high solids matter is staged fermentation, in which acids are produced in the fermenting mass and extracted from that mass as leachate (Ghosh, 1984). The leachate is then fermented to methane in a separate vessel. Acceleration of the process and nutrient conservation are attained.

Section 3

ANALYSIS OF DIGESTER SYSTEMS

In considering the installation of a system for the generation of fuel gas by digestion of wastes two primary concerns are the rate of conversion and the relative costs involved. In this section procedures for the estimation of these factors are presented.

3.1 The Rate of Digestion

In the implementation of anaerobic digestion of agricultural residues to produce fuel gas from a small "controlled landfill" batch digester it is envisioned that these batch digesters will be constructed by excavating an appropriate area and forming a hole with steeply sloping sides and slightly sloped bottom to provide for collection and recirculation of water. The hole will be lined with water impermeable material (clay or plastic liner) and, after filling with the collected residue, the top closed with an airtight plastic liner which is vented for gas collection. This top liner may then be covered with clay. Figure 3.1 depicts such a digestion system.

These digesters are to be operated in a batch mode. The hole is filled with residue, buffer, nutrients, and inoculum. It is then sealed and the digestion process allowed to proceed. As the microbial reactions progress, methane and carbon dioxide gases are generated which may be collected for use. Heat is also evolved from these exothermic reactions. Some of this heat escapes from the digester through its walls or with the product gases. The remainder of the heat raises the temperature of the digester.

The rate of decomposition of organic residues and production of fuel gas is dependent on the digester temperature. The temperature of the digester with time is dependent on the rate of the anaerobic digestion reactions and the heat loss from the digester. The rate of heat loss from the

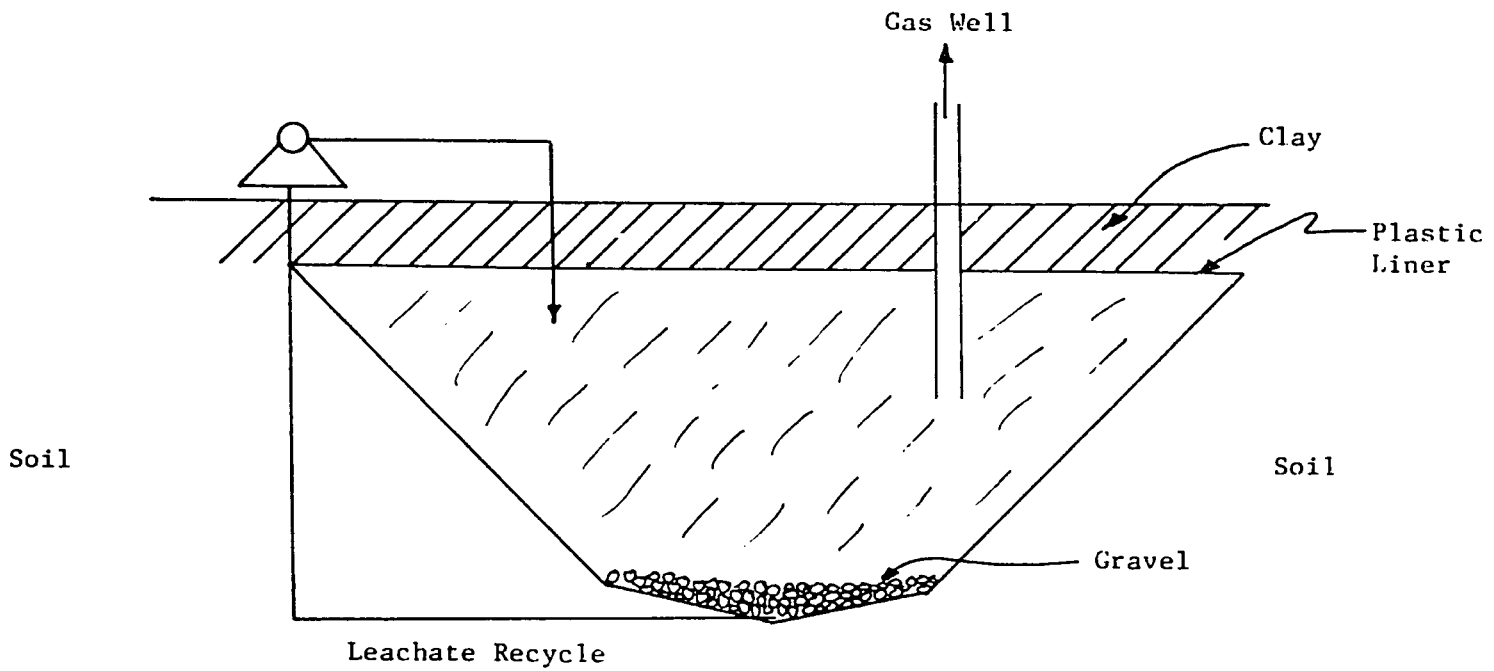


Figure 3.1: Hole In Ground Anaerobic Digester (Cross Section)

digester is a function of digester design and construction and digester temperature. A model has been devised to describe the temperature history of a digester, given its volume to surface area ratio (V/SA).

There are two approaches for modelling the kinetics of anaerobic digestion. One approach, the Monod model (Monod 1949), develops the kinetics by consideration of the growth and removal of microorganisms. A second approach is to consider the microorganisms as "catalysts" and develop and over-all mass transfer kinetic model for a "catalyzed" reaction. This second approach is used in this model. The anaerobic digestion process is also assumed to follow first order kinetics, in which the rate of substrate degradation is linearly proportional to substrate concentration (CB):

$$\frac{d(CB)}{dt} = -(RK)(CB) \qquad (3.1)$$

where RK is the rate constant and CB is the concentration of biodegradable material. The concentration of biodegradable material at any time can be calculated by integrating the above expression between starting time, t = o, and any time later (t):

$$(CB)_t = (CB)_o \exp[-(RK)(t)] \qquad (3.2)$$

where $(CB)_t$ is substrate concentration at time (t) and $(CB)_o$ is initial substrate concentration at time t = o. Similarly, the amount of gas produced can be represented:

$$G = A\,(CB)_o\,[1 - \exp[-(RK)(t)]] \qquad (3.3)$$

where G is total gas production and A is the volume of gas produced per mass converted. An analogous expression for heat released by the exothermic reaction over time can be written:

$$DT = (DH)\,(CB)_o\,[1 - \exp[-(RK)(t)]] \qquad (3.4)$$

where DT is the total heat released and DH represents the heat released by conversion of a unit mass of substrate.

