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food systems

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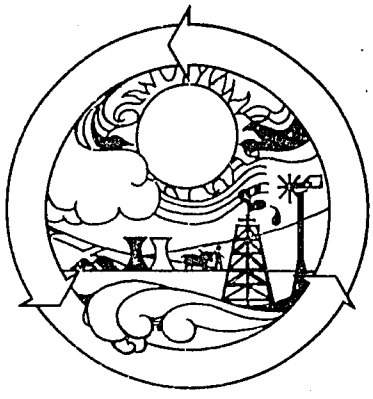

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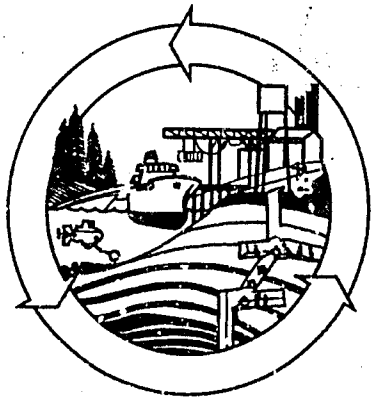

raw materials systems

Energy for Rural Development
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APPLICATION OF THE FUEL-LINKED ENERGY RESOURCES AND TASKS (FLERT) APPROACH TO RURAL HOUSEHOLD AND COMMUNITY SCALE ANAEROBIC DIGESTION SYSTEMS

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ABSTRACT

Anaerobic digesters have been introduced into some areas of Asia and the Pacific with a disappointingly low success rate. Although there have been technical problems, the reasons for failure are more complex than simple technical difficulties.

Because "appropriate" rural technologies should enjoy a sufficient level of acceptance to motivate owners to remedy problems as they occur, it can be argued that the physical, social, and environmental fit between these failed digesters and the rural areas chosen was poor. The FLERT approach provides a well-defined and replicative framework for assessing the physical, social, and environmental resources exploited by anaerobic digesters, and the products and coproducts they produce. This method provides a basis for future development and testing of a model for determining how physical, social, and environmental needs and resources in rural areas can be matched in specific situations by anaerobic digesters.

To develop the information base, the anaerobic digestion "system" is disaggregated into six manageable subsystems. Analysis of the resources exploited by the various subsystems are presented, with three different types of digesters: floating-dome household- and community-scale digesters, fixed-dome underground digesters, and bag-type digesters. Considerable differences were noted in the types of resources exploited by these digesters, and the quantities of resources exploited per cubic meter of biogas production capacity. Estimates were made of the quantity of feedstock raw materials and labor required per cubic meter of biogas produced.

The viability of installed anaerobic digesters in areas of Asia and the Pacific is examined, and a Specifications Plate that follows the FLERT approach is provided to assist policymakers and planners in determining which energy technologies are appropriate for specific areas.

PREFACE

Although there is a substantial amount of literature available about how to construct an "appropriate" energy technology, very little of this literature has systematically examined the nonenergy and nontechnical issues that are at the heart of determining whether a technology is appropriate: that is, the "fit" between the technology and the rural human and natural environment. The FLERT (Fuel-Linked Energy Resources and Tasks) approach, presented in Smith and Santerre (1980), focuses heavily on these nonenergy and nontechnical factors, such as the resource requirements of technologies and the possible local and national implications of using these resources.

In selecting anaerobic digestion systems as the first technology for the application of the FLERT approach, we intended to provide a relatively simple and straightforward example of a technique for evaluating and comparing small-scale energy technologies using a well-defined framework for analysis. This technology was chosen because of the great amount of interest in and experience with anaerobic digesters in our focal region of south and southeast Asia and the Pacific islands. Digestion technologies also appeared to be backed up by a considerable bibliographic database, which we felt would facilitate our analysis.

The technology we selected is neither simple nor well-understood, particularly in a nonengineering sense. Although the references are fairly detailed and consistent in reporting engineering data, very little reliable information could be found concerning the interactions of anaerobic digesters with the day-to-day aspects of life in rural areas. These data are especially important in evaluating and comparing energy technologies for rural areas of developing countries.

We also realized that this application of the FLERT approach would not unfold in quite as straightforward a manner as was initially envisioned because anaerobic digestion systems are as much nonenergy technologies as they are energy technologies--that is, other nonenergy products or services provided by digesters rival their value as producers of biogas fuel. It also became clear that anaerobic digestion systems were capable of interacting more intimately with rural life than we first imagined, touching on such things as soil fertility, cooking, cleanliness of the home, village social structure, and human defecation practices.

This pervasiveness resulted in the addition of further levels of "complexification," both in the report describing the FLERT approach (Smith and Santerre 1980), as well as in the present report. The authors wish to state that the present approach to analysis of anaerobic digesters is of a preliminary nature--improvements in the analysis will come as more information about this technology becomes available, and as the FLERT

approach is refined and improved with additional applications for other small-scale energy technologies.

At this time we would like to acknowledge individuals who contributed their ideas and efforts to this exercise, especially Pramod Pant and Michael Weitzenhoff. We are particularly indebted to Jamuna Ramakrishna for her diligent and capable work in developing a bibliographic database on anaerobic digestion systems (Ramakrishna 1980), and for her helpful comments and suggestions concerning these analyses. We also wish to express our sincere gratitude to Charles Schlegel, whose advice and encouragement contributed a great deal to our analysis of the interactions of technologies and rural life in developing countries.

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INTRODUCTION

Many persons and institutions view anaerobic digestion technologies as a means of providing for the energy needs of rural areas in developing countries, while also leading to other improvements in rural living conditions and environment.

Detailed descriptions of the anaerobic digestion process and anaerobic digester designs are common in the literature (Sathianathan 1975; Singh 1973, 1974; US National Academy of Sciences 1977). Very briefly, anaerobic digestion is defined here as a process in which organic materials are biologically degraded by bacteria in an anaerobic environment into a combustible gas (biogas: a methane and carbon dioxide mixture), and a residue consisting of inorganic and organic compounds (sludge), and bacterial cells. Because biogas can also be made by other means, such as pyrolysis and hydrogasification, anaerobic digestion technologies are a subset of biogas technologies (Barnett et al. 1978).

Without listing all the potential advantages of using anaerobic digesters in rural areas of developing countries, the principal claims may be listed as: (a) anaerobic digestion provides a clean, easy-to-use fuel, while possibly lessening the dependence of rural areas or countries on petroleum-based energy (with consequent political and economic benefits), or increasingly scarce firewood sources (with consequent environmental benefits); (b) anaerobic digestion provides a sanitary means of disposing of human, animal and plant wastes, leading to improved health in rural areas; (c) anaerobic digestion permits improved conservation of nitrogen and soil conditioners (as opposed to the alternative burning of wastes as fuel), while providing a superior manure for crops; and, (d) anaerobic digestion technologies offer employment opportunities, eliminate drudgery, and contribute to other rural development objectives (Barnett et al. 1978; Parikh and Parikh 1977; Sathianathan 1975; Singh 1974; van Buren 1979; Srinivasan 1974).

Although this list is by no means exhaustive, it illustrates the possible pervasiveness of anaerobic digestion technologies in rural areas. While most biomass-based energy systems interact at a more intimate level with rural life than do most nonbiomass systems (e.g. windmills), anaerobic digestion technologies probably interact directly with more facets of rural life than do most of the other types of biomass energy technologies. For instance, introduction of digesters can require or result in changes in the confinement patterns of livestock, changes in the management of crop wastes, or changes in the patterns and practices of human defecation. The introduction of biogas as a fuel might alter food preparation methods, provide lighting for evening educational programs, power communication devices, and promote increased agricultural or rural industrial production and efficiency. Finally, the residues (sludge) from digesters can also be

applied to cropland or aquacultural ponds as fertilizer, be fed to lifestock, or be dried and burned as fuel.

Ideally, institutions and individuals promoting anaerobic digestion technologies would be conscious of both appropriate and inappropriate uses of these systems. Unfortunately, the rate of failure or aba donment of anaerobic digesters, or expression of dissatisfaction by persons who have installed them, is quite high in many places (Coulthard 1978; Karki et al. 1980; Prakasam 1979; Ratasuk et al. 1979; Siwatibau 1978).

The failure of many digesters is most frequently attributed to technical problems such as corrosion and leaking of the gas collector. However, for each technical reasons given for failure it would appear that there is usually an obvious technical "fix" that would make the digester operational again.

Because truly "appropriate" rural technologies should almost by definition be intimately integrated with rural life and enjoy a general acceptance among the majority of rural people, it follows that the owner of an appropriate technology that has a technical problem should, logically, make every effort to get it operational again (Ratasuk et al. 1979). Thus, it can be hypothesized that many of these failed or abandoned digesters were inappropriate technologies--that is, there was a poor physical, social and environmental fit between the technology and rural life.

By analogy, suppose an automobile has a flat tire. The automobile has experienced a technical failure, and can not be operated for at least a period of minutes. However, if days, weeks, or months later the automobile still can not be operated because of the flat tire, then the nontechnical reasons for failure become increasingly significant. Perhaps the problem is that the operator is unable to repair or replace the tire (for financial reasons, lack of tire-repairing service centers, or unavailability of new tires), or is simply not motivated to have the tire repaired or replaced--that is, the operator does not consider the investment of resources (time, money, etc.) in keeping the automobile in good operating condition worthwhile in terms of the benefits provided by the automobile. It is thus possible that this automobile is an "inappropriate technology" for this person at this time, regardless of who or what originally motivated him to invest in this technology.

The question arises as how to predict in advance situations in which anaerobic digesters are appropriate or inappropriate technologies. Answering this question is a two part exercise. The first part, which is being undertaken in the present study, is to establish indicators of interactions between anaerobic digestion technologies and the resources they exploit, and the rural tasks that the digester directly or indirectly provides via the products, coproducts, or services they produce or affect. These indicators must be developed not only for physical resources (e.g. cement, steel, etc.) and tasks (e.g. cooking, powering machinery), but also for social resources

(e.g. labor, infrastructure) and tasks (e.g. altering community organization), and environmental resources (e.g. land, sunlight, wind) and tasks (e.g. decreasing deforestation).

The second part of an analysis of the appropriateness or inappropriateness of anaerobic digesters necessarily demands an examination of a specific anaerobic digester system (of a given design, scale, and configuration) for a specific set of conditions (i.e. location, operating conditions, etc.), to predict success or failure of a particular potential application of the technology (in terms of success or failure, either technically, or from the viewpoint of promoting rural development objectives). In this study, we will not attempt this second part, but will discuss some observations that have been presented in the literature on the viability of these technologies, particularly in south and southeast Asia.

Our discussion largely will be limited to "community-scale" and "household-scale" anaerobic digester systems, and exclude digesters that can be roughly described as "agricultural industry scale" systems, such as the successful operations in the Philippines at Maya Farms (Maramba 1978). This is because household and community digesters are likely to interact at a more intimate level with the social system than digesters processing wastes from agricultural industry (such as large piggeries, for example).

We are also limiting our discussion to relatively simple designs of digesters, not only because of the limitations of the data base, but also because, at least for the near future, the digester designs that will be most suitable for rural communities and households in developing countries will be relatively simple and inexpensive in both design and operation. By constrast, because agricultural industries are more likely to be run by persons with more capital to risk, more willingness to experiment with innovative technologies, and, perhaps more importantly, a more urgent need for better waste management, they will be more likely to use successfully higher performance digesters that are more sophisticated in design and operation. Thus, for example, we will not look at digesters that are artificially heated.

Our analysis will draw mainly from literature concerning anaerobic digestion studies that have been done in south and southeast Asia. The notable exception to this is the valuable recent translation of a Chinese biogas manual, edited by van Buren (1979).

To develop indicators of appropriateness of anaerobic digestion technologies, it is necessary to have a complexification process (Smith and Santerre 1980) that assesses the needs for data as well as the state of the database, since the latter provides information on significant interactions between digester systems and rural society and environment.

This complexification process involves disaggregating what is commonly referred to as an "anaerobic digestion system" into more manageable

subsystems for analytical purposes. The quality and quantity of resources required by each of these subsystems can then be analyzed, while addressing both implications and constraints on exploitation of these resources by anaerobic digestion technologies. This assessment is followed by an appraisal of the tasks that might be promoted in rural areas by the energy or other products and services provided or affected by anaerobic digesters, and discussion of some implications of using these products or services.

In the next section some apparent reasons for failure or success of anaerobic digesters in south and southeast Asia will be addressed. Also, a brief discussion will be provided concerning some recent experiences with household and community-scale digesters in the region.

Once the complexification process is complete, a Specification Plate will be presented to develop a condensed set of data for comparing anaerobic digesters against one another, or against other energy technologies that have potential applications in rural areas of developing countries.

RESOURCE REQUIREMENTS OF ANAEROBIC DIGESTION SYSTEMS

Disaggregation of Anaerobic Digestion System into Subsystems

To help organize the information base for anaerobic digestion technologies, the anaerobic digestion system is disaggregated into its component subsystems:

I. Digester construction subsystem

II. On-site digester operations and maintenance subsystem

III. Feedstock raw materials management subsystem

IV. Digester residue (sludge) management subsystem

V. Energy (biogas or electricity) distribution subsystem

VI. Energy (biogas or electricity) utilization subsystem

Description of the various subsystems and application of the FLERT approach for analysis of the resource requirements of each of them follows.

I. Digester Construction Subsystem

Construction of an anaerobic digester, within the temporal and spatial boundaries defined by the FLERT approach (Smith and Santerre 1980),

involves two phases:

Procurement of construction materials

This phase involves obtaining locally available or locally produced construction materials (when applicable) such as sand, water, clay, and bricks.

Digester construction

This phase includes the following components (for more detailed descriptions of the construction of anaerobic digesters, see Barnett et al. 1978; Maramba 1978; Singh 1973, 1974):

1. The digester pit, into which organic raw materials and water are loaded, and in which anaerobic digestion by bacteria takes place. Digesters may consist of a simple pit or lagoon excavated from the earth and sealed, or a container of concrete, brick, steel, rubber or other materials. The digester may be single- or multi-chambered, and be equipped with stirring or heating apparatus, or other devices to improve performance.

2. The gas collector, which performs the function of collecting and storing the biogas, and ensuring an anaerobic (oxygen free) environment for the bacterial processes in the digester pit. The digester gas collector may be an integrally connected part of the entire digester, as with the fixed-dome digesters (also referred to as "Chinese" or "Janata" designs; Subramanian 1977; van Buren 1979) or the bag-type digesters (also referred to as "Taiwan bag digesters", "red mud plastic digesters", "red mud PVC digesters", or "rubber" or "plastic bag digesters"; Hong et al 1979; Weitzenhoff and Yang 1980). Other important variations of the gas collector are the floating-dome digesters (also referred to as "Indian design"; Singh 1973, 1974), or digesters with external gas collectors connected to the pit by a gas pipe or hose.

3. The feedstock raw materials inlet and residue (sludge) outlets, which allow for loading organic materials and water into the digester pit, and removal of residues from the digester.

4. The slurry mixing tank, into which organic materials and water are combined to form a fairly uniform slurry of materials prior to introduction into the digester via the digester inlet.

Resource Requirements of Digester Construction Subsystem

Very little information is available in the literature surveyed (Ramakrishna 1980) concerning the resource requirements for procuring locally

available construction materials, or for manufacturing these materials locally (Table 1). This information is quite important for small-scale renewable energy technologies because one of the potential attributes of these systems is their ability to capitalize on local resources such as sand, clay, water, and labor.

Although the following information is digester- and situation-specific, and is the only example we found in the literature, it illustrates the possible significance of this type of resource input. In van Buren's (1979) translation of a Chinese biogas manual, it is mentioned that 20 person-days of labor were needed to transport materials for the construction of a 20 cubic meter digester pit. This was almost 60 percent of the reported labor needed to construct the pit itself. Because this information was reported as labor requirements for transporting materials, it is entirely possible that it underestimates the labor needs by excluding the labor required to extract the materials from the ground (unless this was lumped together with the value reported).

Although the translated Chinese biogas manual (van Buren 1979) reported the material ingredients of making "triple concrete" bricks (25 kg of plaster, 250 kg of lime, and 2,500 kg of cinders), other resources such as the labor required to procure these materials and manufacture these bricks were not stated.

In contrast with the state of the information base for other subsystems, more is known about the resources required to construct a digester (Table 1). However, even this information is scant and often difficult to interpret.

The materials and labor required to construct three different types of digesters are presented in Table 2. While this represents a useful first-order comparison of digesters, the reader should be cautioned that these three very different types of digesters were operated under quite different conditions. For example, the floating-dome Khadi and Village Industries Commission (KVIC) digesters ordinarily use cattle manure, while the fixed-dome Chinese designs normally use a mixture of human, animal and crop wastes, and the bladder type digesters have in the past most commonly been fed with piggery wastes. Also, the table uses the data as they were presented in the literature--that is, it is assumed that the authors of the reports from which these data were extracted have included all of the different components of anaerobic digesters as described above.

We have chosen to report the capacities of the digesters in relation to the cubic meters of biogas that they are rated to produce per day, as is the convention in most of the Indian digester literature (Sathianathan 1975; Subramanian 1977). The underlying assumption is of course, that the digester is operated at this stated capacity, which is generally not the case. (Rajabapaiah et al. 1979; Karki 1980).

Table 1. Authors' impressions of the state of the information base concerning the resource requirements of anaerobic digestion technologies.[a]

Subsystem	Resource Requirements
I. Digester Construction	
Materials procurement	2
Digester (pit, gas collector, inlet, outlet) construction	1-2
II. On-Site Digester Operations and Maintenance	2-3
III. Feedstock Raw Materials Management	2-3
IV. Digester Residue (Sludge) Management	3
V. Energy (Biogas & Electricity) Distribution	2-3
VI. Energy (Biogas & Electricity) Utilization	not included

[a]The ratings evaluate published information in developing countries, particularly from south and southeast Asia and Pacific islands. Scores: 1: Information base is adequate; 2: Information base is insufficient or contradictory; 3: Information base is lacking.