The biodegradable substrate in conversion of agricultural residues is assumed to be a hexose polymer (i.e. starch or cellulose). Conversion of this material to methane and carbon dioxide can be described:

$$(C_6H_{10}O_5)_x + H_2O \rightarrow 3x\ CH_4 + 3x\ CO_2 \qquad (3.5)$$

This is an exothermic reaction in which approximately 500 Btu/lb carbohydrate converted are released. (The energy contained in the methane product will be 6074 Btu/lb of carbohydrate converted.) It is the heat released by this exothermic reaction which will provide the energy for reactor heating.

The rate of substrate conversion is dependent on the rate constant (RK). Previous work has been done to calculate the activation energy and pre-exponential factor by compilation of rate constants reported for digestion of agricultural residues at various temperatures (Ashare et al. 1977). An Arrhenius plot (1/T vs rate constant) is shown in Figure 3.2 and provides a reasonable correlation of the data. The rate constant (RK) is estimated as a function of temperature according to the Arrhenius equation:

$$RK = (RK)_o \exp[-Ea/RT] \qquad (3.6)$$

where $(RK)_o$ is the pre-exponential factor, Ea is the activation energy, R is the gas constant, and T is the absolute temperature. From the plot, Figure 3.2, the activation energy is found to be 15,175 cal/mode (27,315 Btu/lb mole). The constant $(RK)_o$ may be adjust to give the desired rate constant at mesophilic temperature.

Heat loss from the digester occurs from the sides, top, and bottom of the digester. Heat loss from the digester walls is a function of

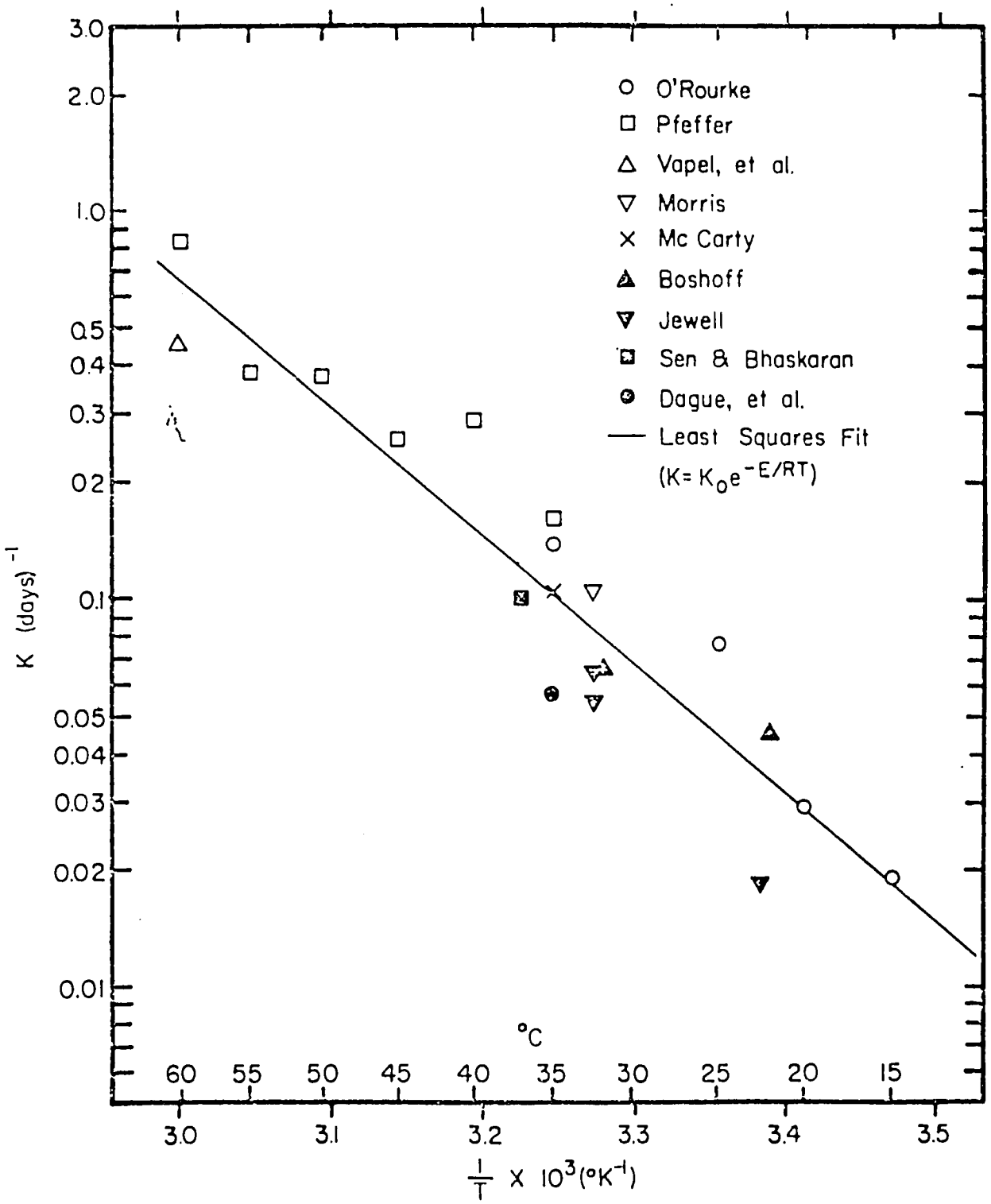


Figure 3.2 Rate Constant as a Function of Temperature

digester temperature, surface area of the digester walls, and heat transfer properties of the walls and the material surrounding the digester. The heat resistance of the plastic liner inside the digester is negligible; the heat transfer co-efficient of the soil (k) surrounding the digester is taken to be 1.0 Btu/hr•ft•°F, the heat capacity of the soil (C_s) 0.25 Btu/lb°F, and the density of the soil (p_s) 120 lb/ft^3. The temperature gradient of the soil surrounding the digester wall one hour after a step change in digester temperature is shown by the series of curves in Figure 3.3. The temperature history of the soil surrounding the digester after a step increase in digester temperature can be determined as in Figure 3.4. Similar plots were drawn for digester temperature increases from 70°F (assumed to be the average ground temperature) to 100°F (mesophilic digestion temperature) from temperature response charts (Schneider 1963). By integrating the area under each successive curve and using the assumed density and heat capacity for the soil, the rate of heat loss can be determined for each time interval. Examination of these graphs shows that the rate of heat loss for each step change approaches a constant value which, for all cases, can be approximated as 0.5 Btu/hr•°F•ft^2 wall area. This value, when multiplied by the temperature driving force (digester temperature minus ground temperature) gives the approximate rate of heat loss for 1 ft^2 of wall area.

It is clear that the actual heat loss rate will vary considerably depending on the nature of the soil used in constructing the digester, particularly its water content. In some instances, insulating materials may be desirable to use in constructing the digester.

The digester is assumed to be formed with trapezoidal sides and square top and bottom. The sides are built at a 45° angle to the horizontal and the height (depth) of the digester does not exceed 10 feet. The volume can be calculated from the following formula:

$$\text{Digester Volume} = 1/3\ h\ [b^2 + 4bh + 4h^2 + b^2 + (b^4 + 4b^2h + 4b^2h^2)^{1/2}] \quad (3.7)$$

Figure 3.3: Temperature Gradient In Soil After Step Change In Digester Temperature

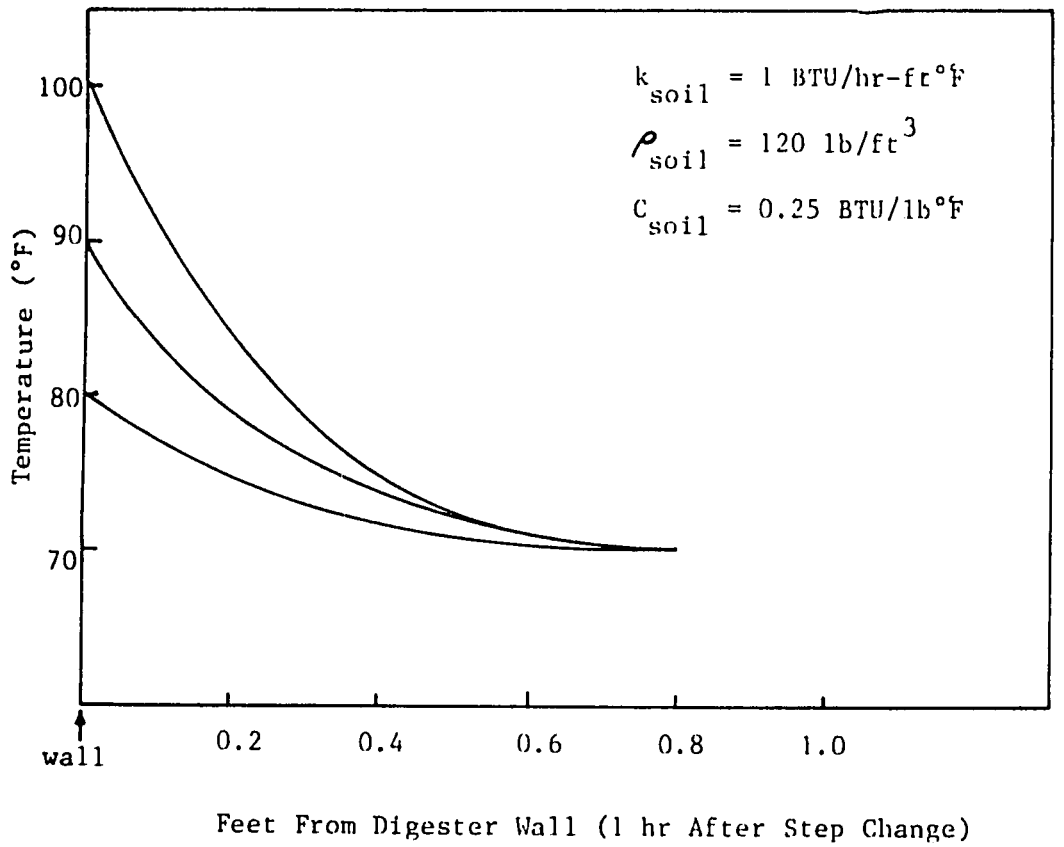
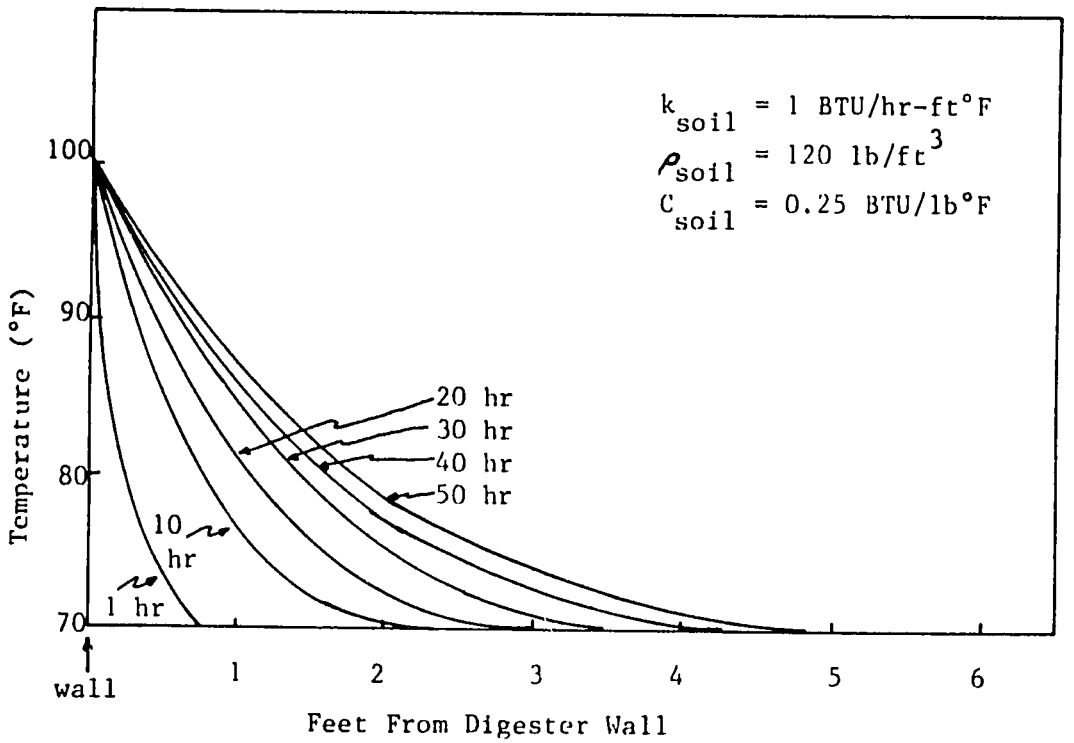


Figure 3.4: Temperature Profile of Soil Surrounding Digester After Step Increase In Digester Temperature



where h is the height (or depth) of the digester and b is the length of one side of the base (bottom). The surface area, including top and bottom is:

$$\text{Surface area} = 2b^2 + 8bh + 8h^2 \qquad (3.8)$$

The rate of heat loss per ft^2 of surface area is assumed to be the same for the sides, top, and bottom of the digester. The estimated rate of heat loss when the digester is at mesophilic temperature is in good agreement with previous by calculated values for the assumed temperature driving force (Jewell 1976).