Table 2. Comparisons of the requirements for principal construction materials and labor by various designs and sizes of anaerobic digesters.[a]

	Floating-dome, KVIC design (Sathianathan 1975: 147-149)		Fixed-dome, Chinese design: brick construction; large volume; circular pit[b] (Van Buren 1979: 49)				Rubber bladder (red mud plastic) design; 20 m^3 volume (Weitzenhoff and Yang 1980, & pers. comm.)
Rated gas production capacity:	2.8 m^3/day	85 m^3/day	1.5 m^3/day	2.3 m^3/day	3.0 m^3/day	3.8 m^3/day	4.7 m^3/day
Principal construction materials per cubic meter per day biogas production capacity							
Bulk or raw unprocessed materials							
cinders	-	-	0.3 m^3	0.3 m^3	0.3 m^3	0.4 m^3	-
sand[c]	1,500 kg	642 kg	989 kg	967 kg	989 kg	1,171 kg	89 kg
stone, chipped[c]	375 kg	161 kg	-	-	-	-	-
water[d]	114 kg	60 kg	43 kg	37 kg	43 kg	45 kg	14 kg
Manufactured component parts or processed materials							
bricks (standard size)	1,040 units	565 units	533 units	434 units	433 units	526 units	-
cement[e]	228 kg	120 kg	85 kg	74 kg	85 kg	90 kg	27 kg
lime	-	-	100 kg	87 kg	100 kg	105 kg	-
steel[f]	55 kg	32 kg	-	-	-	-	-
hollow tile block (20 cm X 46 cm X 10 cm)	-	-	-	-	-	-	21 units
Assembled "ready-to-use" devices							
rubber bladder (red mud plastic: 20 m^3 capacity)[g]	-	-	-	-	-	-	21 kg
Labor (person days per cubic meter per day biogas production capacity)	not given	not given	23	28	27	47	not given

[a]Materials and labor requirements are expressed as kilograms (or units) of materials or person-days of labor per cubic meter of the rated daily production capacity of biogas.

[b]Assumes 0.15 m^3 of biogas produced per cubic meter of pit.

[c]Original data presented in cubic meters; weight assumed to be 1,480 kg/m^3.

[d]Water used for manufacturing concrete assumed to be 0.5 times the weight of cement.

[e]Original data reported as bags of cement: weight of bag of cement assumed to be 43 kg.

[f]Our estimate based on available data; steel plate assumed to be 65% of total; miscellaneous steel components assumed to be 35% of total.

[g]Rubber bladder (one unit required) is assumed to weigh 100 kg.

The digesters reported in the Chinese literature, and the bag-type digester, prefer the convention of reporting the pit size of the digester (van Buren 1979; Weitzenhoff and Yang 1980), and providing a conversion factor for determining the biogas production capacity of the system during a particular season or for a particular feedstock or loading rate. For comparative purposes, we have assumed an average conversion factor, and further assume that this yields a daily biogas production capacity for the digester that permit a comparison with the Indian KVIC design digesters.

Although the differences among the digesters in regard to the feedstock raw materials, operating conditions (particularly climate), and other factors are important, for the purposes of the present discussion we have assumed them to be of minor significance. We believe this is not an unreasonable assumption at the present time, considering the relative scarcity of accurate information about resource requirements of digesters, and also considering that our underlying purpose is to illustrate a method for comparing technologies. The accuracy of the comparisons will undoubtedly improve as the information base improves.

Table 2 illustrates some interesting (although tentative) trends in the relationship of the required labor and construction materials for different types and scales of anaerobic digesters. There is obviously a marked degree of dissimilarity in the efficiencies with which the three digesters transform resources (principal construction materials and labor) into fuel.

The Indian floating-dome digester uses considerably greater quantities of materials, especially steel and cement. In contrast, the fixed-dome and bag-type systems have little or no requirement for steel, and use considerably less cement. However, the bag type digester, although using a resource (rubber) available in some places, is not likely to be locally built because it uses manufacturing techniques not normally found in rural communities. Aspects of the availability of resources in rural areas will be discussed later in this report.

Table 3 provides a different approach to examining the same data for three similarly sized digesters. This approach compares the resource requirements of these digesters in relation to the estimated quantity of methane that each will produce during its lifetime. For the purposes of this example, we are assuming that the biogas produced by the digesters is composed of 60 percent methane.

In order to make this level of comparison, two assumptions had to be made. First, information had to be obtained about the expected life of the digesters. An underlying assumption was that the various component parts of the digester (gas collector, pit, etc.) wear out at the same time. Lacking any reliable information on the life expectancies of these digesters, we assigned life expectancies (also known as "expected service life") of 20, 30, and 10 years to the floating-dome, fixed-dome, and bag-type

Table 3. Comparison of requirements for principal construction materials of three different designs of digesters.[a]

Digester type:	Floating-dome KVIC design (Sathianathan 1975: 147)	Fixed-dome Chinese circular pit design Brick Construction (Van Buren 1979:49)	Bag-type design (Weitzenhoff and Yang 1980 and personal communication)
Rated digester capacity (cubic meters per day)	2.8 m^3/day	3.0 m^3/day	4.7 m^3/day
Service live (hypothetical)	20 years	30 years	10 years
Capacity factor (hypothetical)	85%	70%	85%
Estimated methane (biogas @ 60% methane) production during service life	10,400 m^3	13,800 m^3	8,750 m^3
Principal construction materials per 10,000 m^3 of methane production[b]			
Bulk or raw unprocessed materials			
cinders	-	0.72 m^3	-
sand[c]	4,040 kg	2,150 kg	480 kg
stone, chipped[c]	1,010 kg	-	-
water[d]	307 kg	93 kg	73 kg
Manufactured component parts or processed materials			
bricks (standard size)	2,720 units	942 units	-
cement[e]	615 kg	185 kg	146 kg
lime	-	217 kg	-
steel[f]	147 kg	-	-
hollow tile block (20 cm X 46 cm X 10 cm)	-	-	114 units
Assembled "ready-to-use" devices			
rubber bladder (red mud plastic: 20 m^3 capacity)[g]	-	-	114 kg

[a]Digesters were each assigned a hypothetical service life and a hypothetical operational capacity factor. Materials requirements are reported per 10,000 cubic meters of methane produced by the three systems.

[b]Includes only principal materials used for plan construction; excludes materials required for gas and residue distribution and feedstock raw materials management subsystems; excludes tools and construction machinery.

[c]Original data reported in cubic meters: weight assumed to be 1,480 kg/m^3.

[d]Water used for manufacturing concrete assumed to be 0.5 times the weight of cement.

[e]Original data reported in bags of cement: weight of bag of cement assumed to be 43 kg.

[f]Our estimate based on available data; steel plate assumed to be 65% of total; miscellaneous steel components assumed to be 35% of total.

[g] Rubber bladder is assumed to weigh 100 kg.

digesters, respectively (these estimates are rather generous, and are for illustrational purposes only). We downgraded the service lives of the floating-dome digester and bag-type digester to reflect their significant use of less durable components (steel and rubber) in comparison to the brick and concrete underground fixed-dome digester.

Secondly, an assumption had to be made concerning the percentage of the rated capacities of the digesters at which they are actually operating, or, the "operational capacity factor" or "capacity factor". Periodic shut-downs for repairs or cleaning, or factors affecting the efficiency of the biological digestion process (such as temperature), are responsible for digesters being operated considerably less than 100 percent of their rated capacity. We assigned operational capacity factors of 85, 75, and 85 percent to the floating-dome, fixed-dome, and bag-type digesters, respectively. We downgraded the fixed-dome digester in this case, because it was reported to require more frequent cleaning (either by design or by using a mixture of fibrous or less digestable feedstock raw materials) than the other two digesters (van Buren 1979; Moulik et al. 1978; Weitzenhoff, pers. comm.).

The materials required were then prorated for the total quantity of methane gas produced during the lifetime of the digesters operating at at an assumed capacity factor. In order to facilitate comparison of the three digesters, we report the resources required per 10,000 cubic meters of methane.

This method resulted in a similar set of conclusions about the resource (construction materials) utilization efficiency of the digesters: the floating-dome digester transformed resources into biogas fuel less efficiently than did either the fixed-dome or the bag-type digesters. Indeed, by the resources per unit of energy measure, the floating-dome design is even more materials intensive than would appear on the basis of resources per unit of capacity. As more information about life expectancies and capacity factors becomes available, these conclusions may change.

Another relationhip appearing in Table 2 is that of the resource utilization efficiency in regards to the scale of the digester. While the KVIC design digesters showed a definite economy of scale in transforming resources (construction materials) into fuel, the fixed-dome design was generally neutral within the size range of digesters compared here, and perhaps even showed a diseconomy of scale for the 3.8 cubic meter per day capacity digester. This diseconomy was evident for both the principal construction materials used for this digester and the requirements for labor. If these data provide a valid comparison, it would suggest that there is possibly an increasing amount of materials intensiveness and complexity involved in constructing larger fixed-dome digesters using brick and mortar techniques. [Note: the economy of scale for the larger KVIC digester might be offset by diseconomies of scale for other subsystems, as we will discuss later.]

Information about the labor requirements of floating-dome digesters is scarce. However, Ratasuk et al. (1979) estimated that it requires five person-weeks of labor to construct a 2.0 to 2.5 cubic meter per day capacity digester in Thailand. Most of this labor (86 percent) was obtained from within the family installing the digester, and the remainder from hired sources.

Another important social resource is the level of skill required for construction of a digester. Unfortunately, these data are quite inadequate, with the only significant source of information provided by Bhatia and Niamir (1979) concerning a community-scale floating-dome digester built in India. Although they did not specifically stating the nature of the tasks these persons were performing, their data (Table 4) suggest that different phases of constructing a digester logically require persons with different levels of skill or training.

Other social resources required for construction of a digester include institutions or facilities for grants, loans, obtaining construction materials, training people to build and operate the digester, and community organization. Discussion of these factors are fairly common (KVIC 1978; Sathianathan 1975; Bahadur and Agarwal 1980), and it is clear that such infrastructure can be critical.

Although a large area of land is not needed, lack of land can limit the location of digesters in areas with densely clustered buildings. For example, a household-scale digester might require about 25 square meters (5m x 5m) of land, whereas a community-scale system might require 150 square meters (12m x 12m).

In addition to the amount of land required, consideration must also be given to the accessibility of the site, and its suitability in terms of slope, drainage characteristics of the soil, and other factors. These will affect not only the siting of the digester, but also the selection of construction materials (van Buren 1979). In addition, it is mentioned in the literature that poor soil conditions could result in an increase of 30 to 40 percent in the labor required to construct a digester (van Buren 1979).

II. On-site Digester Operations and Maintenance Subsystem

Included in this subsystem are operations and maintenance activities occurring at the site of the anaerobic digester. Other operations, such as collection of feedstock raw materials or residue distribution, are discussed in other subsystems. The major functions of the present subsystem include:

Table 4. Levels of skill required for various operations of a community-scale anaerobic digester (percent).

	Skilled	Semi-skilled	Unskilled
Digester and gas holder	10	40	50
Gas distribution	50	20	30
Slurry pits	0	0	100
Miscellaneous	10	40	50
Dual-fuel and related machinery	50	50	0
Generator	10	40	50

Source: From Bhatia and Niamir 1979.

Preparation of feedstock raw materials and digester loading

This operation is performed either manually, or with some level of automation (for example, by automatic flushing or dropping of wastes into the digester, such as might occur by siting a digester under a public latrine). Preparation of materials involves mixing the proper types and proportions of organic materials and water and introducing the mixture into the digester inlet. Care must be exercised in selecting raw materials because even apparently minor things such as using wastes from animals that have received antibiotics, or using disinfectant around toilets, are potentially harmful to the anaerobic digestion process (Fischer et al. 1975; van Buren 1979; Subramanian 1978). Inoculum (or "seed"), which consists of slurry from an active digester, can also be introduced into the digester to seed the digester with an active population of bacteria.

Process monitoring and control

This involves monitoring important indicators of performance of the anaerobic digestion process, such as pH, the rate of gas production, color of the flame of a biogas burner, and other factors. Adverse changes in the performance of the anaerobic digestion process can be remedied by appropriate measures, such as modification of the loading rate of feedstock materials, altering the composition of the materials, or adding alkaline materials to the digester. In village settings monitoring techniques requiring special training, chemicals, or equipment are probably impractical and unnecessary.

Digester cleaning

This can be a major operation for certain types of digesters, and may involve periodic emptying of the contents of the digester pit. This activity is more commonly reported for fixed-dome digesters receiving different types of organic materials (especially fibrous substances) than for floating-dome digesters that use cattle dung as feedstock.

Preventive maintenance, trouble-shooting and repair

As with any technology, problems are likely to arise with greater or lesser frequency, depending on the design of the digester, its environmental operating conditions, and the regimen of preventive maintenance observed by the owners or operators of the system. Common types of maintenance include painting metal components of the digesters to prevent corrosion, removal of water from gas lines to permit free passage of the biogas, and the detection and repair of leaks.

Resource Requirements for On-Site Digester Operations and Management Subsystem

The information base concerning the resource requirements of this subsystem is limited (Table 1). The information that we have been able to extract from the literature and apply the FLERT approach to is given below.

Daily operations and maintenance activities

Although there are a number of important daily activities in the operation of a digester, very limited data are presented on the resources needed for these activities. In addition, the information that is available is either "back of the envelope" calculations, anecdotal, or not sufficiently documented with information that would allow extrapolation of the given estimates to other situations. In a comparison of the economics of renewable energy systems for developing countries, French (1979) uses the value of 0.75 hours per day as the time required to mix inputs and operate a 3 cubic meter per day plant. It seems safe to assume that the labor required for these operation activities is relatively independent of the scale of the digester (per cubic meter per day capacity). The community digester system described by Bhatia and Niamir (1979) employed two persons, which is approximately the same (per unit of capacity) as French's estimate.

These assumptions of constant operating costs in relation to biogas production capacity (rather than a cost associated with the surface area to volume ratio: see below) also seem to be borne out by information presented by Ghate (1979) in a survey of KVIC digesters installed in India (Figure 1). These data suggest that, although the initial costs of digesters (per cubic meter of biogas production capacity) showed a definite economy of scale, the operational costs of the digester as reflected in the annual labor costs (again, per cubic meter of capacity) were approximately the same over the size range surveyed.

These estimates are of course liable to considerable variation, and are not applicable to batch-type digesters (which are not loaded on the same schedule as semicontinuous digesters), or to digesters that are automated to receive wastes without further labor input (such as digesters that are receiving gravity-fed latrine wastes). It is also worth mentioning that these estimates are gross rather than net; although these activities would not be conducted if a digester were not present, there may be displacement of labor from activities that were performed prior to the installation of the digester, such as labor used to make dung cakes for fuel. However, determination of net resource needs can not be performed in many cases in the absence of situation-specific data. Our Specifications Plate, which will be presented later in this report, will use gross resource estimates because of this limitation.

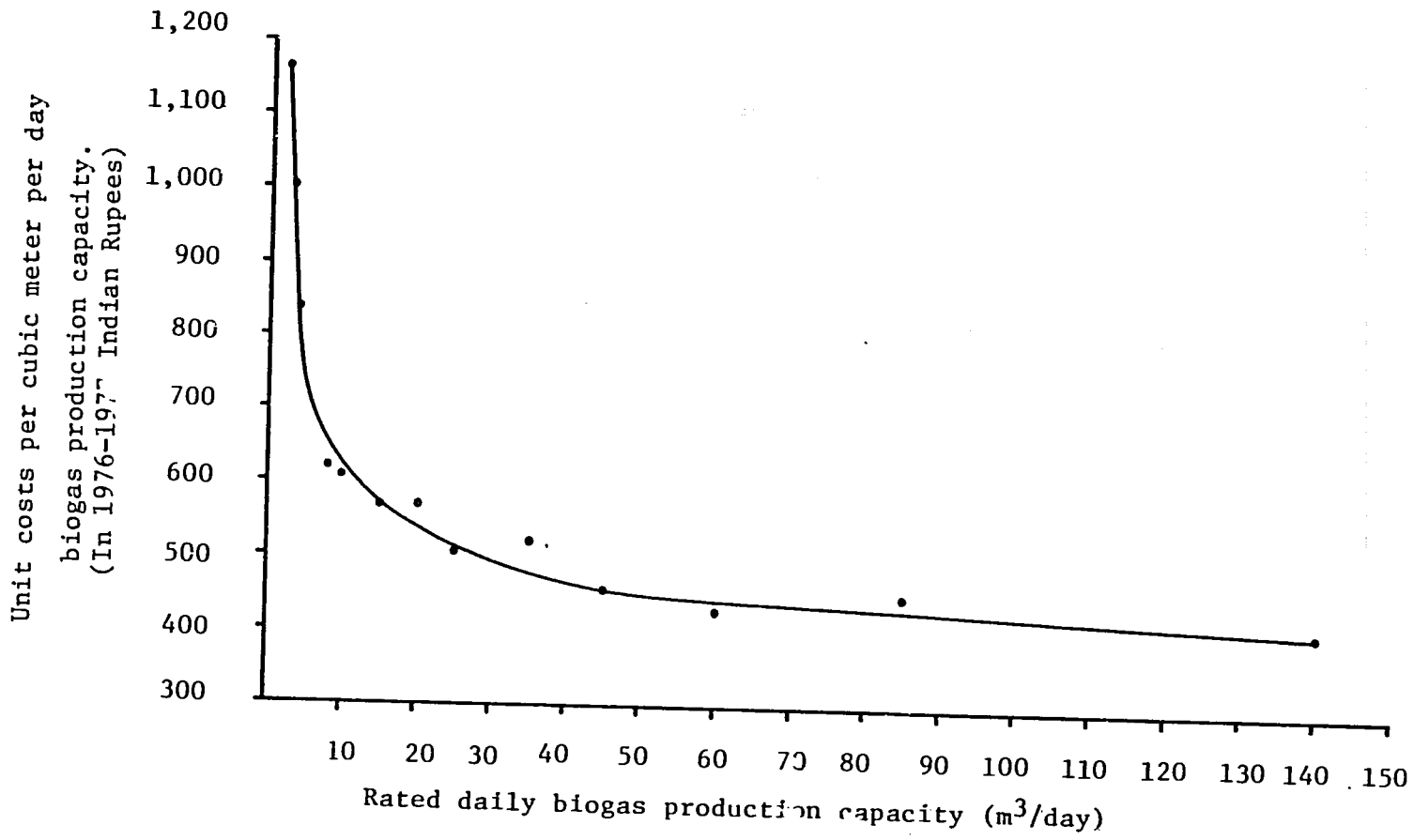

Figure 1. Economies of scale in anaerobic digesters. Comparative initial costs of various sizes of floating dome anaerobic digesters, per cubic meter of installed daily biogas production capacity (after Ghate 1979)

Seasonal, annual, and nonperiodic operations and maintenance activities

Typical activities in this category include periodic cleaning of the digester, repairing gas or water leaks, and painting ferrous components of the digester to prevent corrosion.

The resource requirements for these activities depend particularly on the type of the digester, and types of feedstock raw materials being used in it. For example, interviews of the owners of 173 household-scale digesters in India (see Table 15) indicated that most of the digesters were operated for periods up to five years without cleaning (Moulik et al. 1978). In comparison, the fixed-dome digesters in China are typically emptied and cleaned annually or semi-annually. This procedure involves interruption of the biogas production process, and can last for one to two months (van Buren 1979).

Based on personal experiences, we would estimate that the time needed to prepare (remove rust and old paint flakes) and paint the gas collector of a floating-dome household-scale digester to be approximately two days. [Sathianathan (1975) indicated that the portion of the gas holder that moves in and out of the slurry must be painted semi-annually. Our example of painting the entire exterior of the gas holder is arbitrary, and strictly for illustrational purposes.] Based on a paint application rate of one liter of paint for eight square meters of surface, we estimate that it would require about 0.8 liters of paint for the exterior of a 2.8 cubic meter per day KVIC digester.

For an 85 cubic meter per day KVIC digester, we estimate the paint requirements to be about 11 liters. If both labor and quantity of paint are in direct proportion to the surface area to be painted , then the labor requirements for the larger digester should be about 27 person-days. Interestingly, the smaller digester requires more paint and labor per cubic meter of biogas production capacity than does the larger, because smaller digesters have relatively higher surface area to volume ratios. This relationship of surface area to volume ratios of small versus large plants also explains the economies of scale of larger plants in the use of construction materials (Table 2).

This calculation points out a possible discrepancy in the information presented by Ghate (1979) and illustrated in Figure 2. On the basis of the calculation, one would anticipate a lower maintenance cost per cubic meter of installed capacity for larger digesters than for smaller digesters, unlike the constant relationship illustrated in Figure 2. There may be offsetting labor requirements that have not been taken into account either in our calculations or in Ghate's; likewise the annual resources needed for painting the gas collector that scale with gas collector surface area rather than volume may be a relatively insignificant fraction of the total operational labor needs. There is an obvious need for considerably

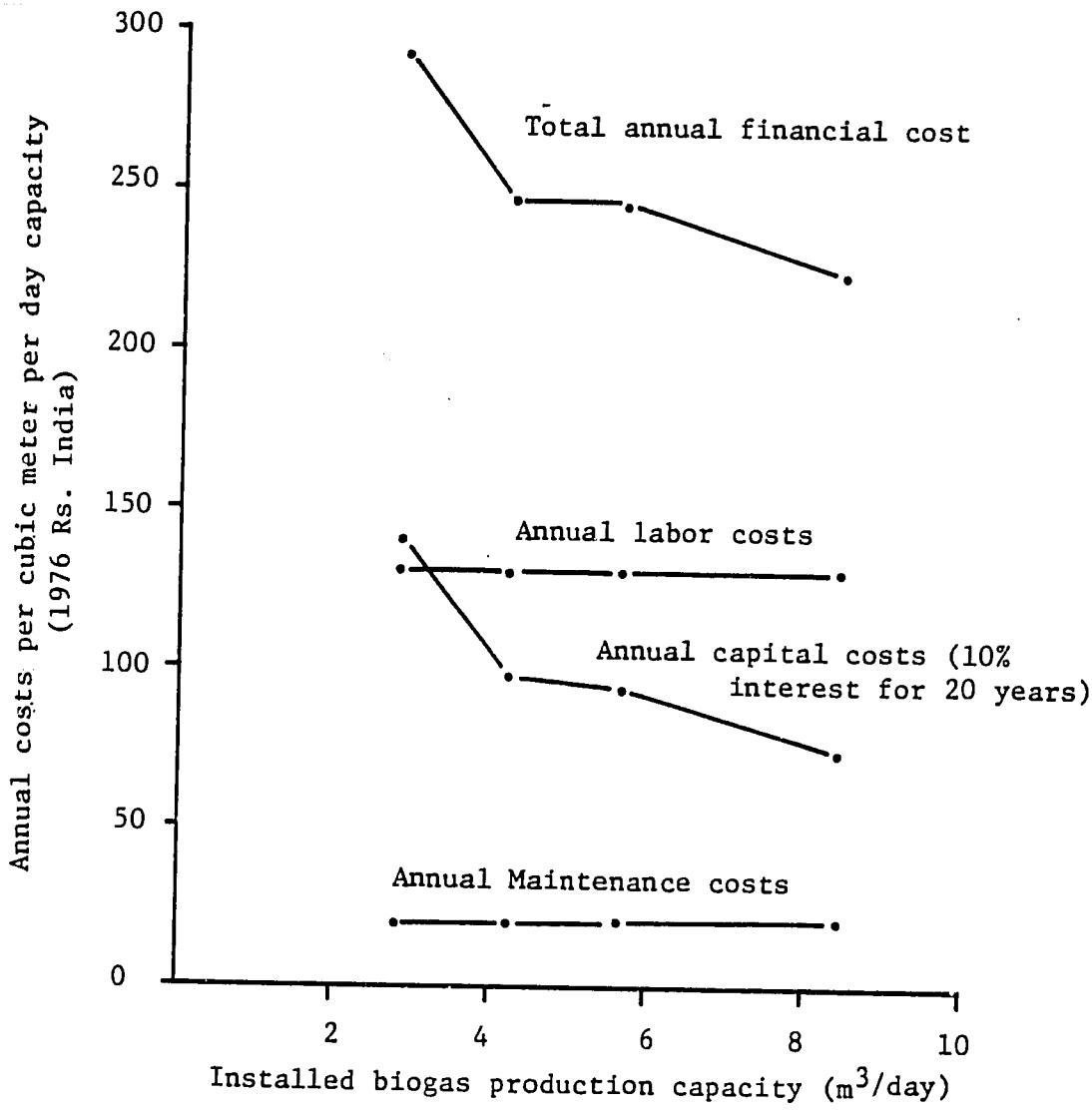

Figure 2. Economics of scale in anaerobic digesters including operation costs. Comparative annual costs of various sizes of various size floating dome digesters, per cubic meter of daily biogas production capacity (after Ghate 1979)

more information on the resource requirements of maintaining and operating anaerobic digesters.

III. Feedstock Raw Materials Management Subsystem

Many types of raw material are potentially usable by anaerobic digesters. Water, of course, is essential. Organic materials that may be available in rural households or communities include human and animal body wastes (feces and urine), agricultural crop wastes, forest and tree litter, and garbage and other wastes from preparing and processing food. Aquatic weeds are also potential organic feedstock raw materials, as they are readily available in some locations, or are being considered for cultivation as "energy crops" (e.g. water hyacinth).

The organic materials mentioned above may be used singly or in combination, depending not only on their availability, but also on their chemical composition that affects the rate and completeness of anaerobic digestion. Organic materials that are more resistant to breakdown by anaerobic bacteria, can be pretreated by use of enzymes, acids or other treatments. However, this is probably of limited near-term importance for rural community and household systems due to the expense and sophistocation of such techniques.

Resource Requirements for Feedstock Raw Materials Managements Subsystem

Within the limits of our survey, the literature dealing with this subject varies from nonexistent, to insufficient and contradictory (Table 1).

Analysis of the resource requirements of this subsystem is divided into two sections: analysis of the feedstock raw materials required to produce biogas, and assessment of the resources needed to grow, collect, store, and transport these materials.

Feedstock raw materials requirements for biogas production

As mentioned earlier, the principal feedstocks required for anaerobic digestion are water and degradable biomass.

The quantity of water required for diluting biomass feedstock is most frequently stated as being equal in weight to the quantity of "fresh" biomass added (Barnett et al. 1978; US National Academy of Sciences 1977), although this will vary with the type of biomass added and the season (van Buren 1979).

Water can be a critical limiting factor in areas with an absolute or temporal scarcity of water. However, unlike the relatively minor quantities

of water used to make concrete used in constructing digesters (Tables 2, 3) which is a net resource requirement (that is, not shared for other purposes), the water used as a diluent for organic raw materials can be either a net or a gross resource requirement. For example, this distinction will depend on whether the digester residue (sludge) is dried before being used (e.g. to fertilize crops), or is used in the watery state (thus, also having potential irrigation benefits).

In the case of drying the sludge, the net requirements for water are quite high--that is, the water becomes unavailable (within the system boundaries of the FLERT approach) for other purposes. If the sludge is used in the watery state, then although the gross requirements are identical to the requirements of the drying pathway (either method requires initial dilution with the same quantity of water), the net requirements are much smaller. This is because the diluent water remaining in the sludge is shared by a totally different activity, such as irrigating a crop or replenishing aquaculture pond water. Of course, there are obvious tradeoffs to handling dried versus watery residues, which will be discussed later in the section about Subsystem IV.

Both the quantity and the quality of the biomass raw materials will affect the resulting biogas yield. The two most important measures of biomass quality are the percentage of volatile solids present, and the carbon to nitrogen (C:N) ratio.

The C:N ratios most suitable for efficient biogas production are between 20:1 and 30:1 (van Buren 1979; Barnett et al. 1978; Sathianathan 1975). Certain feedstock biomass, such as cattle dung, usually is reported to fall within this optimum range. Others, such as peanut husks and straw, have high C:N ratios and yield more biogas when mixed with nitrogen-rich materials such as urine, nightsoil, chicken manure, or even with inorganic fertilizer nitrogen (van Buren 1979; Sathianathan 1975).

Although there are a number of reports of the chemical composition of biomass feedstock raw materials, many of the reported chemical values are very situation specific, and are not likely to be generally applicable to other areas within the focal geographic region.

This problem arises in part because many authors fail to discuss their measurement methodologies and assumptions in any detail. For example, in reporting either the C:N ratios or proportion of volatile or total solids for cattle dung, most authors fail to report the age or water content of the dung, the nutritional state of the cattle, or other conditions which are critical to interpreting such data (Sathianathan 1975). For example, Table 5 illustrates the very rapid changes in the chemical composition of dung within a relatively short period of time after defecation.

In addition, the amount of dung produced by an animal species differs considerably among geographic locations in the region emphasized in

Table 5. Decrease in ammonia nitrogen between defecation by dairy cattle and spreading the manure on land.

Condition of Manure	Dry Matter Content Of Manure %	Total Nitrogen %	Ammoniacal Nitrogen as % of Total Nitrogen %
As defecated (includes feces and urine)	11	5.7	61
Farm-fresh (about 24 hours old at time of daily cleaning)	15	3.1	36
Farm-stored (stored in pile for indefinite period)	24	1.8	25
Farm-stored after spreading on soil surface following period of several days	46-85	1.5	4.5

Source: From Lauer 1975.

the present study. There are very large variations in the robustness of cattle in different locations, which is perhaps largely due to their nutritional status. Also, the percentage of dung that is recoverable for use as feedstock will vary, depending on whether the animal defecates in a location convenient for recovery of the dung, such as a cattle shed. It logically follows that the yield of biogas per head of cattle will depend on both qualitative and quantitative factors.

The question thus arises as to the best system for calculating the dung (or other waste) requirements for producing a given quantity of biogas. Although a sophisticated approach based on the chemical composition of the wastes is more accurate, the information base is inadequate. Likewise, a simpler approach (in the case of, say, cattle manure, which is perhaps the most abundant animal waste in many parts of the region) to estimating the requirements based on the quantity of available dung or available cattle has inherent inaccuracies because of the ephemeral chemical properties of the dung, wide variations in cattle size throughout the region, or other factors.

Faced with a choice between the two methodologies, it seems at the present time that resource estimates using the more sophisticated approach would be inappropriately precise. Despite the drawbacks of the second approach, we have chosen this method in the absence of a clearly better alternative.

Some estimates of the quantities of biomass raw materials that are required to produce one cubic meter of biogas are incorporated in Table 6. Although biogas yields per unit of raw material are based on a number of important factors, such as temperature, hydraulic residence time (a function of loading or dilution rates and digester volume), and the chemical composition of the feedstock, adequate information on all of these factors are generally not provided in the literature.

For example, although Idnani and Varadarajan (1974) present information on the relationship among air temperature, cattle dung quantity, and biogas yield (Figure 3), the hydraulic residence time apparently was held relatively constant. The amount of materials added to the digester daily is, ideally, adjusted to the ambient operating temperature of the digester (in the absence of temperature control devices) to maximize gas production throughout the year. That is, low winter temperatures cause a reduction in the reproduction rate of bacteria (Gotaas 1956) in the digester. Maintaining the same dilution rate in winter as in summer (when bacteria populations are reproducing much more rapidly) could deplete the standing stock of bacteria in the pit by washing out undigested material and bacteria, and cause lower gas production rates than if some raw materials were withheld from the digester.

Hence, more investigation is required to determine the optimum operating conditions for digesters under the range of conditions (dung composition, temperature, etc.) present in rural areas.

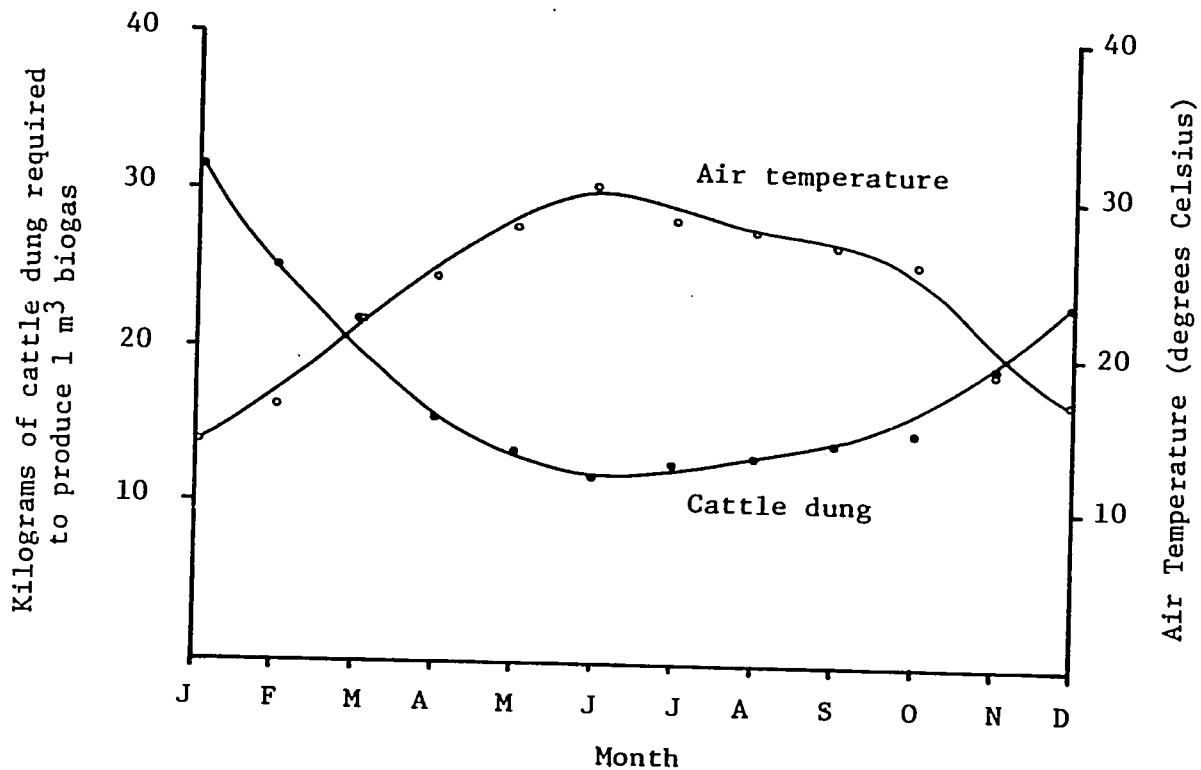

Figure 3. Effects of temperature on gas production. Kilograms of cattle dung required per cubic meter of biogas, in relationship to air temperature. (After Idnani & Varadarajan 1974.)

In Table 6 we have attempted to estimate the quantity of organic raw materials that might be required to operate a household-scale digester servicing the cooking needs for a family of five persons. Our calculations are based on data reported in the literature either as the per capita biogas requirements for cooking, or the biogas requirements for cooking for a "typical" family of five persons. We also use data that are reported for the quantity of various types of raw materials needed to produce one cubic meter of biogas.

Estimates of the biogas needs of a family of five vary considerably with the data used, ranging from 1 cubic meter per day (Garg 1978; van Buren 1979) to 3.5 cubic meters per day (Singh 1974). If one then includes the range of values for biogas yields per kilogram of cattle dung, the resulting estimate of the cattle dung requirements for producing biogas for a family of 5 is between 12 and 110 kilograms per day! Bahadur and Agarwal (1980) estimate that under average conditions, the amount of recoverable manure from a head of cattle is approximately 8 kilograms (6 kg for young animals, 12 kilograms for full grown animals). Thus, the estimated number of cattle required to supply a household-scale anaerobic digester (using data describing Indian conditions) will be between 2 and 14 head per family to meet their total cooking requirements. Further discussion of this will be presented later in this report.

Resource requirements for growing, collecting, storing and transporting raw materials to the digester site

The following is a brief discussion of the resources needed to make feedstock raw materials available for anaerobic digestion. On this issue, very little information can be distilled from the literature, and that mostly concerns labor requirements. Because the estimated quantities of raw materials needed to produce a given amount of biogas differ so much, it can be assumed that estimates of the resources available or needed to grow, collect, store, and transport these materials will be similarly inconsistent.

Sathianathan (1975) estimated that it would take one or more weeks (person-hours not provided) to accomplish the initial filling of 1,000 kilograms of fresh dung into a 3.0 cubic meter per day capacity digester, with no additional dissaggregation or qualification of the types of labor or activities involved. In an interview, the owner of a digester in China stated that the time to collect dung for his family biogas pit, "took no longer than the time to smoke a cigarette" (van Buren 1979).