All materials added to the digester (assumed to be primarily agricultural residues such as straws, manure, and water) are added at ambient temperature (assumed to be 70°F) and must be heated to digester temperature. In our model, we assume the digester is filled with 20 lb solids/ft^3 and an equal weight of water (20 lb/ft^3). The solids are 75% volatile and 25% ash. The ultimate conversion of the volatile solids is 50%, making the initial loading of biodegradable solids 7.5 lb/ft^3. Raising the digester temperature by 1°F (assuming heat capacities of 0.4 Btu/lb°F for the solids and 1 for water) initially requires 28 Btu/ft^3 of material. Thus, raising the digester to mesophilic temperature from 70°F requires approximately 800 Btu/ft^3 under adiabatic conditions. This represents the heat evolved by conversion of 1.6 lb of organic material to biogas.

A computer program which calculates the digester temperature at indicated time increments was written following the logic in Table 3.1. The assumptions made for these calculations are indicated in Table 3.2.

It is clear that for a given conversion rate constant, the heat loss rate at which the digester is able to maintain its temperature can be calculated. Figure 3.5 is a plot of mesophilic rate constant vs the quotient of heat loss rate and volume to surface area ratio of the digester. This plot can be used to determine digester size once the conversion rate constant of the substrate is known. For instance, if the mesophilic rate constant has been measured as 0.01 $days^{-1}$, the maximum heat loss quotient is

Table 3.1

LOGIC FOR PROGRAM CALCULATIONS DIGESTER TEMPERATURE HISTORY

1. Input Initial Values:

   - Ambient temperature,
   - Digester initial temperature,
   - Digester solids loading,
   - Fraction solids which are biodegradable,
   - Digester water content,
   - Reaction activation energy,
   - Pre-exponential constant,
   - Heat loss rate as function of temperature driving force, and
   - Volume to surface area ratio of digester;

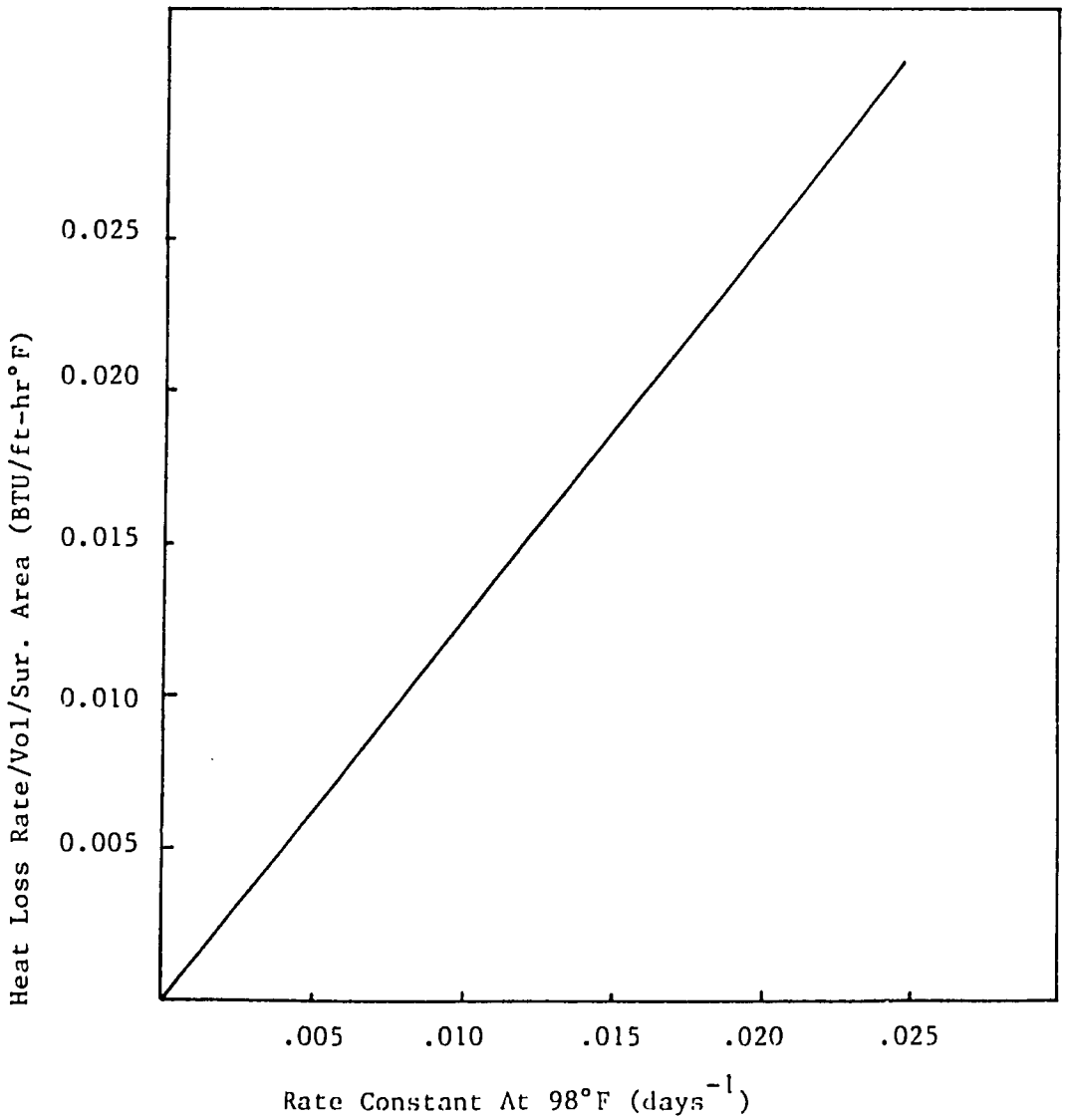
2. Calculate Arrhenius rate constant;
3. Calculate heat released in time increment;
4. Calculate heat loss in time increment;
5. Calculate specific heat of digester contents;
6. Calculate new digester temperature;
7. Calculate new substrate concentration in digester;
8. Print values calculated for time increment; and
9. Return to step 2 or stop.