Perhaps the best estimates of the labor costs of operating a digester are presented by French (1979). He assumes a distinction between gross resource requirements for operation of a digester, and net requirements. French's economic analyses are based on the assumption that the labor requirements for collecting dung for anaerobic digesters would be

Table 6. Estimated quantities of various feedstock raw materials required on a daily basis in order to produce sufficient biogas for the cooking requirements of a family of five.[a]

Feedstock raw materials	Quantity (kg/day) needed to produce: 1.0 m^3 biogas/day	3.5 m^3 biogas/day	Environmental conditions (if stated)	Sources
Cattle dung	12	41	Summer (30°C mean air temperature)	Idnani and Varadarajan 1974
	28	98	25°C	Rajabapaiah, et al. 1979
	31	110	Winter (14°C mean air temperature)	Idnani and Varadarajan 1974
Poultry dung	16	56	None given	Srinivasan 1978
Night soil	14	49	None given	Srinivasan 1978
Pig manure	13	44	None given	Srinivasan 1978
Rice husks (dried)	1.6	5.6	None given	Van Buren 1979
Fresh grass (dried)	1.6	5.6	None given	Van Buren 1979
Maize straw (dried)	1.2	4.3	None given	Singh 1974

Assumptions:

- Family size: five persons.[b]
- Quantity of gas required for cooking by family of five persons[c]:
  a. 1.0 cubic meters of biogas per day (Garg 1978; Van Buren 1979).
  b. 3.5 cubic meters of biogas per day (Singh 1974).

[a]Two values of the daily biogas requirements are estimated to illustrate the possible range of this value. The values given are representative of the literature, often giving no additional information that might be relevant (e.g., nutritional condition or size of animal producing feces; percentage moisture of manure or dung, etc.) to determining the quantities required for production of a certain volume of biogas.

[b]This is a common reference point used in literature on anaerobic digesters; no other assumptions are given, e.g., age of family members, etc.

[c]Literature cited make no reference to amount of food cooked, or efficiency of cooking or cooking appliances.

the same as the labor requirements for collecting the fuel formerly used for cooking.

Although French (1979) assumes the net labor requirements for collecting dung are zero, he does estimate the labor requirements for the hauling of water for a household-scale digester to be one-half hour per day (Table 7).

As was done by French to avoid possible double counting, the resources that would normally be invested for purposes other than anaerobic digestion should not be counted in the net resource requirements for anaerobic digestion.

To provide another example, since it is probable that crop land or grazing land would be used whether or not crop or livestock wastes were exploited by anaerobic digesters, there is no reason to count this land as a net resource requirement for this subsystem (despite the fact that these lands are essential for supplying raw materials).

However, if additional facilities are required to store the raw materials needed for digestion, or to confine livestock to increase the recoverability rate of the dung, such facilities would have to be accounted for in terms of the resources they would exploit. We are not able to make such estimates, however, as the data on this topic are unavailable.

IV. Digester Residue (Sludge) Management Subsystem

The management of residues following removal from the anaerobic digester involves a number of possible activities:

Drying or chemically treating the residue

Following removal from the digester, it might be desirable to dry the sludge to reduce the possibility of toxic substances being present in the residue (Sathianathan 1975; Maramba 1978), or to reduce the volume of residue in order to facilitate handling and storage.

Since a percentage of the harmful pathogens or parasites present in animal wastes (particularly from pigs or humans) will survive the anaerobic treatment, further treatment may be desirable. Chemical treatment of sludge, for example, by adding lime, aqueous ammonia, or other chemicals, serves to disinfect it (McGarry and Stainforth 1978), and perhaps also to increase the fertilizer concentration in the sludge prior to its application to aquaculture ponds or cropland.

Table 7. Labor requirements for operating a family-scale anaerobic digester in India.

Activity	Labor requirements	Comment
Collecting dung	0 net hours per day[a]	Activity assumed to be equal to time formerly spent collecting fuel
Hauling water (80 kg)	0.5 hours per day	
Mixing inputs and operating plant	0.75 hours per day	
Distributing slurry (140 kg)	0.75 hours per day	Total weight of inputs times 0.9
Total	2 hours per day	

Source: After French 1979.

[a]Assumes that time requirement to collect dung for digestion is equivalent to the time spent for collecting other cooking fuels. (Therefore, what this table attempts to measure is the additional requirements over alternative methods of obtaining fuels.)

Storing digester residue

Because fertilizers are usually applied at specific times during the year, a storage facility might be required as part of the digester system. Batch digesters, which are loaded once and then emptied when the digestion process is at or near completion, might not require further storage facilities if the emptying of the digester is timed to coincide with the demand for fertilizer. Certain residual substances might remain in the digester itself, if their specific gravities are significantly lower or higher than the digester slurry, examples being digester scum and settled solid materials. This necessitates a periodic emptying of the contents of the digester, such as has been reported for the Chinese fixed-dome digesters receiving a mixture of feedstock raw materials (van Buren 1979).

Transporting digester residues

Digester residues must be transported either by foot (or hoof), vehicle, or pipeline (or sluice), to the site where the residues will be used.

Utilizing the digester residue

Digester residues can be used either in the dried state or in the watery state, and possible final dispositions are summarized as follows:

1. Land or water disposal (dumping), with no intention to fertilize or otherwise benefit the receiving area.

2. Application to land for fertilization, soil conditioning, or plant-watering purposes.

3. Application to aquacultural ponds or other bodies of water for fertilization, or other purposes.

4. Feeding directly to livestock.

5. Combustion of dried residues as fuel.

6. Conversion of dried residues into other fuels by technologies such as pyrolysis.

Aspects of the fertilizer, soil conditioning, and health benefits that may be gained by anaerobic digestion of wastes will be discussed later in this report.

Resource Requirements for Digester Residue (Sludge) Management Subsystem

Very little information is available on the resource requirements of this subsystem from the viewpoint of labor, land, and materials needed to manage digester residue.

The chemicals that might be used for disinfecting sludge, particularly sludge produced from the digestion of pig or human excreta, are given in McGarry and Stainforth (1978). Twelve kilograms of 20 percent ammonia solution are added to one cubic meter of sludge two days prior to using the sludge for agricultural or aquacultural purposes. Schistosome eggs that might be present in the sludge can be killed by adding lime at the concentration of one kilogram per ten kilograms of sludge.

The resource requirements for the possible drying of the sludge might require a considerable land area. The amount will be determined by the quantity of sludge to be dried per day, and the local climatic conditions, including temperature, humidity, wind speed, and precipitation. Soil porosity is also a factor, since seepage is another means of dewatering digester residues. Sathianathan (1975) suggested that a roof might be required over the drying area if rewetting of the sludge during the rainy season is to be avoided.

If digester residues must be stored (manures are usually applied at specific times during the year: Sathianathan 1975) then the land required for the storage facility might approach the quantity of land occupied by the digester itself. If a household-scale anaerobic digester receives a daily input of 50 kilograms of dung and an equal amount of water, then the digester residues removed daily will be only slightly lower than this amount--say, 98 kilograms. In a situation where the sludge is applied as fertilizer to agricultural lands on a semi-annual basis, then a storage capacity for approximately 17 tons of watery materials (assuming no evaporation or seepage) might be required, or a volume of 17 cubic meters. For a two-meter-deep pit, 8 square meters of surface might be needed in addition to the space occupied by the digester.

French (1979) estimated that the labor resource requirement for distributing 140 kilograms of sludge from a household digester was about three quarters of an hour per day (Table 7). This residue management estimate apparently assumed that the sludge was not stored, and was applied to the fields in a watery state on a daily basis. Unlike drying the sludge, this method conserves water. Although French reported this as a net resource requirement, it might be a gross requirement if the farmer was having to haul water to irrigate the crops anyway. The same is true of the time requirement French assigns to hauling 80 kilograms of water each day.

Some of the resource tradeoffs from the alternative practices of applying sludge wet or dried are described below:

Wet sludge

1. Might require less land than that required to dry the sludge.

2. Might not require a means to keep rainfall out of the storage or drying pit during the rainy season.

3. Potentially retains more of the original fertilizer properties of fresh sludge (discussed later in this report).

4. Might require more labor or other resources for transport and application.

5. Conserves water for purposes of agriculture or aquaculture.

Dried sludge

1. Potentially requires more land than the wet sludge approach, since drying the sludge is related to the surface area exposed to the air.

2. Might require a roof or other means to prevent re-wetting the sludge during the rainy season.

3. Exposure to drying conditions alters the fertilizer value of the residue.

4. Dried sludge could require less labor or other resources for transport and application.

5. Drying sludge does not conserve water within the agricultural system.

V. Energy (Biogas or Electricity) Distribution Subsystem

Biogas, while fairly versatile when applied with stationary technologies, is not readily compressed or liquefied, and therefore of limited use for powering vehicles or technologies located any distance from the digester. Consequently, biogas does not compare favorably in terms of the second indicator of spatiality, density, in relation to some of the fuels it replaces, such as kerosene, diesel fuel, and charcoal (see Smith and Santerre 1980).

The biogas that remains after potential "auto-recycling" applications (such as using biogas to heat the digester to optimal temperatures or perform other system operations) can be distributed to end-use technologies by either pipe or refillable container, or be used to generate electricity and distributed by an electric power transmission system. However, we will not discuss the resources required for generating and transmitting electric power.

We are including the following as subsets of the biogas distribution subsystem:

1. Pipes and refillable containers for distributing biogas.

2. Valves for regulating biogas pressure and flow rates.

3. Gas conditioning devices to remove impurities (carbon dioxide, water, hydrogen sulphide) from the biogas.

4. Biogas storage devices in addition to the storage capacity provided by the digester's gas holder.

Resource Requirements of Energy (Biogas or Electricity) Distribution Subsystem

As is true for the Feedstock Raw Materials Management and the Digester Residue (Sludge) Management subsystems, the resource requirements of the present subsystem will be in part a function of the distance between the origin of the materials (the source of raw materials for Subsystem III; the digester for Subsystems IV and V) and the place of use (the digester for Subsystem III; agricultural land or aquacultural water confinements for Subsystem IV; energy consuming end-use technologies for Subsystem V).

That the distance relationship of resource requirements for biogas distribution is significant is evident in statements by Ghate (1979) and Bhatia (1979), that the gains in economies of scale for constructing community digesters (instead of household digesters: see Table 3; Figures 1, 2) might be offset by diseconomies of scale inherent in the greater dung collection or gas and sludge distribution distances involved. However, this is very dependent on the population density of the community--an economy of scale could conceivably occur for biogas piping systems in relatively tightly clustered communities. We do not have any data about the resources used for distributing biogas from community-scale digesters. A survey of the owners of household digesters in India (see Table 15) indicated that most of these systems were less than 25 meters from the residences, so that only a relatively small quantity of pipe or hose would be needed. If these pipes are made of plastic and exposed to the elements, they might have to be replaced every few years because they harden and become subject to leaking (van Buren 1979).

There is little discussion in the literature of the use of inflatable rubber or plastic gas bladders as an alternative means of gas distribution for community-scale digesters. This approach might require less material than the piping alternative. It would involve the patrons of the digester transporting an unfilled bag to the digester (perhaps when they transport dung to the digester). The bag could then be filled with one or more cubic meters of biogas, transported to the residence, connected to the

household gas line, and pressurized by putting weights on the bag.

Gas conditioning devices (Sathianathan 1975; KVIC 1978) vary in complexity from simple water-traps, to more sophisticated methods for removing hydrogen sulphide (by passing the gas through iron oxide particles) or removing carbon dioxide (by scrubbing with caustic potash or monoethanolamine). The tradeoffs of utilizing these more sophisticated procedures have not been assessed, in terms of resource requirements, improvements in performance, or changes in reliability of the digester system.

VI. Energy (Biogas or Electricity) Utilization Subsystem

Most aspects of this subsystem will be discussed later in this report. Because the present application of the FLERT approach does not consider the resource requirements for end-use technologies (for example, the steel used in a biogas stove), these will not be discussed at this time.

ASSESSMENT OF TASKS, PRODUCTS AND COPRODUCTS PROVIDED OR AFFECTED BY ANAEROBIC DIGESTION SYSTEMS

The following is a classification scheme by which the tasks, products, and coproducts provided or affected by this technology in rural areas can be organized for analysis:

1. Physical tasks

   a. From biogas:

      Cooking (including boiling drinking water)
      Lighting
      Refrigeration
      Space heating
      Vehicle transport and mobile tasks (plowing, etc.)
      Stationary tasks requiring shaft power (grinding grain, pumping water, etc.)
      Electrically-powered tasks (via electricity generated from biogas)

   b. From digester residues (coproducts):

      Fertilizer for crops and ponds
      Water for plants or aquaculture confinements
      Feed for livestock
      Solid fuel (combusting dried sludge) or feedstock for producing fuel (e.g. by pyrolysis)

2. Environmental tasks (net)

a. Environmental changes from using biogas due to:

Changing fuel type
Changing task performance

b. Environmental changes from feedstock and residue management due to:

Changing raw materials management practices
Changing properties of feedstock raw materials
Storing, tranporting or utilizing digester residues

c. Environmental changes from digester system construction and operation due to:

Procuring locally-exploitable digester construction materials
Constructing digester and its appurtenances

3. Social tasks

a. From biogas:

Changes in labor or employment (direct and spin-off changes)
Organizational changes
Equity changes
Economic changes
Changes in quality of life (e.g. health)

b. From feedstock and residue management:

Changes in labor or employment (direct and spin-off changes)
Organizational changes
Equity changes
Economic changes
Changes in quality of life (e.g. health)

c. From digester construction and operation:

Changes in labor or employment (direct and spin-off changes)
Organizational changes
Equity changes
Economic changes
Changes in quality of life (e.g. health)

The following discussion is intended as an evaluation of this database, and an illustration of some of the factors that will be important in evaluating the products, coproducts and tasks provided by anaerobic

digestion technologies.

Physical tasks from biogas

Quite a variety of tasks can be provided by biogas-fueled technologies in rural areas (Ashworth and Neuendorffer 1980; Sathianathan 1975). A listing of some of the technologies (intermediate and end-use) that can be powered by biogas and their rates of consumption of biogas and service provided by one cubic meter of biogas is given in Table 8.

As presented earlier (Table 6), estimates given for the quantity of service from a cubic meter of biogas (or the inverse: rate of biogas consumption by a technology) vary considerably within the literature. How the various estimates were determined, whether by empirical or theoretical means, is usually not discernible. For cooking, it appears that the gas consumption is about 0.3 cubic meters per day per capita, or 1.5 cubic meters for a "typical" family of five persons (Table 8). Since no other information usually is reported about the cooking habits of these persons or families, the data are subject to change with improvement in the database.

Although we are unable to provide any documented empirical information on the rate of consumption of biogas for cooking, or on the quantity of service from a technology per cubic meter of gas, it is useful to show how such a value might be derived theoretically, and discuss the linkage between resources available in rural areas and the tasks provided. In the following example, we will examine two different pathways of cooking based on the same resource--cattle dung. In the first case, dung cakes will be dried and used for cooking; in the second, dung will be anaerobically digested and biogas will be used for cooking. We will assume an equivalent starting point of 100 kilograms of "fresh" cattle dung, and try to estimate the quantity of cooking that a family of five could obtain, by using either dung cakes or biogas (Figure 4).

The information in Bhatia and Niamir (1979) indicates that the daily per capita energy requirement for cooking is about 580 kilocalories of useful energy (the data, however, are based on an apparently well-off village and might not pertain to other villages). Dung cakes, having an assumed energy content of 2,440 calories per kilogram, are used at an assumed efficiency of about 11 percent (Bhatia and Niamir 1979). Consequently, we calculate the quantity of dung cakes required per capita per day to be about 2.1 kilograms, or 10.6 kilograms for our five-member family.

Assuming that 100 kilograms of fresh cattle dung can be dried to 20 percent of its original weight in making dung cakes, this quantity of dung will meet the cooking needs of this family for almost two days.

Using biogas, and assuming that biogas has an energy content of about 4,500 kilocalories per cubic meter and that it is used for cooking at

60 percent efficiency (Bhatia and Niamir 1979), this family of five would have a daily requirement of 1.1 cubic meters of biogas. This value agrees well with those provided by van Buren (1979) and Garg (1978), which were presented in Table 6. Using the values provided by Rajabapaiah et al. (1979), and assuming a constant rate of conversion of dung into gas (holding temperature, loading rate, and other factors constant; Table 6), production of 1.1 cubic meters of biogas would require about 31 kilograms of fresh cattle dung. Thus, our family of five would be able to cook for slightly more than three days using an equivalent amount of dung resource.

This analysis is incomplete in that it considers only dung, and not the other resources (labor, water, etc.) utilized via the two different technology and fuel pathways to provide for cooking. Figure 4 does, however, indicate the fertilizer implication of different pathways.

The task of lighting is one that also has interesting tradeoffs. A biogas-powered mantle can provide around seven hours of service (approximately equivalent to a 40 watt electric bulb) from one cubic meter of biogas (Table 8). However, if biogas is used to generate electricity, one cubic meter of biogas can provide about 32 hours of lighting with a 40 watt electric bulb. There are some important resource tradeoffs. Although the electric generator and bulb alternative provides greater service per unit of biogas, it also entails the presence of a generator, a skilled operator, and other resources, whereas the biogas mantle lamp uses very few material resources in its construction and is easy to operate. However, the availability of electric power can provide services that might only be operated by electricity, such as radios and televisions.

Physical tasks from digester residues

The relative value of anaerobic digester residue as fertilizer or soil conditioner is very much in question at this time (Bhatia 1979). Although digester residues have been claimed by many (KVIC 1975; Garg et al. 1971) to be superior to untreated feedstock (cattle dung) as fertilizer, we are in agreement with Bhatia (1977) that adequate scientific data supporting such claims are unavailable. The literature that provide such results (Table 9) in terms of gains in crop yields from sludge treatments over untreated manure treatments, do not discuss the nature of their experiments in sufficient detail. For example, information is not provided concerning the soil conditions (nutrient content, moisture, etc.) or most other experimental conditions. Some of these experiments compare wet or dried digested sludge and manure (all of which contain a variety of fertilizer substances) to a single commercial fertilizer compound (Table 9). It would have been more scientifically valid to test the manure or sludge against an optimal spectrum of inorganic commercial fertilizers.

Another deficiency that occurred in these studies was that the conclusions were evidently based on the outcome of short-term (one crop

Table 8 . Biogas utilization by various technologies.[a]

Service Per Cubic Meter of Biogas	Biogas Consumption Rate	Reference
BIOGAS STOVE	(m^3/head/day)	
Cook 3 meals for famil. of 5 to 6	0.17 - 0.20	Van Buren 1979
Cook meals for 1.4 persons for 1 day	0.7	Singh 1974
Cook meals for 4.4 persons for 1 day	0.23	KVIC 1975
Cooking and boiling drinking water for 2 persons for 1 day	0.5	McGarry and Stainforth 1978
Cooking and lighting for family of 5 for 1 day	0.2	McGarry and Stainforth 1978
Cooking 2 meals and lighting for 2.5 persons for 1 day	0.4	Pang 1978
Cooking for 2.4 - 2.9 persons for 1 day	0.3 - 0.4	Garg 1978
BIOGAS LAMP	(m^3/hour)	
6 - 7 hours for equivalent of 60 watt bulb	0.14 - 0.17	Van Buren 1979
12 - 14 hours for single mantle lamp	0.07 - 0.08	Singh 1974
7.7 hours for equivalent of 40 watt bulb	0.13	Subramanian 1977
10 hours of 200 candlepower illumination	0.1	McGarry and Stainforth 1978
14.1 hours for equivalent of 40 watt bulb	0.07	Garg 1978
ELECTRIC LIGHT BULB (via electricity from biogas powered generator)	(m^3/hour)	
1.3 hours for twenty-five 40 watt bulbs (or 32 hours for one 40 watt bulb)	0.8 (or, 0.03 per 40 watt bulb)	Subramanian 1977
ENGINE		
2 hours for 1 horsepower gasoline engine	0.5	Van Buren 1979
0.4 hours for 5 hp engine (type not given)	2.5	Singh 1974
0.2 hours for 10 hp engine (type not given)	5.0	Singh 1974
2.2 hours for 1 hp dual fuel engine (80:20 biogas to diesel fuel)	0.45	Srinivasan 1978
2.4 hours for 1 hp engine (type not given)	0.4	Pang 1978

(continued)

Table 8. (continued)

Service Per Cubic Meter of Biogas	Biogas Consumption Rate (m^3/hour)	Reference
ELECTRIC GENERATOR		
1.3 hours for 1 kilowatt generator	0.8	Van Buren 1979
2.1 hours for 0.25 kilowatt generator	0.5	Singh 1974
0.7 hours for 1 kilowatt generator	1.3	Singh 1974
1.1 hours for 2 kilowatt generator	0.9	Hong et al. 1979
0.11 hours for 10 kilowatt generator	9	Hong et al. 1979
0.04 hours for 25 kilowatt generator	25	Hong et al. 1979
BIOGAS REFRIGERATOR (flame-operated)		
14 hours for 0.06 m^3 capacity refrigerator	0.07	Singh 1974
0.8 hours for 1 m^3 capacity refrigerator	1.2	Pang 1978
12-14 hours for 0.2 m^3 capacity refrigerator	0.07 - 0.08	Maramba et al. 1978
INCUBATOR		
18-24 hours for 0.09 m^3 capacity incubator	0.04 - 0.06	Singh 1974
VEHICLE		
Power a 3 ton lorry for 2.8 km	0.35	Van Buren 1979
Power a 0.5 ton pick-up truck (4300 cc engine) for 5.3 km	0.19	Lapp et al. 1975

[a]Values are reported as operational time or service per cubic meter of biogas, or as biogas consumption rate.

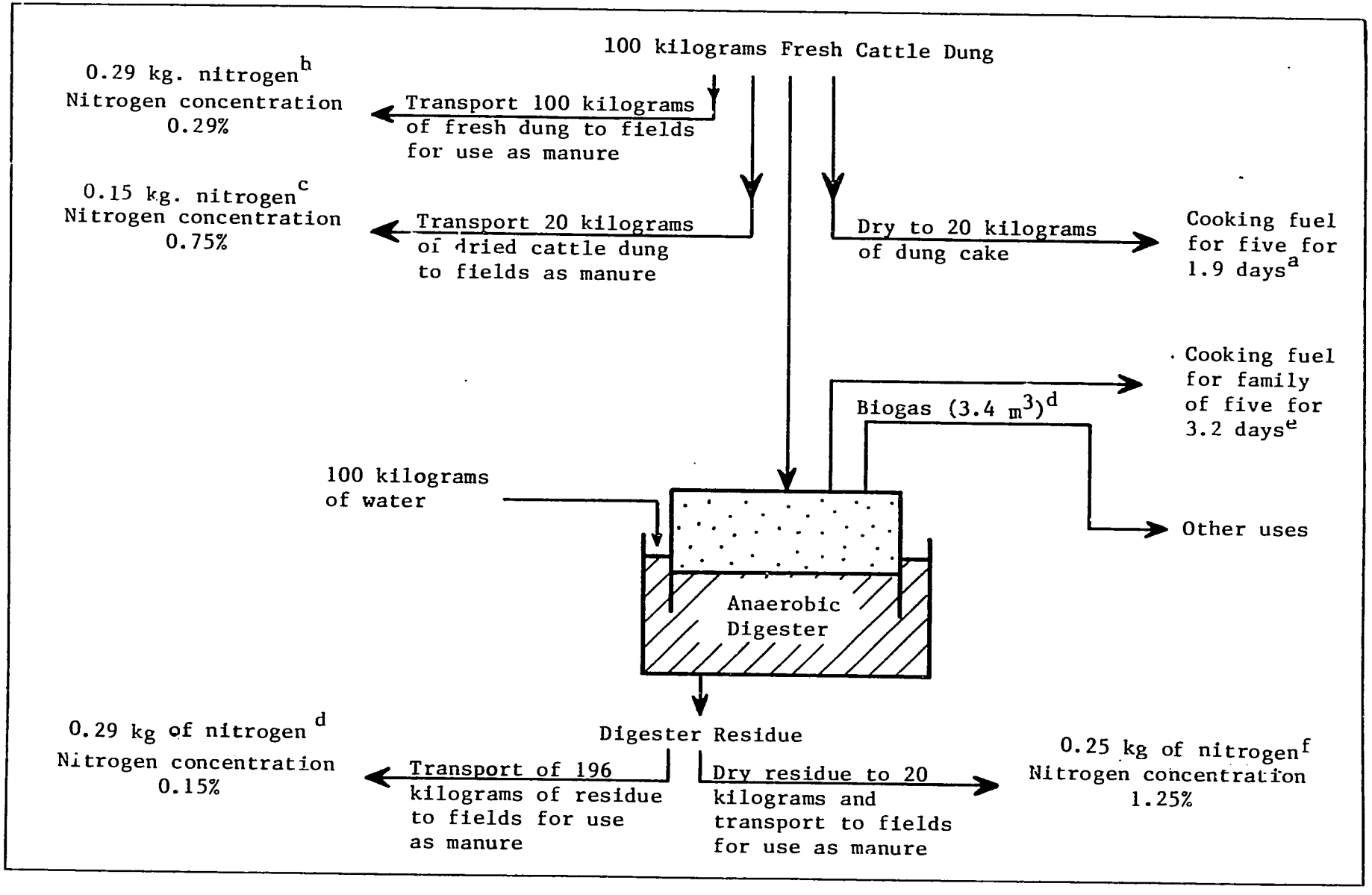

Figure 4. Some alternative options for utilization of 100 kilograms of fresh cattle dung. Values are approximations based on best available information.

FOOTNOTES:

[a] 1. Assumes the daily per capita energy requirements for cooking = 578 kilocalories of useful energy (after Bhatia & Niamur 1979).

2. Assumes dung cakes thermal value = 2,444 kilocalories per kilogram which are used at 11.2 percent efficiency for cooking, and hence have useful energy content = 273.7 kilocalories per kilogram.

3. Household daily dung requirement for cooking =

$$\frac{(578 \text{ kilocalories/capita})(5 \text{ persons})}{273.7 \text{ kilocalories/kilogram}} = 10.6 \text{ kilograms of dung cakes}$$

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

[b] After Rajabapaiah et al. 1979: assumes nitrogen content of 0.29 kg and no losses between digester and field.

[c] After Rajabapaiah et al. 1979: 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.]

[d] After Rajabapaiah et al. 1979.

[e] 1. Assumes energy content of biogas = 4,500 kilocalories per cubic meter, which is used at 60 percent efficiency by biogas stove (Srinivasan 1978), and hence has useful energy content = 2700 kilocalories per cubic meter.

2. Household daily biogas requirement for cooking =

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

3. Assuming conversion rate of 28.2 kilograms of fresh dung into one cubic meter of biogas (Rajabapaiah et al. 1979), then daily household requirement for dung =

$$1.1\text{m}^3 \times 28.2 \text{ kilograms} = 31 \text{ kilograms of fresh dung}$$

100 kilograms of fresh dung thus provides for 3.2 days of cooking fuel.

[f] After Rajabapaiah et al. 1979: 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 is not given.]

TABLE 9 . Results of experiments conducted to compare the effects on crop yields of anaerobic digester residues and other manures or commercial fertilizers

CROP	EXPERIMENTAL TREATMENT	YIELD
Idnani and Varadarajan 1974:		grams of dry matter per pot
WHEAT	No manure	grain: 9 straw: 13
	Wet digested slurry (from cowdung) @124 kg N/ha	grain: 10 straw: 15
	Sun-dried digested slurry (from cowdung) @124 kg N/ha	grain: 11 straw: 17
	Farmyard manure @124 kg N/ha	grain: 10 straw: 16
	Ammonium sulphate @30 kg N/ha	grain: 14 straw: 20
MARUA	No manure	grain: 10 straw: 31
	Wet digested slurry (from cowdung) @124 kg N/ha	grain: 12 straw: 34
	Sun-dried digested slurry (from cowdung) @124 kg N/ha	grain: 14 straw: 37
	Farmyard manure @124 kg N/ha	grain: 12 straw: 35
	Ammonium Sulphate @30 kg N/ha	grain: 15 straw: 41
SANNHEMP	No manure	93
	Wet digested slurry (from cowdung) @124 kgN/ha	107
	Sun-dried digested slurry (from cowdung) @124 kg. N/ha	117
	Farmyard manure @124 kg N/ha	104
	Ammonium sulphate @30 kg N/ha	121

(continued)

TABLE 9. (continued)

CROP	EXPERIMENTAL TREATMENT	YIELD
Maramba et al. 1978:		Grams per $1m^2$ plot
RICE	Control, no fertilizer	grain: 479 straw: 835
	Digester effluent (from pig manure) @5.7 liters/plot	grain: 507 straw: 814
	Digester effluent (from pig manure) @0.4 liters/plot	grain: 556 straw: 876
	Ammonium sulphate (8gm)+ Disodium phosphate (8gm)+ Potassium sulphate (3gm)	grain: 543 straw: 969
Eusebio et al. 1976:		(tons/hectare)
RICE (C-4 variety)	Control	4
	Algae water*	8
	Digester sludge* (from pig manure)	8
	Commercial urea*	9
RICE (C-22 variety)	Control	5
	Algae water*	9
	Digester sludge* (from pig manure)	9
	Commercial urea*	5

*Treatments on equivalent nitrogen basis

cycle) experiments. Much of the organic nitrogen present in cattle manure is converted by anaerobic digestion into ammonia nitrogen (Table 10; Hart 1963), a form of nitrogen that is more readily available to plants. This ammonia nitrogen, however, is very volatile and is rapidly lost to the atmosphere when the sludge is dried (Table 11), or when manure is applied to a field (Figure 5). Although Figure 5 uses data for cattle manure rather than for digested sludge, it does show that ammonia loss can be quite rapid (a half-life on the field from 2 to 4 days). This ephemeral quality of ammonia seems to indicate that the nitrogen present in the solid portion of the residue is the most important source of nitrogen for plants (Sathianathan 1975), at least for land-based crops. Future experiments should consider a comparison between treated and untreated manure in longer term experiments, say several crop cycles. This would provide information concerning the potential "slow-release" fertilizer value of organically-bound nitrogen substances which decompose slowly in the soil, and thus release nitrogen to plants at a slow, constant rate.

In order to illustrate the linkage of resources and tasks, Figure 4 incorporates an estimate of the fertilizer value of 100 kilograms of fresh cattle dung for several different manure management practices. In this example, we assume that changes do not occur in nitrogen content during handling (except during drying), and that all forms of nitrogen are equally available to plants.

Our first management alternative is to use the 100 kilograms of fresh cattle dung directly as manure. The manure contains 0.29 kilograms of nitrogen, and therefore has a mass concentration of 0.29 percent (after Rajabapaiah et al. 1979).

The second management alternative would be to dry the dung, say to 20 kilograms. Some nitrogen would be lost in the drying process (decreasing from 0.29 to 0.15 kilograms), but in terms of concentration, the nitrogen content would increase from 0.29 to 0.75 percent.

The next two management alternatives proceed via the anaerobic digestion route. Because of the addition of 100 kilograms of water, and some minor weight loss due to the removal of biogas and some water vapor from the system, there are 196 kilograms of digester residue to handle in the third management pathway. The nitrogen is assumed to be equal to the initial nitrogen concentration of the fresh cattle dung, 0.29 kilograms, but the concentration is now only 0.15 percent. The fourth alternative assumes that these residues are dried to 20 kilograms, with a subsequent loss of nitrogen from 0.29 to 0.25 kilograms. However, based on these assumptions, the nitrogen is 1.25 percent nitrogen, the highest of the four alternatives. [Note: these data are based on incomplete information. Rajabapaiah et al. (1979) provided the nitrogen value of dried and wet sludge, and dried and fresh manure in terms of a percentage of volatile solids, but did not indicate the possible absolute changes in the quantity of solids caused by the drying].

Table 10. The composition of cattle wastes, with respect to nitrogen and solids concentrations, before and after treatment by anaerobic digestion, and in a wet versus dried state.

Wastes or Manure Condition or Treatment	NITROGEN			SOLIDS		Sources
	Total Nitrogen (TN)	Ammoniacal Nitrogen (AN) (% of TN)	Organic Nitrogen (ON) (% of TN)	Total Solids (TS)	Volatile Solids (VS) (% of TS)	
A. Cattle Dung						
• fresh	1.7%[a]					Rajabapaiah et al. 1979
• after 10 days in open air	0.9%[a]					
Digester Residue (from cattle dung)						
• fresh	2.2%[a]					
• after 3 days in open air	1.9%[a]					
B. Digester Residue (from cattle dung)						
• wet digester residue	2.2%[a]					Subramanian 1977
• dried digester residue	1.8%[a]					
C. Dairy Manure						
• fresh wastes	5.2% of TS 5.6% of VS	37.6	62.4	80.0 grams/liter	87.1	Jewell et al. 1976
• digester residue[b]	6.9% of TS 5.6% of VS	44.6	55.4	45.2 grams/liter	81.2	
D. Dairy Manure						
• fresh manure	3.7% of TS 4.3% of VS	24.0	76.0	10.1%	81.6	Hart 1963
• digester residue[c]	3.9% of TS 4.7% of VS	49.0	51.0	6.5%	77.0	

a as percent of dry weight of manure.
b batch-fed digester; retention time: 30 days; 32.5° operating temperature
c high-rate digester, 23°C operating temperature

Table 11. Results of laboratory experiments fermenting anaerobically fresh cattle dung (1.5 kg) for four weeks[a]

	Total Nitrogen		Ammoniacal Nitrogen		Organic Nitrogen	
	Grams	%	Grams	%	Grams	%
Nitrogen recovered						
In gases	<0.01	0.1	<0.01	0.6	nil	0
In digested slurry	4.53	99.9	0.80	99.4	3.74	100
TOTAL	4.54		0.80		3.74	
Nitrogen recovered After drying slurry	3.73	82.2	0.03	3.5	3.70	99.0

Source: After Idnani and Varadarajan 1974.

Note:

a. Values reported are the nitrogen components (in grams) in the gases evolved, in the digested slurry, and in dried digested slurry.

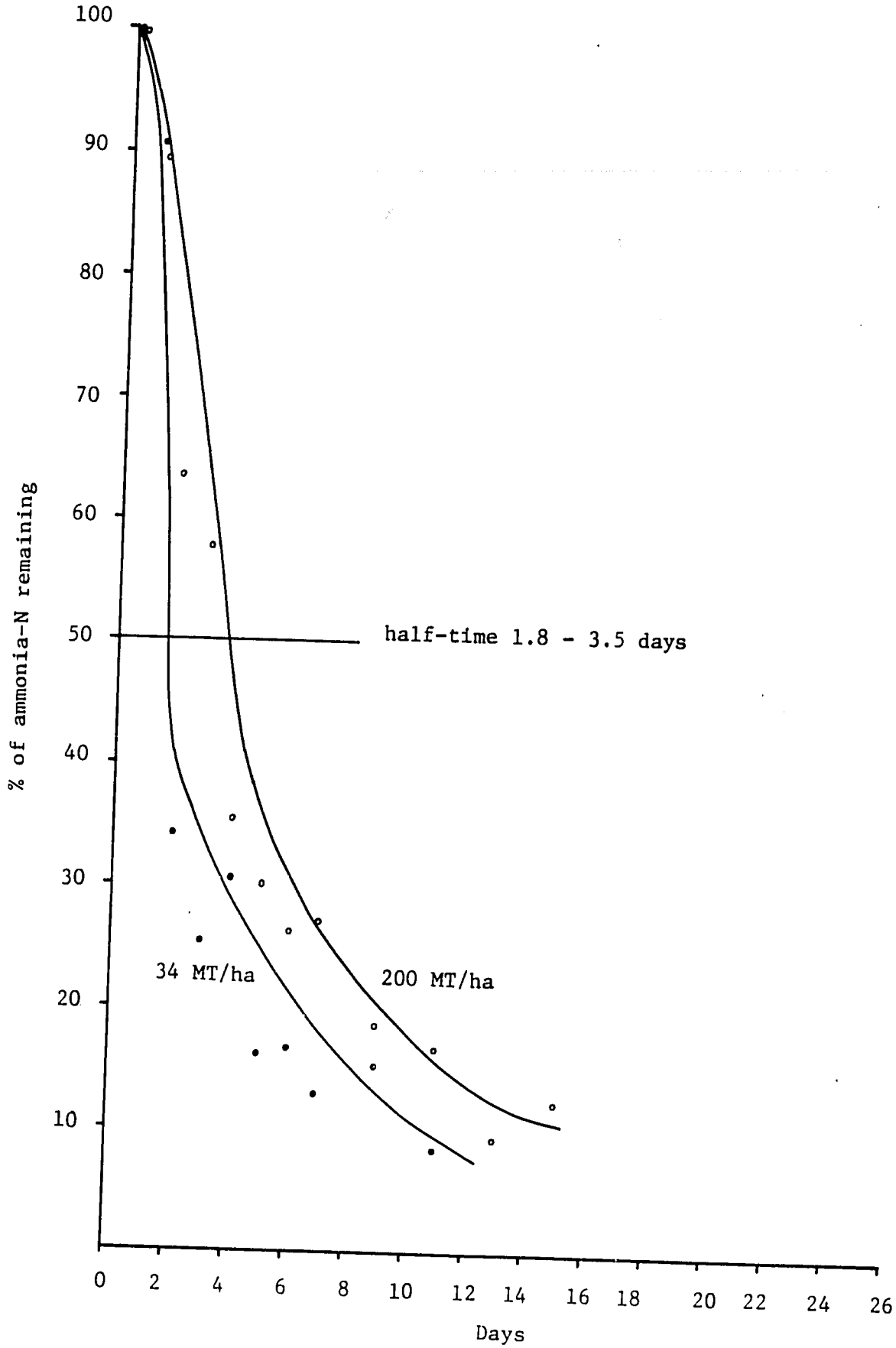

Figure 5. Daily ammonia losses from dairy manure applied to soil at rates of 34 and 200 metric tons/hectare (after Lauer, 1975)

These have possible implications in terms of the resources needed to utilize these materials as fertilizers, as is further illustrated in Table 12. Here, the quantities of bulk materials that are required to supply one kilogram of nitrogen fertilizer are compared. Urea appears to be the most efficient, as handling (transport, etc.) of only two kilograms of this substance is required to provide one kilogram of nitrogen. Anaerobically digested cattle dung sludge in the wet state is the most inefficient from the point of view of nitrogen. Over 600 kilograms of materials must be transported and applied in order to receive the benefits of one kilogram of nitrogen (assuming that this nitrogen is equivalent in value to urea or other commercial source of nitrogen). We have provided two other columns (50 and 25 percent availability) to illustrate the possibility that fertilizer nitrogen from manures (fresh, dried, or anaerobically digested) might not be as effective a source of nitrogen as the nitrogen from commercial fertilizers.