Table 3.2

ASSUMPTIONS FOR CALCULATING DIGESTER TEMPERATURE HISTORY

1. Ambient and ground temperature is 70°F.
2. Digester is at uniform temperature at all times.
3. Heat loss rate can be calculated as a function of digester temperature, ground temperature, and volume/surface area ratio of digester.
4. Anaerobic digestion reaction rate can be described by an Arrhenius rate expression.
5. Total solids loading in the digester is 20 lb/ft^3.
6. Total solids of 37.5% are biodegradable.
7. Heat capacity of solids is 0.4 Btu/lb•°F.
8. Water content of digester is 20 lb/ft^3.
9. Activation energy is 15,175 cal/gmole.
10. Pre-exponential constant is adjusted to give desired rate constant at mesophilic temperature.
11. Heat loss occurs at the same rate for all digester surfaces (top, bottom and sides).
12. Once the digester reaches mesophilic temperature, heat is removed from the recirculating leachate to prevent further temperature increase.

Figure 3.5: Calculation Of Maximum Heat Loss Rate For A Digester Maintaining Mesophilic Temperature As A Function Of Digestion Rate Constant



0.0125. If the digester is constructed with a volume to surface area ratio of 4.0, the heat loss rate must not exceed 0.05 Btu/hr•°F•ft^2 surface area.

The volume to surface area ratios for the digester, if designed with trapezoidal sides and a 45° slope, can be calculated from the formulas presented earlier. If this is the design employed, with a maximum allowable depth of 10 feet, then to achieve a volume to surface area ratio of 4, a digester with a base (bottom) 100 feet long and depth of 10 feet must be constructed. This will have volume of 115,400 cubic feet. Some representative volumes and volume to surface area ratios are indicated in Table 3.3. Thus, by examining the digester dimensions, insulating properties of the materials of construction, and loading and conversion rate of the substrate the temperature history of the digester can be predicted.

The information can also be used to determine the relative merit of preheating the digester (for example, by heating the leachate being recirculated) to mesophilic temperatures. For a digester with a volume to surface area ratio of 4.0, heat loss rate of 0.05 Btu/hr•°F•ft^2 surface area, and substrate conversion rate constant of 0.01 days^{-1} at 98°F the percent conversion to biogas vs time is plotted in Figure 3.6. The difference in conversion with and without digesters heat-up can be clearly seen from this plot.

Prior to construction and operation of this "controlled landfill" batch type digester, its performance may be predicted based on the following information:

1) Rate and conversion data of the substrate;
2) Density of solids in the digester;
3) Water content of the digester;
4) Digester dimensions;
5) Insulating properties of materials of construction of digester; and
6) Ground temperature.

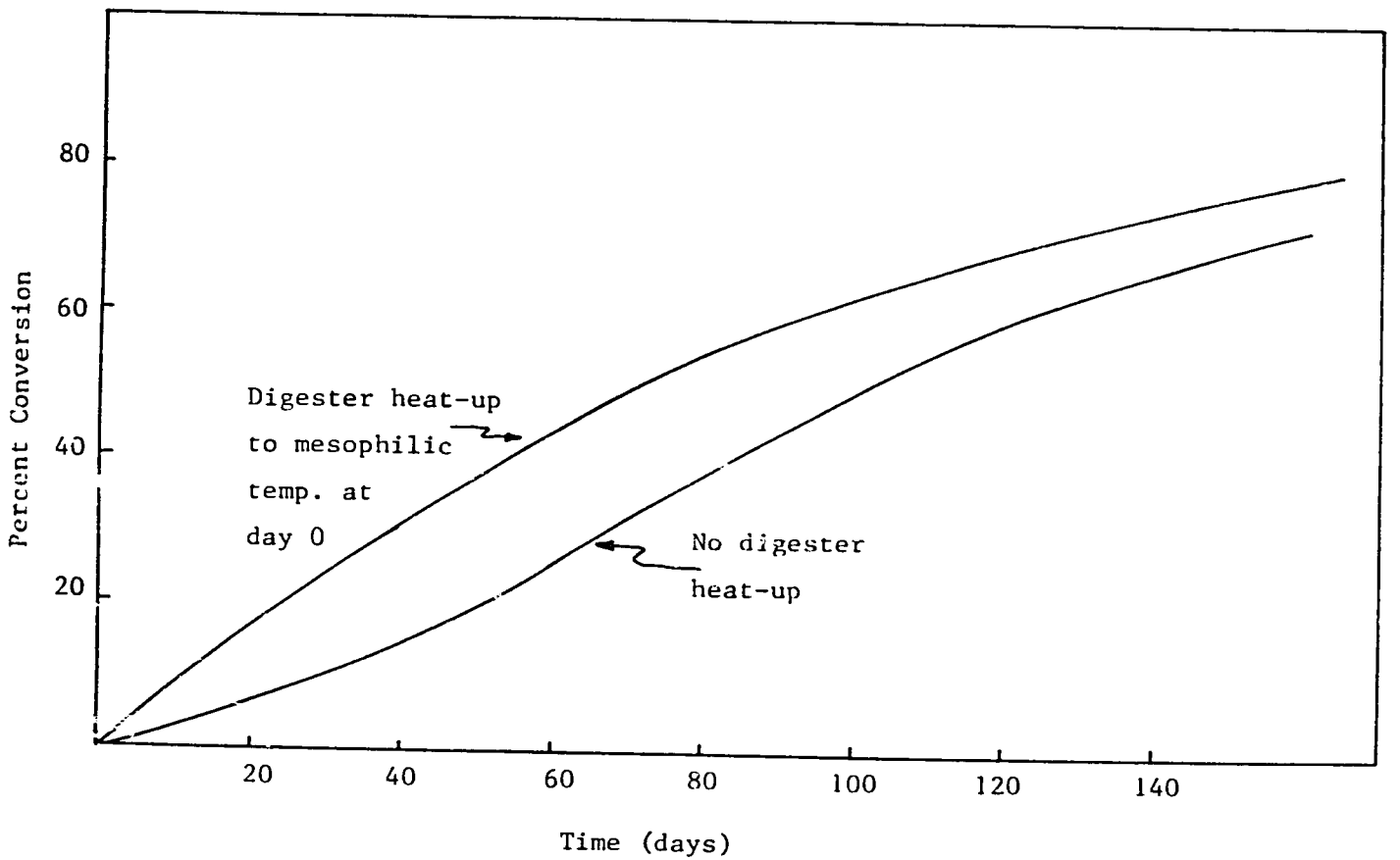
Since this information will vary depending on the residue chosen as substrate and the location of the digester, specific information for each site must be known prior to designing an efficient digester.

Table 3.3

VOLUME TO SURFACE AREA RATIOS OF DIGESTERS BUILT WITH 45° SLOPING TRAPEZOIDAL SIDES

HEIGHT	LENGTH OF VOLUME	VOLUME	VOLUME/SURFACE AREA
10 ft.	10 ft.	4,110 ft^3	2.28
10 ft.	20 ft.	8,600 ft^3	2.69
10 ft.	5 ft.	2,525 ft^3	2.02
10 ft.	100 ft.	115,400 ft^3	4.01
10 ft.	200 ft.	429,000 ft^3	4.43
5 ft.	5 ft.	517 ft^3	1.15

Figure 3.6: Comparison Of Conversion History Of Digesters With And Without Preheating To Mesophilic Temperatures*



*Rate constant at 98°F is 0.01 days^{-1}. Heat loss rate is 0.05 BTU/hrft°F. Volume to surface area ratio is 4.0.