There is an important caveat to this analysis, however. These analyses fail to give the values of other substances present in manures or residues, such as phosphates, potassium compounds, and even water. The resources required to handle the extra bulk present in watery sludge might be worthwhile if, for example, water is scarce, or there is an efficient means of transporting wet sludge. The technique of transporting wet sludge to the fields by means of irrigation sluices is used in China (M. Weitzenhoff, pers. comm.).

Environmental tasks from biogas

The principal environmental tasks or effects from using biogas can occur either from changes in the type or quantity of fuel previously used to perform rural tasks, or from quantitative or qualitative changes in the accomplishment of the tasks themselves.

Environmental changes due to changing the type of fuel might best be illustrated by information on the reduction in the dependencies of other fuels in places where biogas was introduced. For example, Karki (1980) states that biogas was found to substitute for about 50 percent of the household consumption of firewood in a district in Nepal, and van Buren (1979) reported that a family of nine that used biogas saved (apparently annually) 2,500 kilograms of coal and 1,000 kilograms of firewood. The environmental benefits of these savings in firewood could be significant from the viewpoint of reversing trends of deforestation. However, any gross environmental benefits (e.g. forest conservation) must be weighed against the effects of change in waste management practices (e.g. using crop residues as feedstock) that could have possible detrimental effects, such as on soil conservation (see below).

Environmental change arising from biogas utilization might occur at the end-use site, such as a reduction in smoke in the kitchen. This will be discussed later.

Table 12. Estimated quantities of manures or fertilizers needed to supply one kilogram of nitrogen to any given area of cropland[a]

Nitrogen availability:	Quantity needed (kg) 100%	50%	25%
Ammonium phosphate	9		
Ammonium superphosphate	33		
Ammonium sulphate	5		
Urea	2		
Cattle dung (fresh)[b]	345	690	1,380
Cattle dung (dried to 20% of fresh weight)[b]	133	266	399
Anaerobically digested cattle dung sludge (wet)[b]	676	1,350	2,030
Anaerobically digested cattle dung sludge (dried to 10% of wet weight)[b]	80	160	240

Note:

a. The nitrogen present in inorganic fertilizers is assumed to be potentially 100 percent available to plants. For comparative purposes, the availability of nitrogen in organic manures is assumed to range from 25 percent (e.g., see Idnani and Varadarajan 1974) to 100 percent. Both inorganic fertilizers and organic manures often contain plant nutrients in addition to nitrogen, or provide important soil conditioning factors. Although important for soil fertility and plant growth, these are not presented in this table for the sake of simplicity.

b. Nitrogen value of manures are based on Rajabapaiah et al. 1979.

Environmental tasks from feedstock and residue management

As mentioned earlier, in comparison to the combustion of agricultural wastes (as fuel or for disposal), anaerobic digestion provides a possible means of conserving fertilizers and soil conditioners within the agricultural system. The net difference between combustion and anaerobic digestion in terms of this benefit would be between the benefits from returning the burnt ash to the soil (Briscoe 1978; Bhatia and Niamir 1979) and returning digester residues to the soil. If the choice is between removing agricultural wastes from the soil (for anaerobic digestion) and leaving them on the soil, then the situation is more complex. Although it can be argued that much of the fiber and other organic and inorganic substances present in agricultural wast passes unchanged through the digester (i.e., is not converted to gas or dissolved inorganic fertilizer), there is evidence that anaerobic digestion of crop wastes could have a long-term deleterious affect on soil quality. Lauer (1975) states that

> "...even the best managed return of digester residue to the fields where the crop residue was obtained is not sufficient to prevent a potentially significant loss of N as volatized ammonia from the soil-plant system. Long term operation of a methane generator augmented by harvesting crop residues may well cause a general decrease in the N fertility status of the soil."

Environmental tasks from digester construction and operation

Construction of an anaerobic digester would seem to involve either environmentally neutral or environmentally negative components, including the effects of exploitation of locally available materials, such as sand, clay and water. Furthermore, operation of the digester is not likely to produce any positive environmental tasks or benefits, except for the digester residue management subsystem described above.

Social tasks from biogas

The utilization of biogas could have an impact on labor or jobs in the rural area. Labor is defined here as the amount of time that a person uses to perform a task; a job is defined as labor for which a person receives remuneration. In terms of cooking, households that use biogas could have more time available if the net difference between the previous cooking-associated tasks (collecting fuel, etc.) and biogas-associated tasks is positive.

We do not have enough data to calculate the net employment change as a result of biogas being adopted in any given situation, although there is a likelihood of positive benefits (persons hired to operate plant) as well as negative ones (persons losing jobs as a result of less demand for previous

fuel). Spin-off labor and jobs resulting from possible increases in agricultural production have yet to be assessed (Islam 1980).

Organizational benefits have been mentioned as possibly occurring with the introduction of a community digester, resulting in a cooperative community feeling (e.g. Bahadur and Agarwal 1980). However, the reports seem speculative and do not provide any sociological data about such benefits.

The use of biogas might affect the equity situation in the rural area. As we will discuss later, anaerobic digesters have tended to be adopted by relatively elite persons in rural communities, which in some areas has limited access to dung by poorer households (Bhatia 1980), as a result of increased confinement of cattle by digester owners who wish to increase their feedstock raw materials for anaerobic digestion.

Conversely, there could be impacts from this technology that would have a positive influence on equity for example, if much of the time-consuming task of collecting fuels were replaced by the technology that uses the raw resource (agricultural wastes) more efficiently, as well as providing other benefits. Hypothetically, more time could be made available for performing more productive activities than collecting fuels, thus allowing persons to improve their economic condition. Economic benefits from using biogas as fuel could also occur at the national level by the possible reduction of dependence of a country on imported petroleum.

Changes in the quality of life as a result of using biogas have been mentioned in the literature but data substantiating such claims are seldom provided. Benefits could occur from the reduction of eye irritation and disease (by not burning dung, coal or wood), improved cleanliness of clothing and the home, increased life expectancy of cooking utensils, and time saved in cooking duties (Sathianathan 1975; Bahadur and Agarwal 1980).

These benefits must be weighed against the possible health and safety hazards arising from the possibility of fire or explosion inherent with using a combustible gas (Sathianathan 1975; van Buren 1979), or the possibility of creating a poisonous gas by adding unsuitable feedstock materials to the digester (van Buren 1979).

Social tasks from feedstock and residue management

One of the principal claimed benefits of anaerobic digesters is that they reduce parasites or pathogens present in wastes, particularly pig and human excreta. While these claims are substantiated by empirical data (Table 13), and are based mainly on Chinese experience with digesters, there are obvious design and operational factors that are critical in realizing this benefit--not all anaerobic digesters are equally effective in destroying harmful organisms, and an improperly operated (though properly designed) digester can be ineffective.

TABLE 13. Effects of anaerobic digestion on parasite and pathogen survival

Parasite or Pathogen	Treatment Time	Mortality
Van Buren 1979:		(%)
schistosome eggs	summer: 14 days winter: 37 days	99
hookworm eggs	30 days	90
flatworm and tapeworm eggs	70 days	99
dysentery bacillus	30 hours	*
McGarry and Stainforth 1978:		
schistosome eggs	summer: 14 days autumn: 22 days winter: 37 days	* * *
hookworm	(not stated)	99
hookwork eggs	30 days winter: 70 days	90 99
E. coli	(not stated)	99
dysentery bacteria	30 hours	*
spirochetes	30 hours	*
parasitic eggs		
without drop board**	(not stated)	80
with drop board	(not stated)	98

*Time period reported as survival time of parasites or pathogens in digester.

**A drop board is a baffle to prevent material settled on bottom of digester from being swept into digester sludge outlet.

That the design of the digester is critical is inferred from data on the change in parasite eggs surviving digestion (Table 13) with a digester modification known as a "drop board." The drop board is a baffle that prevents settled eggs and other materials from being convected into the outlet when feedstock is added to the digester or residue is removed. The possibility of agitation of the parasitic organisms settled on the floor of a digester is a tradeoff that the Chinese consider in operating their digesters--a tradeoff between mixing the contents of the digester to increase gas yield, or not disturbing the contents to ensure that parasites remain settled (Weitzenhoff, pers. comm.).

Destruction of parasites and pathogens requires a sufficient period of exposure to the chemical environment present in the digester, thus, the hydraulic residence time (the length of time an average particle spends in the digester) is critical (Barnett et al. 1978). The temperature of the digester is also critical, because the amount of time that harmful organisms must be in the digester to achieve a satisfactory kill rate is inversely related to temperature (Table 13).

Equally important in realizing the sanitation benefits from anaerobic digestion in regard to the management of excreta, is the conscientious management of the residues used as agricultural or aquacultural fertilizer. Because some parasites and pathogens survive anaerobic treatment, the residue still must be considered hazardous.

Equity considerations might be as important with regard to access to cattle dung for fertilizer as is sometimes true for access to dung for fuel by the rural poor. Control of digesters by wealthier persons who own and control cattle or other sources of wastes could affect the agricultural productivity of those persons who are not as well off, but used to have access to some of the wastes.

Social tasks from digester construction and operation

Jobs could be created in rural areas by construction of anaerobic digester (Bhatia and Niamir 1979; Ratasuk et al. 1979), as well as for their operation (Bhatia and Niamir 1979). Some of the labor requirements for construction are discussed earlier in this report for the case of a community-scale digester. Bhatia and Niamir (1979) indicated that two permanent jobs that were created to operate and maintain one such system were filled by relatively poor villagers.

As stated earlier, the net impact of jobs from anaerobic digesters must be determined for both construction of the digester (which is likely to not cause any displacement of persons employed in other activities) and the day-to-day operation of the digester (which could displace some workers, such as those involved with collecting and marketing fuelwood). Fourteen percent of the labor needed to construct digesters in Thailand has been met from

hired labor sources (Ratasuk et al. 1979), and in India, about one quarter of the digesters use hired labor for their operation (Moulik et al. 1978).

INDICATORS OF FIT AND EXPERIENCE-TO-DATE

In the previous two chapters we have illustrated by way of example and by survey of available literature, how resources are exploited and combined by anaerobic digesters to produce fuel and anaerobic digestion coproducts. We have also examined how these coproducts and fuel might be used to perform tasks, or otherwise affect social or environmental changes in rural areas.

The following discussion considers some of the possible relationships between anaerobic digesters and their fit in rural households and communities, on the basis of their use of resources and performance of tasks. We also survey some of the experiences described in recent reports concerning the success of digesters that have been introduced into south and southeast Asia and the Pacific.

Because the present application of the FLERT approach concentrates on the utilization of resources by anaerobic digesters, this discussion will focus principally on measures of the fit of digesters in rural areas based on characteristics of their resource exploitation. These measures will be highly subjective because, although the technology is not new, it is only fairly recently that critical examination of its interrelationships in rural areas has occurred.

Measures of the fit of an energy technology should consider three factors in relation to resource exploitation. First, the type and quantity of the resource should be examined in detail for the different types of digesters likely to be selected. Second, there should be an assessment of which resources are available locally, and which must be imported into the village. And, third, consideration must be given to the possible consequences of exploiting these resources (see Smith and Santerre 1980). We have already provided some examples to illustrate a methodology for assessing and comparing the resources exploited by digesters, and have found a considerable shortfall of data concerning the resource requirements for various phases of the fuel cycle of this technology.

In regard to assessing the locational availability of resources, we would like to requote (see Smith and Santerre 1980) a portion of a report on the utilization of resources by technologies:

> "Priority should be given to those energy technologies which exploit locally available energy, human, and material resources in rural areas as far as possible, so that the rural income remains in rural areas." (UNIDO 1978)

An important part of this quotation is the phrase, "as far as possible." There are some constraints to using locally available resources:

1. The resource may be unavailable locally.

2. The use of such a resource, although technically feasible, may seriously compromise the efficiency, reliability or safety of the system.

3. The use of such a resource might be detrimental to the environment, socially incompatible, or create undue hardship on non-users of the technology.

4. The resource may have more valuable uses in the rural area than its utilization by anaerobic digestion systems.

Some efforts to implement biogas systems in south and southeast Asia seem to be partly constrained by digester designs that rely heavily on materials that are scarce in those countries. This appears to be the case for the wide spread introduction of floating-dome digesters in India (KVIC 1976) and Nepal (Karki 1980). Of the three digester designs that we analyzed earlier (Tables 2,3), the floating-dome digester appears to be not only the most resource intensive (per capacity and per energy production), but also the design that relies most heavily on steel and cement, materials that are in short supply in these countries. In terms of availability, although local substitutes for cement are available in rural areas (van Buren 1979), we are unaware of any successful cases where the floating dome was made from local materials. It would appear that the increasing interest in underground fixed-dome digesters and in bag-type digesters is justified by their more efficient use of resources, and their greater potential for using locally available resources.

There also is interest in economizing by increasing the scale of digesters. Statements have been made that community plants have "clear-cut" economies of scale in comparison to household-scale digesters (Reddy and Subramanian 1979), but there is little evidence that this is a universal phenomenon. As mentioned by Ghate (1979), the costs of the biogas distribution system, together with the resources (labor) required to transport dung and sludge, could offset the economy of scale inherent in the actual digester plant itself. Clearly, the differences in economy of resource utilization must be considered in specific situations.

Community-scale digesters have also attracted interest because they can provide services to a broader spectrum of persons in rural areas, especially those who do not have access to sufficient quantities of feedstock raw materials to own a household-scale digester (Bhatia 1980). The unequal ownership of cattle among rural households is illustrated in Figure 6. Large variations exist among both householders and villages. If it is assumed that the minimum number of cattle required to provide adequate feedstock for a household-scale digester is two, then, although 85 percent of the households

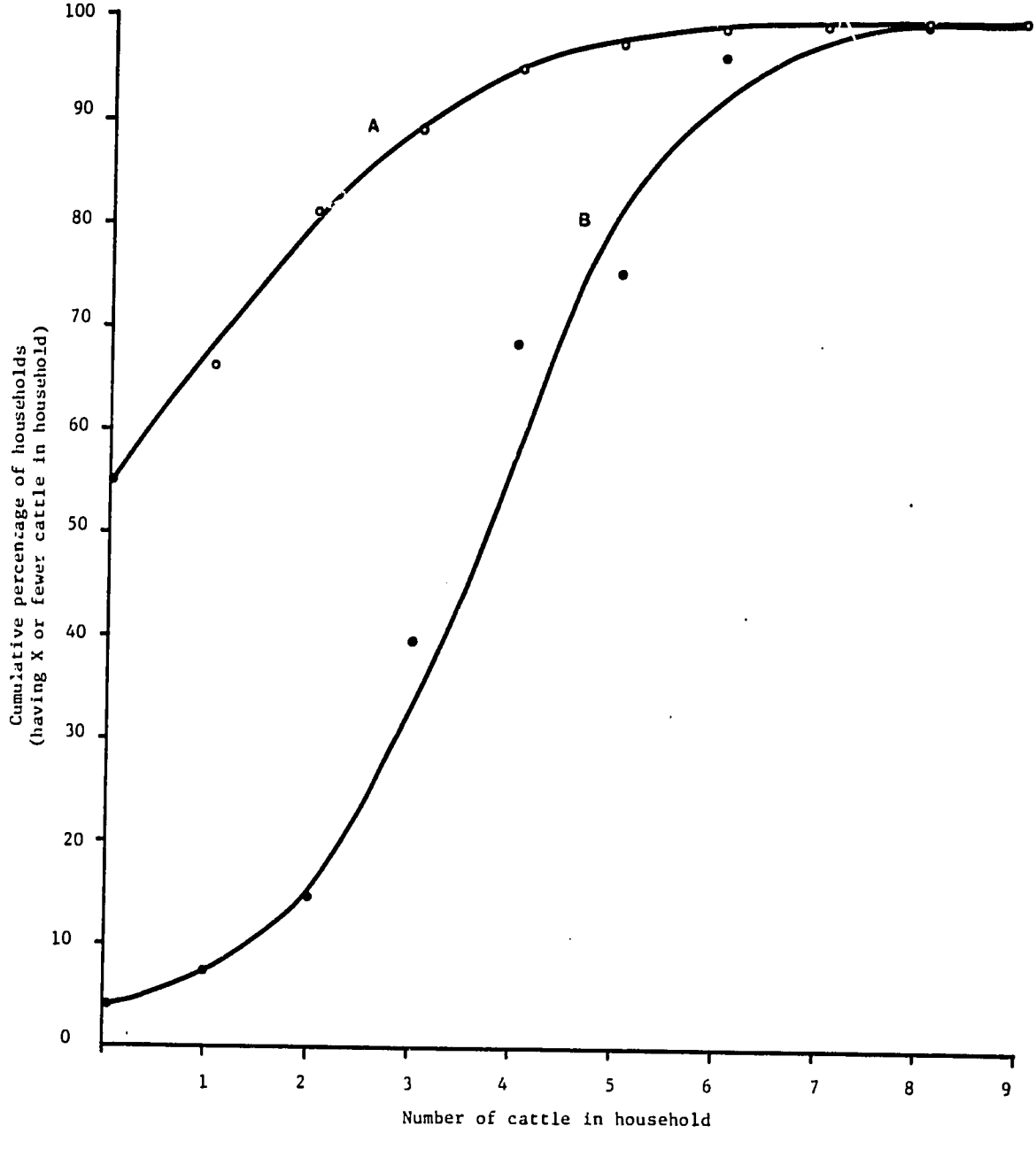

Figure 6. Distribution of Cattle Ownership.
Cumulative percent distribution of cattle, A. among 1,600 households in the Ganges flood plain in Bangladesh (Islam 1978); and B. among 28 households in Fateh Singh Ka Purwa village in India (Ghate 1979).

in Fateh Singh-ka-Purva village in India have sufficient cattle to consider ownership of a digester (after Ghate 1979), only 20 percent of the households surveyed in the Gangetic Plain in Bangladesh own the minimum number (after Islam 1980).

There are alternative raw materials to dung that might be considered for digester feedstock, such as agricultural crop wastes and human excreta. Although human and pig excreta are apparently used to a large degree in China (van Buren 1979), there have been problems in other areas of Asia with the use of these wastes. In Thailand, although pig excreta is a principal feedstock material in northern and northeastern regions of the country, in southern regions, due to the attitudes or beliefs of the local Moslem population, the use of such wastes is not common (Ratasuk et al. 1979). Experiences with the use of human excreta in anaerobic digesters on the Indian subcontinent have been mixed. In Haryana, India, about 30 percent of the digesters have attached latrines, however, some have been discontinued due to pressure from elderly persons (Barnett et al. 1978). It was also mentioned in this report that students in a women's college refused to cook with biogas that was made from nightsoil. A similar occurrence was noted by Sathianathan (1975), where biogas made from nightsoil was wasted into the atmosphere because of a reluctance to use it for cooking. The digester continued to receive waste and promote sanitation, with the proceeds from the sale of sludge being used to pay for the costs of the system.

Briscoe (1978) emphasizes the potential of using human excreta for anaerobic digesters in India, and estimates that the wastes from one person could produce 15 to 20 percent of that person's biogas needs for cooking. The KVIC (KVIC 1975) estimated that the excreta from 60 adults would be sufficient to operate a 2.0 cubic meter per day plant.

Two important aspects of the fit of anaerobic digesters into the environment are the temporal and spatial relationships of the associated resources and tasks (Smith and Santerre 1980). In addition to accounting for the quantity of dung or other feedstock resource required for anaerobic digestion, the frequency and predictability of the resource will influence the quality of energy service provided by the digester. Fortunately, most agricultural wastes and human excreta are either available throughout the year, or readily storable. The temporal distribution of the labor required for digester construction and operation is another important factor, about which there is relatively little information available. Construction of a digester might be timed to coincide with annual periods of slack agricultural activity, or periods during the year when the soil is more workable and requires less labor to excavate (van Buren 1979). There are also important temporal considerations for the operation of a digester, as the time required to collect and haul organic wastes and water, and to haul and apply sludge, could conflict with other activities (Bhatia and Niamir 1979).

As mentioned in Smith and Santerre (1980), biogas is possibly a less predictable source of fuel than either the fuel it replaces, or the feedstock

raw materials on which it is based, because possible variations in the supply of biogas due to minor or major perturbations in the anaerobic process itself. There is very little information concerning experiences with anaerobic digestion fluctuations for non-experimental situations. Barnett et al. (1978), Sathianathan (1975), and van Buren (1979) all point out the need to maintain constant operating conditions, to avoid introducing contaminating substances into the digester, and to watch for indicators of a "sick" digester. Seasonal or annual changes in a digester's performance are to an extent predictable, based on temperature fluctuations or changes in the quality or quantity of raw materials. The effects of these changes on the quantity and quality of biogas produced can be factored into the planning of a digester system in terms of pit size, storage capacity, and requirements for backup fuels.

There are likely to be both predictable and unpredictable variations in the quantity of biogas required to perform rural tasks. Cooking is likely to be accomplished at well defined times during the day. However, the amount of cooking may vary somewhat over a period of time, and may increase substantially during periods of feasting, or decline during periods of religious fasting. Likewise, the use of biogas for powering irrigation pumps will have both a predictable (e.g. seasonal) quality, and an unpredictable quality (caused by variations in rainfall). Various biogas-powered tasks might compete with one another for the use of biogas, as described by Bhatia and Niamir (1979) for a community digester in India. A deficit in biogas was observed during the month of November, when gas production was low, and the demand for gas by irrigation pumps was high. Biogas was diverted from cooking, which had to fall back on the use of traditional fuels.

The spatial aspects of resources and tasks for anaerobic digestion systems relate to the flexibility of siting the digester, and the density of the fuel flow (Smith and Santerre 1980). Anaerobic digesters have relatively flexible siting requirements in comparison to some technologies, such as windmills and hydropower installations (requiring sites with good wind and water energy resources). There are, however, certain relationships between the spatial siting of a digester and its resource requirements. We have already mentioned how soil conditions could affect labor requirements for excavating and building a digester, or affect the choice of design and use of materials by the digester (van Buren 1979). Slope is probably another important consideration, although not mentioned as such in the literature. One important restriction on siting an anaerobic digester is avoidance of locations that could result in contamination of drinking water sources.

The second aspect of the spatial relationship of anaerobic digesters is density. As a fuel, biogas is less dense and often more demanding to handle than the fuels it is likely to replace in rural areas, and requires the utilization of pipelines, valves and specially built stoves. However, from the viewpoint of the consumer, once these devices are in place, the "handling" of biogas is potentially more convenient than the previously used fuel, since the simple opening of a valve is all that is now required to

obtain access.

There is also an important density consideration with respect to handling one of the coproducts of digestion--namely, digester residue. As stated earlier, organic feedstock raw materials are usually diluted with an equal proportion of water. In one sense, this results in a decrease in the density of certain valuable components of the residue, such as nitrogen and organic soil conditioner, which has certain resource implications (e.g. additional labor for transport and application to cropland). The water, however, may also be considered a valuable component of the residue for irrigational purposes.

Experiences with anaerobic digesters

As stated in the Introduction, there are many reports of failure, dissatisfaction, or abandonment of anaerobic digesters. Examples are provided below:

* In the Chitwan district of Nepal, the owners of digesters were asked what they would do if they had to decide again about the ownership of a digester: 32 percent of the present owners indicated that they were dissatisfied with their systems and would not install a digester again (Karki et al. 1980). Twelve percent of the plants (apparently constructed less than four years ago) were not operating.

* In Fiji, 37 percent of the installed digesters included in a survey (16 were surveyed of an estimated 20 installed) were not in use (Siwatibau 1978).

* In Thailand, out of 141 (of a possible 200) anaerobic digesters surveyed, 61 percent were described as being inactive (Ratasuk et al. 1979).

* In India, a 1978 survey (Moulik et al. 1978) indicated that approximately 8 percent of the plants were inactive. However, in a follow-up site visit of 174 household and 25 institutional plants, 26 percent were found to be not operating (Prakasam 1979). Of the 25 institutional plants, only 6 (24 percent) were still operating.

* In Papua New Guinea, of the 16 anaerobic digester projects initiated at the time of the cited report, it was stated that, "not one has really functioned properly over any reasonable period of time" (Coulthard 1978).

The failure of these digesters could result from a physical failure of a component part of the digester, such as a cracked gas holder, or from improper operations and maintenance procedures. Institutional failure plays a role in some cases and includes factors such as the lack of adequate repair facilities, the lack of adequate follow-up or extension services, and poor advice to prospective owners as to the costs (both in a monetary and

non-monetary sense) as well as the benefits of the technology.

It is not presently possible to provide any definitive analysis of the reasons why some digesters fail and others succeed. Very few studies have attempted to determine the causes of success or failure of digesters. We shall use the remainder of this section to discuss the observations presented in reports on the "Indian design" floating-dome types of digesters. Other types of digesters are not widespread in south and southeast Asia, and literature concerning the wide-scale use of fixed dome digesters in China is only now becoming available in English.

Two important studies have incorporated demographic and economic profiles of the owners of digesters. These studies were conducted for the owners of 173 digesters in four states in India (Moulik et al. 1978), and for the owners of 25 digesters in the Chitwan district of Nepal (Karki et al. 1980). The anaerobic digesters in India (Table 14) were mostly installed after 1970, and the digesters in the Nepal study were apparently less than four years old. In addition, the Nepal study included a survey of 100 non-owners of digesters for comparitive purposes.

As is seen in the information summarized in Table 14, the level of education of the owners of digesters in these countries is quite high. In India, the average digester owner has almost 11 years of schooling, and 95 percent of the owners were literate. By comparison, the World Bank's (1980) most recent estimate of the adult literacy rate in India is 36 percent.

In the Nepal study (Table 14), all of the owners surveyed were literate, compared to a literacy rate of 60 percent for non-users (the World Bank estimate for the rate of adult literacy in Nepal is 19.2 percent). It was also observed that the owners of digesters in Nepal tended to be leaders in their communities.

The land and cattle ownership patterns for digester owners seemed to indicate that these persons were well off. Even those persons in the Indian study who owned less than four hectares of land were often relatively affluent, in that many were professionals. The Indian owners had a considerable portion of their land under irrigation, and tended to live near cities. In Nepal, one of the criteria for siting a digester was proximity to a jeep road, together with low elevation. The latter was related to both transportation requirements and average annual temperatures.

Moulik et al. (1978) and Karki et al. (1980) provide fairly detailed surveys of the experiences of the owners of digesters in India and Nepal, who were profiled in Table 14. A brief abstract of these experiences is provided in Table 15, including information on the location of the digester, the collection of dung, the motivation of the people for installing digesters, and technical and maintenance problems that were encountered by the owners or noted by the surveyors.

Table 14. Demographic and economic profiles of owners and nonowners of anaerobic digesters, in Nepal and India, by source.[a]

	SOURCE:				
	MOULIK, ET AL. 1978		KARKI, ET AL. 1980		
Location of sample:	Madhya Pradesh, Uttar Pradesh, Andhra Pradesh, and Haryana, India		Chitwan district, Nepal		
Size of sample:	173 owners[b]			Owners	Nonowners
				25[c]	100
Size range of digesters:	1.7 to 35 cubic meters per day biogas capacity. Distribution: 70 plants < 5.6 m^3/day 62 plants 5.6 - 7.0 41 plants > 7.0 m^3/day				
		%			
Age of digesters:	Installed before 1960:	1	Assumed to be less than four years as this is age of Nepal's digester program		
	Installed before 1961 and 1970:	18			
	Installed after 1970:	80			
				%	%
Education of owner:	College education:	28	Literate:	100	60
	Some high school education:	32	Leadership responsibilities:	84	14
	Illiterate :	5			
	Mean education: 10.8 years				
Family size:	< 4 persons:	28	1 to 3 persons:	0	7
	5 or 6 persons:	34	4 to 6 persons:	12	40
	7 or 8 persons:	20	7 to 10 persons:	24	30
	> 9 persons:	18	More than 10 persons:	64	23
	Mean family size: 7				
	Digesters more common among larger families				
Land ownership:	< 4 hectares:	38	< 2.4 hectares:	0	28
	4.5 to 8.1 hectares:	32	2.4 to 9.6 hectares:	4	46
	8.5 to 20.2 hectares:	21	9.8 to 24.0 hectares:	36	25
	> 20.7 hectares:	10	24.4 to 36.0 hectares:	28	1
	Mean land owned: 12.5 hectares		> 36.0 hectares:	32	8
	Some persons in first category were landless; some were professionals.				
Cattle ownership (number of head):	6 or less:	27	0:	0	10
	7 or 8:	25	< 3:	0	5
	9 to 12:	24	4 to 6:	12	40
	> 13:	14	7 to 10:	24	30
	Mean: 12		> 10:	64	15
Irrigated land:	< 50% of land irrigated:	10			
	50 to 75% of land irrigated:	7			
	> 75% of land irrigated:	83			

[a]Four surveys conducted in Nepal (Chitwan district) and India (Madhya Pradesh, Uttar Pradesh, Andhra Pradesh, and Haryana). Comparative information for nonowners is from a random sample of farm householders in Nepal (Karki, et al. 1980).

[b]An additional seven digesters were rejected because they were not operating.

[c]An additional seven digesters were rejected due to incomplete information.

Table 15. Survey of experiences of owners of anaerobic digesters in Nepal and India, by source.

	SOURCE:			
	MOULIK ET AL. 1978		KARKI ET AL. 1980	
Location of survey:	Madhya Pradesh, Uttar Pradesh, Andhra Pradesh, Haryana, India		Chitwan district, Nepal	
Size of sample:	173 owners		25 owners	
		%		
Distance of digester from residence:	2 to 10 meters:	29		
	11 to 20 meters:	29		
	20 to 25 meters:	14		
	> 30 meters:	28		
Persons collecting dung:	Self:	41		
	Family members:	11		
	Self + family members:	20		
	Hired labor:	24		
	Others:	3		
	Persons with smaller plants, small to medium-size farms, and less education, typically performed function themselves.			
				%
Frequency of dung collection or loading:	Collection:		Put into digester:	
	Once daily:	67	Daily:	92
	Twice daily:	32	Less frequently:	8
	Thrice daily:	1		
Quantity of dung collected, purchased or used:	Owners purchasing dung:	0	Owners that indicate they have sufficient dung:	92
	Owners using all the dung they collected daily:	75		
	Owners that indicate they have sufficient dung:	100		
	Amount of dung: 8 to 550 kilograms daily			
Motivation for installing plant or uses of digester products	Free cooking fuel:	99	Cooking and lighting:	12
	Fuel for machines:	1	Cooking, lighting and production of manure:	76
	Lighting:	7	Cooking and manuring:	12
	Rich manure for fields:	18		
Technical and maintenance problems:	Surveyees' responses:		Surveyors observations:	
	No problem:	60	Condition of drum:	
	Excess water in gas pipe:	28	Very good:	52
	Leakage of gas and water:	17	Good:	28
	Preparation of slurry is time consuming and monotonous:	7	Rusted:	20
	Rusting of pipeline joints:	4	Plant operation:	
	Rusting of gas holder:	3	Working at present:	88
			Out of order:	12
Stoppage of plant for cleaning:	Non-stop use:	96		
	Stopped once only:	2		
	Stopped once in two years:	1		
	Stopped once in five years:	0		

Water accumulating in the gas pipes, leakage of gas and water from the digester and its pipes, and rusting of the metal gas holder are all frequently cited problems. For example, 20 percent of the digesters surveyed in Nepal had rusted domes, and according to Karki (1980), 50 percent of the users ignored the fact that painting increases the life expectancy of this part of the digester. This also seemed to be true in India, where digester maintenance indicated lack of knowledge or resources necessary to provide basic preventive maintenance. Perhaps some of these problems could have been corrected at the institutional level through follow-up activities by trained technicians who might conduct frequent site visits to digesters and help to correct such deficiencies (Karki 1980). Other institutional deficiencies were pointed out in these surveys. For example, many of the digester owners in India either indicated that digester repair services were unavailable in their villages or expressed dissatisfaction with the quality of the available repair services.

In Thailand, the high failure rate of digesters was apparently due in part to the motives for installing them. According to Ratasuk et al. (1979), many of the digesters (of the floating-dome "Indian design") that were installed in local health centers, were not put there to meet energy or sanitation needs, but were introduced to please promotional officials who were using them for demonstrational purposes only. This program was useful, however, because it demonstrated some interesting relationships among the factors contributing to the success and failure of anaerobic digesters.

According to the authors, there was little motivation for the persons to keep the digesters operating. The local health centers did not have any animal dung to put into the digester, and had difficulty in enlisting volunteer labor to collect dung and perform other digester operations. The digesters that were constructed for rural monastaries were successful, perhaps because of their ability to attract community support in donations of labor, dung and other resources.

There was also no sense of ownership of the digesters, as they were financed by the government. When other more convenient energy sources became available, such as electricity, there was no logical reason for many owners to continue operating their system. Some users abandoned their digesters because of abandonment of animal husbandry and difficulty in getting manure from their neighbors. This reason was cited as a principal constraint to further introductions of household systems in Thailand, since there is a tendency in this country for larger industrial-scale animal husbandry activities to replace cottage level husbandry. Other reasons given for abandonment of digesters included technical failure of the digester, the lack of operators, and lack of time or boredom with the chores of running a digester.

Certain factors appeared to be correlated to the success or failure of digesters in Thailand. Ratasuk et al. (1979) noted that digesters had a greater acceptance rate among persons with a moderate amount of education,

and among persons from middle economic status. The rate of abandonment of digesters was higher among the most educated persons. Clustered settlements appeared to have higher rates of failed digesters, which the authors speculate might be related to access to better roads, leading to changing lifestyles (e.g. abandonment of animal husbandry, and hence, a source of feedstock), and better access to other energy sources. There was also a tendency for the digesters to have a lower acceptance rate among large-scale farmers who have been increasingly replacing draft animals with machinery, limiting the availability of feedstock.

The authors of this report concluded that small-scale simple digesters would probably not contribute significantly to the solution of Thailand's energy problems, although fixed-dome digesters could compete economically with charcoal if significant cost reductions are made for these systems.

There are two detailed studies of a community-scale digester in Fateh Singh-ka-Purva village in India (Ghate 1979; Bahadur and Agarwal 1980). Most of the following information is abstracted from the latter report. Two community-scale plants were built in this village, and interconnected in order to ensure a minimum gas supply should one of the plants become temporarily unoperational. Several criteria were used for selecting the site of this system, including: an adequate quantity of dung for cooking, lighting, and a surplus of gas for other purposes; availability of houses in a cluster; accessibility of the site; assurance of cooperation by the villagers; and relative social and economic uniformity of the inhabitants.