3.2 Example of Village Biogas Potential

The potential biogas production for a village may be calculated as described below. The number of animals, available agricultural residues, etc., were obtained by site visiting the village of Nawagai in the SWAT Province of Pakistan, but the calculations should be representative for other villages. Both animal manure and agricultural residues are considered for anaerobic digestion to biogas.

3.2.1 Biogas Potential From Animal Manures

The maximum available amount of manure is given as follows:

Animal	Manure lb/day/animal Dry Weight	Number of Animals	Total Manure (Daily; Dry Weight, lb)
Cows	10	200	2,000
Buffalo	10	150	1,500
Donkey	2	40	80
Sheep	1	2,000	2,000
Poultry	2.5/100	400	10
			5,590

The manure available for biogas production, however, must take into consideration the collection efficiency and the fraction that is biodegradable. While hand collection may be possible for buffalo and cows this is impractical for sheep. Chickens may be placed in confinement to isolate droppings. Thus, if an over-all collection efficiency of 50% is assumed, and this collected manure is assumed to be 50% biodegradable (50% refractory organic), then the manure convertible to biogas will be:

$$5{,}590 \text{ lbs/day total} \times 0.5 \text{ collection efficiency} \times 0.5 \text{ biodegradable} \approx 1{,}400 \text{ lbs/day} \quad (3.9)$$

The biogas yield will be (assuming 60% conversion):

$$1400 \text{ lb/day} \times (7 \text{ ft}^3 \text{ } CH_4)/\text{lb} \times 0.6 \text{ conversion efficiency} \times 1 \text{ MCF}/1000 \text{ ft}^3 = 5.9 \text{ MCF/day} \quad (3.10)$$

$$5.9 \text{ MCF/day} \times 0.85 \text{ service factor} \times 365 \text{ days/yr} \approx 1{,}800 \text{ MM Btu/yr or } 1.8 \text{ billion Btu/yr} \quad (3.11)$$

Note: At unit cost of $2.00/MCF the yearly production of biogas would have a value of: 1,800 MCF/yr x $2.00/MCF = $3,600. MCF = thousand cubic feet (1MCF = 28.3 m^3)

Thus, for a very simple method of obtaining a capital cost, and if a one year pay-off is required, an investment of $3,600 for manure biogas units would appear to be merited.

3.2.2 Biogas Potential From Agricultural Residue

The maximum available agricultural residues are given as follows:

CROP	MAXIMUM LAND IN CROP		TONS AGRICULTURAL RESIDUE PER ACRE PER YEAR	AGRICULTURAL RESIDUE AVAILABLE (TONS/YR)
	HECTARES	ACRES		
Corn (maize)	810	1944	4	8,000
Wheat	810	1944	4	8,000

Since agricultural residue from corn was stated by village leaders to be used for both fuel and fodder, only 25% was estimated by those leaders as being available for biogas production. Likewise, wheat straw is used for fodder (30%) and is also sold by the village for production of paper (70%). Village leaders strongly indicated a willingness to sacrifice the gains made from selling the straw in order to produce biogas. On this basis, 70% of the wheat straw produced was estimated as being available for biogas production. Thus, the village leaders comments led to these figures as the available agricultural residue:

AGRICULTURAL RESIDUE	AGRICULTURAL RESIDUE TOTAL (tons/yr)	FRACTION AVAILABLE FOR BIOGAS	AGRICULTURAL RESIDUE AVAILABLE FOR BIOGAS PRODUCTION (tons/yr)
Corn	8000	0.25	2,000
Wheat	8000	0.70	5,600
			7,600

Assuming a 70% collection efficiency:

$$7600 \text{ tons/yr} \times 0.70 \approx 5000 \text{ tons/yr} \tag{3.12}$$

The potential biogas production for the village may be calculated by combining the animal manure available and the agriculture residues available:

COMPONENT	TONS/YR
Agricultural Residues	5,000
Manure	500

Thus, it is noted that the ratio of available manure to available agricultural residue is in the ratio of 1/10, a suitable ratio for conversion. Further, it may be seen that by introducing agricultural residues for consideration in the conversion to biogas in addition to manure, an approximately 10-fold amplification of total biogas potential results.

3.2.3 Combined System

For a combined manure/agricultural residue biogas system, the fuel gas production may be estimated as:

$$5{,}500 \text{ tons/yr} \times \underset{CH_4/lb}{6.6 \text{ ft}^3} \times \underset{\text{Efficiency}}{\overset{0.35}{\text{Conversion}}} \times 2{,}000 \text{ lb/ton} \times 1 \text{ MCF}/1000^3 \approx \underset{\text{MCF/yr}}{25{,}000} \quad (3.13)$$

(or 25,000 million Btu/yr)

$$\approx 70{,}000 \text{ ft}^3 \text{ CH}_4/\text{day}$$
$$\approx 2{,}000 \text{ m}^3 \text{ CH}_4/\text{day}$$

On the basis of $2.00/MCF and with a one year pay-off desired, a very rough estimate of capital expenditures that may be allocated to a projected system is $50,000.

3.2.4 Impact on Village

The impact on a village of this total estimated amount of gas may be seen by noting that 40 people were estimated to use 1,000 ft^3 CH_4/day. Thus, a village of 3000 people (Nawagai) would require 75,000 ft^3 CH_4/day. Thus, it appears that the entire village could be supplied with gas (on the same basis selected for 40 persons).

3.2.5 System Size

The size of a combined manure/agricultural residue system may be shown by assuming that approximately 10 such systems will be used in the village, perhaps each one operated by an entire family (discussions indicated a village such as Nawagai had perhaps 10 principal families).

Note that a compaction "density" of 0.5 should be assumed and that corn and wheat each are cropped once a year. Thus 10 batch digesters 10 feet deep and 20 feet wide will each have a length:

$$\underset{[10' \times 20' \times L']}{10 \text{ Units}} = \text{Total Volume}$$

$$= 5{,}000 \text{ tons/yr} \times 2{,}000 \text{ lb/ton} \times 1 \text{ yr}/2 \text{ fills} \times 1 \text{ ft}^3/37 \text{ lb} \quad (3.14)$$

$$= 135{,}000 \text{ ft}^3$$

$$L = \frac{135{,}000}{10 \cdot 10 \cdot 20} \approx 70 \text{ ft}$$

This analysis implies that each of the 10 village families would operate two batch digesters of general dimensions 10 ft x 20 ft x 70 ft. Because corn (maize) and wheat are harvested approximately every six months, one set of digesters would be filled at each harvest and the digestion in that digester allowed to continue over the following 12 months. The methane produced by each family's set of two digesters will average approximately 7,000 ft^3/day (7 million Btu/day). (Note: The gas produced will actually be about 60% methane/40% carbon dioxide; these calculations all show methane (only) because only this component has heating value).

The potential appears to exist for using the fuel gas produced for not only cooking, but for conversion to electricity or for vehicle power, such as a dual fuel tractor. Further, additions of grass clippings or other crop grown biogas to the batch digesters should be considered.

Section 4

DIGESTION EXPERIMENTS

In order to provide tangible demonstration of the value of the principles recommended here, the support of ten investigators around the world was enlisted to provide experimental data on gas generation from waste materials. The researchers participating and their institutional affiliations were listed above in Section 1.

Each of these investigators was free to choose one or more substrates of local interest to be subjected to anaerobic digestion. Guidelines were offered concerning the apparatus and conduct of the experiments. These guidelines were intended to bring elements of uniformity into the program, without restricting the experimental design.

Batch reactors were specified, the volume to be in the range 4 - 200 ℓ. Continuous, or cumulative, gas measurement was requested. Provision of a liquid collection and redistribution system was recommended. Maintenance of constant temperature was required, with mesophilic operation recommended, but not required. Guidelines were suggested for moisture level, inoculum sources, buffer addition, and attention to nutrient balance. Standard analytical procedures were supplied for total solids, total volatile solids, chemical oxygen demand, Kjeldahl nitrogen, phosphorus, pH, alkalinity, and gas composition.

4.1 Summary of Experiments

The investigators cooperating in this program elected to study the digestibility of the following seven substrates:

Barley Straw	Municipal Solid Waste
Coir Dust	Rice Straw
Corn Stalks	Sesame Hulls
Cotton Stalks	

Each of these has a significance to the region of the investigator choosing it for study, but it will be seen that the list includes substances of universal occurrence. All of the samples evaluated were locally derived. In some experiments the substrates were given a pretreatment deemed useful and practical in large-scale processing. In two sets of experiments additives apart from inoculum, nutrients, or buffer were included. The duration of the experiments was between 26 and 182 days. Individual circumstances of the experiments are summarized as follows:

Calzada

Cylindrical metal, batch digesters of 16 ℓ capacity were maintained at 35°C. The substrate studied was the waste resulting from the alkaline dehulling of sesame seed. Since the sesame seed waste is a bulky material, bagasse in the proportion of 25% the total solids was added to provide porosity. Sugar cane bagasse is readily available in the areas of sesame cultivation. For inoculum the mixture was seeded with 12% cow manure. Digestion was carried out for 100 days at 11% total solids with recirculation of the digester leachate.

Chin

Experiments were carried out with municipal solid waste (MSW) in 200 ℓ steel containers maintained at 28° - 32°C. In four batch digesters, 2 were seeded with digested sewage sludge and 2 were not seeded. Solids content was less than 50% and no buffer was added. Leachate was removed as it formed and the volume of liquid removed was replaced with rain water. Digester performance was monitored for 140 - 180 days.

In parallel experiments tests were made of the digestibility of swine manure, water hyacinth, and palm oil mill effluent (POME) in continuous stirred tank reactors.

El-Din

The digestibility of municipal solid waste was observed in batch digesters involving three variables: solids content (10, 25, 35%), presence of sewage sludge, and temperature (10° - 30°, 35°, and 55°C). Calcium carbonate in the proportion of 10% of total solids was added to digesters of 1.25 - 3.5 ℓ volume. Performance was followed for 161 days.

Marchaim

Following the picking of cotton, the plant matter remaining in the field, except the root, is referred to as cotton stalks. This is composed of stalks, stems, and smaller proportions of leaves and fibers. After some preliminary trials for orientation, batch digestion tests of cotton stalks were carried out for 150 days in 5 ℓ plastic vessels. Temperature was maintained at 35°C and an inoculum of actively digesting slaughter house waste was added. The solids content was initially 9%. Ammonium nitrate was added to half of the 6 digesters.

Mata

Four, 200 ℓ steel batch digesters containing barley straw at 12% total solids were maintained at 35°C in tests extending for 110 days. As inoculum, digested manure was added in the proportion of 2% of the solids content. Fresh cow manure was added in the proportion of 1, 2, 5, and 11% of the solids in the four successive vessels. Leachate was recycled at a rate of 4 ℓ per day in each digester.

Padolina

In the manufacture of coir fiber from coconut husk a residue termed coir dust remains. The digestibility of water washed and unwashed coir dust was observed in four, 4 ℓ digesters held at ambient temperature in the Philippines for a period of 26 days. Inoculum was provided from an

established digester, and dried manure was added. Total digester solids were 5% and 8%, the coir dust being 43% and 61% of these solids.

The digestibility of rice straw in three forms was tested: chopped, water presoaked 24 hours; chopped, dried; and dried, ground to 60 mesh. Active digester inoculum was added in the proportion 10% - 20% of straw solids. Total digester solids in the range 5% - 30% were subjected to tests at ambient temperature in 4 ℓ digesters. The duration of test was: presoaked, 214 days; chopped-dried, 140 days; ground-dried, 66 days.

Suhirman

The digestion was studied of chopped, dried rice straw with admixture of *Clitoria ternatea* (a legume) to adjust nitrogen content. Five digesters of 21 ℓ capacity were operated at 0, 51, 76, 88, and 100% rice straw content with *Clitoria ternatea* plus manure as inoculum and calcium carbonate (5% of total solids) buffer. Temperature during digestion ranged between 24° - 30°C. Observations continued for 56 days.

Verastegui

Corn husks were subjected to an aerobic "pre-fermentation" in water for two weeks to remove waxy substituents. The treated, chopped husk was charged to 4, 200 ℓ digesters with 6 - 13% manure, 1 or 6% calcium oxide, 1.5 - 1.9% diammonium phosphate, and 3% urea. Total solids content was maintained at 18 - 33%. Test continued for 91 days.

4.2 Experimental Results

One of the basic questions in evaluating the energy potential of a given waste is the amount of fuel gas that can be derived through anaerobic digestion. Accordingly, in this survey a principal basis for comparison was the gas generation per unit of substrate charged to the digester. These data are summarized in Table 4.1.

Table 4.1

TOTAL GAS GENERATION OBSERVED IN THE BATCH ANAEROBIC DIGESTION OF SEVEN WASTE MATERIALS

DIGESTION SUBSTRATE	GAS GENERATION*, m^3/kg substrate	RESEARCHER
Barley Straw	0.1	Mata
Coir Dust	0.1	Padolina
Corn Husks	0.1-0.2	Verastegui
Cotton Stalks	0.2	Marchaim
Municipal Solid Waste	0.1-0.2	Chin
Municipal Solid Waste	0.2-0.4	El-Din
Rice Straw	0.1-0.3	Padolina
Rice Straw	0.1	Suhirman
Sesame Hulls	0.3	Calzada

* Product gas as generated, measured at ambient conditions.

The gas generation figures presented in Table 4.1 concern the as-produced gas, that is, a mixture of methane and carbon dioxide. Since the gas utilized on-site from most digesters will be as-produced, rather than purified methane, the raw gas generation is a useful figure of merit. It must be recognized, however, that the temperature and pressure of measurement was not closely standardized in these trials. Bearing this in mind, the data are presented with only one significant figure to the nearest tenth m^3/kg.

The methane content of the gas produced in these experiments generally was slightly enriched in methane content, as is typically the case. The methane content was observed to rise during the course of these batch fermentations, again a typical result. The highest level of methane content was observed in the gas produced through digestion of sesame hulls (up to 84% CH_4), coir dust (up to 73%), and corn stalks (up to 71%). The gas composition from cotton stalks was about 63% CH_4. The methane content of gas produced from municipal solid waste showed substantial variation. Digesters held at ambient temperature (10° - 30°C) by El-Din produced gas of only 20% methane content. MSW digesters held at higher temperatures produced gas containing 40 - 60% methane, but composition varied with time. The methane content of the gas from the straw samples was consistently modest, about 50 - 55% CH_4.

With these factors in mind the range of gas generation data is judged to be quite consistent. It is notable that gas generation figures in the range 0.1 - 0.2 m^3/kg are commonly observed in these experiments in many laboratories with a wide range of substrates. This result provides support and encouragement for consideration of energy recovery from available wastes of disparate locations and nature. If gas composition is conservatively presumed to be 55% methane, then 0.2 m^3 gas/kg substrate is equivalent to 4 x 10^9 joules per tonne of substrate digested. In terms of a familiar fuel this is equivalent to 116 ℓ gasoline per tonne of waste processed.

The details of procedures and full data obtained in these investigations are presented in the proceedings of a workshop conducted by the project participants (Anon., 1984).

4.3 Discussion of Results

In judging the digestion performance obtained in these experiments it is worthwhile to establish a maximum gas generation potential as a basis for comparison. It is reasonable to presume that the readily digestible component of these waste materials is the cellulosic matter present. The conversion of cellulose to gas by anaerobic digestion may be represented by the following stoichiometry:

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

Accordingly to this equation, digestion of one kg cellulose will yield 0.82 m^3 gas measured at 0°C and standard atmospheric pressure. If the measurement is made at a higher, ambient temperature the volume increases, e.g., to 0.92 m^3/kg at 30°C.

The digestion of other classes of matter, vegetable waxes, for example, will be governed by different stoichiometry, but the prevalence of cellulose as a digestible substrate in plant matter justified cellulose as a reasonable basis for comparison. Adjustment must then be made for the proportion of refractory or indigestible matter present. for example, if half the substance is not readily digestible, theoretical gas yield from an otherwise cellulosic substrate is only about 0.4 m^3/kg. It will be seen that gas yields approaching this level were observed in the experiments reported here.

In parallel experiments with his tests of coir dust and rice straw, Chin carried out continuous stirred tank (CSTR) digestion of palm oil mill effluent (POME). This material (5.4% total solids, 28,200 mg/l BOD, 0.7 oil content) yielded 0.9 m^3 gas per kg of removed biological oxygen demand (BOD). These results are not directly comparable with those given in Table 4.1 for batch digestion experiments characterized in terms of gas yield per unit of total solids subjected to digestion. It is judged, however, that the yield from POME digestion is comparable to the higher yields cited

in Table 4.1. This experience furnishes an additional example of a waste material appropriate for productive energy recovery.

These data also may be compared with the work of others. Hobson, Bousfield, and Summers (1981) cited batch digestion studies of straws alone in which gas yields of 0.4 - 0.5 m^3/kg were achieved. The digestion of straw in combination with manure is of interest because straw from bedding and feed is present in manures and because these wastes co-occur in agricultural areas. Hobson, Bousfield, and Summers (1981) cite data for digestion of straw and manure under a variety of circumstances. Wujick (1980) determined the effect of total solids content on the batch digestion of cattle manure at 35°C. These data showed that manure at less then 32% total solids yielded 0.3 m^3 raw gas per kg manure solids. Gas yields in the batch digestion of municipal solid waste were reported by Buivid and co-workers (1981) to be as high as 0.4 m^3/kg, but the yield was shown to be dependent on a number of variables such as moisture content, presence of nutrients, and particle size. Buivid and co-workers (1981) suggested 0.3 m^3/kg as a regularly achievable gas yield in a packed bed MSW digester. Yields as high as this also were reported by Jerger, Dolenc, and Chynoweth (1982) for the batch digestion of various woody plants.

This experience, both the data reported here and that cited from published literature, offers strong encouragement to investigate the recovery of fuel gas from available wastes. The breadth of suitable substrates is impressive, so investigation is warranted, but planning must be tempered by recognition that some substrates may prove unsuitable. For example, Wise and co-workers (1981) reported the successful batch digestion of alkali pretreated straw and of tomato processing residues, yet another agricultural residue, garlic and onion waste, did not yield gas. The presence of a specific metabolic inhibitor of anaerobic microorganisms was believed to be the cause of this behavior. Similarly, some of the woods investigated by Jerger and his co-workers (1982) showed low gas yields.

The benefits potentially available, whether to a nation or to a limited region, through utilization of waste materials or of crops grown for

the purpose may be estimated, as in the example provided by Wise, Wentworth, and Ashare (1979). An especially appropriate approach to the realization of such benefits is the utilization of the high solids landfill batch reactor concept proposed by Augenstein and co-workers (1976). The low capital cost "hole-in-the-ground" anaerobic fermenter proposed and demonstrated by these authors and further tested by Augenstein, Wise, and Cooney (1976/1977) is especially appropriate to energy recovery from agricultural and municipal wastes. Guidance in making economic projections of the cost and economic return of such batch anaerobic digesters is provided by Augenstein and co-workers (1976) and Jewell and co-workers (1982).

Section 5

LIST OF REFERENCES

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