Considerable enthusiasm was evident in the village prior to the construction of the system, and the authors (Bahadur and Agarwal 1980) stated that the villagers apparently did not expect that they would be asked to pay for the gas they used for cooking. This was not the case, and it caused some dissatisfaction among villagers when they were asked to pay for their gas, especially because they considered the previously used cooking fuels (dung, straw, etc.) to have been "free."

The quantity of biogas provided to the villagers was at one time in the project estimated to be sufficient, with a surplus available for non-cooking purposes. However, some villagers felt that the quantity of biogas supplied was inadequate for their needs, and they began withholding dung from the community system to use for direct cooking. This perceived shortage of gas, together with a decline in the cattle population, resulted in less dung being delivered to the digester, and eventually, an actual shortfall in gas. Only 19 percent of the households in the survey indicated that all their cooking needs were met by biogas. About 38 percent said that the gas met three-quarters of their needs, and 42 percent felt that the biogas met only half of their requirements for cooking fuel. The deficits were met with agricultural wastes and firewood, both used in the chulhas already available. Also, there were certain types of food preparation for which villagers were inclined to continue using traditional fuels because of

the flavor these fuels imparted to the food.

It was also determined in the survey that women in the village thought biogas was more convenient to use than their previous fuel, and saved them time. Fifty percent of the women indicated that their spare time was now devoted to agriculture, animal husbandry, and basketmaking. However, it was not determined whether there was any increase in economic activities as a result of the increased leisure time afforded by the use of biogas.

The biogas was also used to generate electricity (dual-fuel engine) for street and domestic lighting for three hours daily. All 27 houses in the village were provided with electric power, but 7 of them could not afford lightbulbs. Many of the villagers (58 percent) continued to use kerosene for lighting because they felt that the cost of electricity (and bulbs) did not justify its convenience. For some purposes, such as a portable source of light, gas and electric lamps could not compete with the convenience of kerosene lamps (S. Sarvate, pers. comm.).

Cattle dung was contributed by each household according to its access to dung. Some households contributed more dung than others, the quantity being related to cattle ownership (Figure 6). Biogas was apportioned equally to all the households. However, sludge from the digesters was redistributed in proportion to the quantity of dung contributed, and it was observed that the villagers seemed reluctant to use the sludge as manure. Although they apparently understood the fertilizer value and use of farmyard manure, there was a bottleneck in transporting the sludge from the digester pits to the individual household pits. The villagers apparently did not need the sludge throughout the year and thought that the project staff would guard their allocated sludge until they did need it.

SPECIFICATIONS PLATE

The "Criterion of Parsimony" (Smith and Santerre 1980) will be applied in this section to condense the large quantity of information presented earlier into a smaller number of indicators that are most essential for describing anaerobic digestion technologies. This Specifications Plate is intended to provide a compact and consistent set of data by which: (a) anaerobic digesters can be assessed for their fit with conditions present in rural areas; (b) different types and scales of digesters can be compared with one another; (c) anaerobic digesters can be compared to other small-scale energy technologies; and, (d) other types of estimates can be performed, such as assessment of the impact of resource exploitation for large-scale programs for introducing digesters into rural areas.

A Specifications Plate is provided in Table 16 to compare the physical, social, and environmental resource requirements of a household-scale (3 cubic meter per day biogas production capacity) fixed-dome digester with a community-scale (85 cubic meter per day) floating-dome

Table 16. Specifications Plate. Gross physical, social, and environmental resources required to construct and operate a 3 cubic meter per day fixed-dome household-scale digester and an 85 cubic meter per day community-scale digester.[a] Data between parentheses are not based on actual measurements.

	1. Construction (per cubic meter of biogas production capacity)				2. Operation (per cubic meter of biogas produced)			
	3 m^3 fixed-dome digester Lifetime: 30 years		85 m^3 floating-dome digester Lifetime: 20 years		3 m^3 fixed-dome digester Capacity factor: 85%[b,h]		85 m^3 floating-dome digester Capacity factor: 85%[b,h]	
	Local	National	Local	National	Local	National	Local	National
PHYSICAL RESOURCES								
Materials[c]								
Steel (kg)[c,d]	--	None	--	(32)	--	--	--	--
Bricks[d,e]	--	433	--	565	--	--	--	--
Lime (kg)[d,e]	--	100	--	None	--	f,g	--	f,g
Cement (kg)[d,e]	--	85	--	120	--	g	--	g
Paint (liters)[g]	--	--	--	--	--	--	--	(<0.01)
Cinders (m^3)	0.3	--	None	--	g	--	g	--
Sand (kg)	989	--	642	--	g	--	g	--
Stone, chipped (kg)	None	--	161	--	--	--	--	--
Energy								
Cattle dung "fresh" (kg)	--	--	--	--	(28)	--	(28)	--
Other	?[j]	?[j]	?[j]	?[j]	--	--	--	--
Water (kg)	(43)	--	(60)	--	(28)	--	(28)	--
SOCIAL RESOURCES								
Labor (person-days)								
Unskilled	(40[l])	?[m]	?[n]	?[n]	(0.14[o])	--	(0.12[p])	--
Skilled	(13[l])	?[m]	?[n]	?[n]	(0.01[o])	--	(<0.01[p])	--
Extensive Measures								
New job types (+,0)	+	0	+	0	+	0	+	0
Village organization (low, medium, high)	low	n.a.*	medium	n.a.	low	n.a.	high	n.a.
Sophistication (low, medium, high)	high	low	medium	medium	medium	low	medium	low
Monetary economy (low, medium, high)	low	n.a.	medium	n.a.	low	n.a.	medium	n.a.
Cultural taboos	--	--	--	--	potential[s]	--	potential[s]	--
ENVIRONMENTAL RESOURCES								
Land (m^3)								
Exclusive	(25[r])	--	(150[r])	--	--	--	--	--
Shared	--	--	--	--	u	--	u	--
Extensive Measures								
Temperature	--	--	--	--	warm[t]	--	warm[t]	--

OTHER MEASURES

Fuel Predictability: Anaerobic digesters, compared to all other small-scale energy technologies, score "1" on a scale of 1 (predictable) to 3 (stochastic).

Energy Resource Siting Flexibility: Anaerobic digesters, compared to all other small-scale energy technologies, score "1" on a of 1 (flexible siting) to 3 (special requirements).

Fuel Density: Biogas scores a "3" for fuel density, on a scale from 1 (high density) to 3 (low density); digester sludge, in terms of nitrogen fertilizer density, scores a "3" if in the wet state, and a "2" if in the dried state. The energy density of biogas is between 0.019 and 0.026 MJ/liter (US National Academy of Sciences 1977).

3. Totals (for lifetime)[w]		4. Totals (per 10,000 cubic meters of biogas)[w]		5. Totals (per 10,000 cubic meters of methane)[k,w]	
3 m^3 fixed-dome digester	85 m^3 floating-dome digester	3 m^3 fixed-dome digester	85 m^3 floating-dome digester	3 m^3 fixed-dome digester	85 m^3 floating-dome digester
None	(2,700)	None	(51)	None	(85)
1,300	48,000	465	911	777	1,520
300	None	107	None	179	None
255	10,200	91	194	152	323
--	(220)	None	(4.2)	None	(7.0)
1	None	0.4	None	0.6	None
2,970	54,600	1,060	1,036	1,770	1,730
None	13,700	None	260	None	433
(781×10^3)	$(14,800 \times 10^3)$	(280×10^3)	(280×10^3)	(467×10^3)	(467×10^3)
--	--	--	--	--	--
(781×10^3)	$(14,800 \times 10^3)$	(280×10^3)	(280×10^3)	(467×10^3)	(467×10^3)
$(4,010^q)$	$(61,100^r)$	(440^q)	$(1,160^r)$	$(2,400^r)$	$(1,930^r)$
(210^q)	$(3,217^r)$	(76^q)	(61^r)	(126^r)	(100^r)

NOTES:

*n.a. not applicable

a. Data are based on van Buren (1979), Sathianathan (1975), plus our own estimates (See Table 2).
b. Hypothetical lifetimes and capacity factors (see text).
c. Resource requirements are based on original data source that we suspect includes only digester plant construction; not included: tools; gas distribution system; structures or devices for feedstock or residue management subsystems; biogas utilization devices.
d. Only primary requirements for steel are included; the estimates might underestimate requirements for steel by floating-dome plant, based on information presented in Sathianathan (1975:163). Resources required to manufacture steel are not estimated here.
e. For convenience of these calculations, bricks, lime and cement were assumed to be manufactured outside of our village boundary: the manufacture of these materials requires additional resources (energy, labor, materials) not included here.
f. Lime might be added to the digester slurry as a buffer, or to the sludge for disinfection purposes: these are not included in this table.
g. Cement, lime, cinders, sand, and water might be required for repairing the digester: these are not included in this table. Eleven liters of paint are assumed to be required annually by the floating-dome digester.
h. The 85 cubic meter per day digester, operated at 85 percent of capacity, produces 527,000 cubic meters of biogas during its 20-year lifetime. The 3 cubic meter per day digester, operated at 85 percent of capacity, produces 27,900 cubic meters of biogas during its 30-year lifetime. Because both digesters are assumed to use cattle dung as feedstock, both were also assumed to have the same capacity factor.
i. Fresh cattle dung and water are assumed to be the only feedstock raw materials used. Twenty-eight kilograms of each are added to the digester, to produce 1 cubic meter of biogas. This is assumed to be a year-round average yield.
j. Energy is required also for manufacturing construction materials, transporting the materials, and construction. Although important, these data are not known and are not presented in this table.
k. Biogas is assumed to be composed of 60 percent methane.
l. Building the fixed-dome digester is assumed to take 80 person-days of labor (van Buren 1979), plus an additional 40 person-days for procuring locally-available construction materials. Construction of the gas distribution system, the feedstock raw materials and the residue management subsystem is assumed to require 40 person-days. Construction labor is assumed to be 75 percent unskilled and 25 percent skilled.

m. Some labor is probably required for the manufacture of materials outside the village, but is not tabulated here due to lack of data.

n. Data were unavailable for the labor requirements for constructing a community-scale floating-dome digester.

o. The operational labor requirements for fixed-dome digester are calculated as follows:

1. Assume that for 10 days per year a total of 30 person-days of labor are needed for emptying, cleaning, repairing and refilling the digester.
2. Assume that for each of the remaining 355 days per year that the digester requires 1 person-hour for collecting 84 kilograms of fresh dung, and 2 person-hours to haul water, mix inputs and add them to the digester, and distribute sludge. For a 10-hour workday, this totals to 0.3 person-days.
3. Calculations:
   - total labor = (30 person-days/year x 30 years) + (0.3 person-days x 355 days x 30 years) = 900 person-days + 3,195 person-days = 4,095 person-days
   - 4,095 person-days + 160 person-days (for construction) = 4,255 person-days
   - 4,255 person-days ÷ 27,900 meters of biogas = 0.15 person-day per cubic meter of biogas (assume that 95% of labor is unskilled and 5% is skilled).

p. The operational labor requirements for floating-dome digester are calculated as follows:

1. Assume that for 10 days per year a total of 200 person-days of labor are needed for emptying, cleaning, repairing and refilling the digester (this is proportionately lower than that required by the smaller plant because this size plant may employ some special equipment for some downtime tasks, such as emptying the digester with a pump).
2. Assume that for each of the remaining 355 days 2 persons are employed at the site (Bhatla and Niamir 1979). In addition, 6.5 person-days per day are required to collect dung (2,380 kilograms), and haul dung and sludge to and from the digester (this is assumed to be 25 percent higher per kilogram of dung than for the smaller digester because of the greater distances between the source of dung and the digester).
3. Calculations:
   - total labor = (200 person-days/year x 20 years) + (8.5 person-days x 355 days x 20 years) = 4,000 person-days + 60,350 person-days = 64,350 person-days
   - 64,350 person-days ÷ 527,000 cubic meters of biogas = 0.12 person-days per cubic meter of biogas (assume 95% of labor is unskilled and 5% is skilled). [Note: excludes construction labor.]

q. Excludes labor outside of village.

r. Excludes all construction labor.

s. Handling human or animal excreta could be affected by taboos or cultural tradition.

t. Optimum production of biogas (in mesophilic range) occurs at about 35° Celsius; gas production ceases at 10° Celsius.

u. Land is required for grazing by cattle, as well as for production of crops (and crop wastes), but is not tabulated here due to lack of data.

v. Only includes estimate of land area at digester site: excludes land area needed for sludge or raw materials treatment, storage, and gas distribution system.

w. Resources required for dismantling digesters are not included.

digester.

As we have indicated throughout this report, information about the resource requirements of anaerobic digesters is sparse, except for data about the materials required for building the plant itself. Consequently, some of the data presented in Table 16 are based on our own "educated guesses" or "back-of-envelope" calculations. These data are placed in parentheses to indicate that they are not based on direct measurements. Of course, measured values are preferable, but we have included our estimates in this table to give a flavor of how a more complete specifications plate would appear.

The data presented on the use of construction materials by the digesters are derived from the same sources as used in Table 2 (van Buren 1979; Sathianathan 1975), however, we changed some of the assumptions for operation of the household fixed-dome digester. First, we assumed that both digesters were fed with "fresh" cattle dung, and that 28 kilograms of dung combined with 28 kilograms of water yield one cubic meter of biogas (Rajabapaiah et al. 1979). Second, we assumed that both digesters were operated at an 85 percent capacity level (in Table 3 we assumed that the fixed-dome digester was operated at a lower capacity level due to using raw materials that necessitated frequent cleaning).

We chose to continue the assumption used in Table 3 that the floating-dome digesters would have only a 20 year lifetime due to the use of steel for critical components, and that the fixed-dome digester has a lifetime of 30 years.

The gross physical and social (intensive) resource requirements in Table 16 are divided into five principal columns:

1. The resource requirements for construction of the digester system, reported as units required per cubic meter of biogas production capacity.

2. The resource requirements for operating the digester, including subsystems II, III, IV, and V, and reporting the requirements as the units required per cubic meter of biogas produced by the digester.

3. The total resource requirements for constructing and operating the digester over its lifetime, reported as the total units required.

4. The total resource requirements for constructing and operating the digester over its lifetime, reported as the units required per 10,000 cubic meters of biogas.

5. The total resource requirements for constructing and operating the digester over its lifetime, reported as the units required per 10,000 cubic meters of methane gas.

The data presented in Table 16 for the physical resources for constructing the digesters include only the subsystem components (unspecified) that were considered by the authors of the original sources (see van Buren 1979; Sathianathan 1975). Consequently, our tabulations probably underestimate the physical resources required by these two digesters. Our best judgment is that the following items are not included in the values given in this table:

1. Resources required by the energy distribution system.

2. Physical resources required for the feedstock raw materials management subsystem, such as new structures or devices for confining livestock, storing organic wastes, or hauling raw materials.

3. Physical resources required for the digester residue management subsystem, such as new structures or devices for removing, storing, treating, transporting, or applying sludge.

4. Physical resources required for utilization of the biogas, such as biogas-powered appliances and engines.

In addition, minor construction materials were not included, such as valves, inlet pipes, pressure gauges, monitoring devices, and similar items.

The data presented in Table 16 about the labor requirements to construct and operate the digesters were based on very little actual data, and relied mostly on our own educated guesses. Consequently, they are mainly useful for illustration of the methodology.

Estimates of the labor needed to construct a brick fixed-dome digester were based on data presented by van Buren (1979), which indicated that 80 person-days of labor were needed to build a 3 cubic meter plant. We added 40 person-days to this to account for labor possibly required to procure locally available construction materials, plus 40 person-days for construction of the biogas distribution, feedstock raw materials, and residue management subsystems. We were unable to obtain any estimates of the labor needed to construct a community-scale floating dome digester.

We estimated that the household-scale digester would require 1 hour per day to collect cattle dung, and an additional 2 hours to mix the inputs and add them to the digester, to haul water, and to transport and apply the digester sludge, or a total of 0.3 person-days of labor per day (based on a 10 hour workday). We also assumed that this digester would require (on the average) 10 days per year of annual maintenance; for this period, a total of 30 person-days of labor were required.

For the community digester, we used the data given by Bhatia and Niamir (1979) that two persons were employed on a full-time basis to operate the digester. We added 6.5 person-days per day to this amount to account for

the labor needed to collect and transport dung, and to transport sludge. This value is 25 percent higher per quantity of dung and sludge (for collecting and transport) than the value we used for the household-scale digester, because we assume there are greater distances involved with hauling materials for the community system.

We have also assumed that the community digester requires 10 days per year of annual maintenance, and 200 person-days to perform the various tasks. This value is proportionately lower than that of the household digester because we assume some economy of scale occurs for the larger system, and that labor-saving devices (e.g. pumps to empty the digester) might be used for the community digester.

The skill requirements for construction of either digester have been arbitrarily set at 75 percent unskilled and 25 percent skilled labor; the skill requirements for operation have been arbitrarily set at 95 percent unskilled and 5 percent skilled labor for both digesters. We are not accounting for any labor needed for training, extension, or other institutional activities.

Both digesters are assumed to transform dung and water into biogas with an equal degree of efficiency although, in practice, the fixed-dome digester might have some advantage during cooler months by virtue of its being underground and subject to more constant temperatures. Based on the above assumptions, the community-scale digester is a more efficient user of labor (per cubic meter of biogas produced) than the household-scale digester, but the community digester is less efficient in its use of construction materials. The community digester is also more heavily dependent on the use of imported construction materials (mainly steel), and if the system boundary were expanded to include manufacturing activities outside the village, would probably show a similar dependence on labor from outside the village.

The extensive social and environmental resource indicators presented in Table 16 are subjective and very tentative. An adequate means of comparing these indicators among small-scale energy technologies remains to be developed, and our presentation is largely intended to create an awareness of the need for such data and analytical technique.

We felt that both types of digesters would have the potential of producing new job types at the local level, but would not likely create any significant number of new job types at the national level, since digesters do not require any exotic new supporting technologies, such as might be needed by solar photovoltaic systems.

The next extensive indicator, village organization, was judged more critical for the community digester than for the household system. Illustration of some of the components of village organizations were presented in Table 7 in Smith and Santerre (1980).

The level of sophistication required to construct a brick fixed-dome household digester of the types used by the Chinese (van Buren 1979) was estimated by the present authors to be higher than for the floating-dome system. Very precise brick-laying techniques are required for the construction of a brick fixed-dome digester, and any level of discipline less than perfection will likely result in a troublesome digester (van Buren 1979). The floating-dome digester, because of its use of steel, requires more sophistication at the national level, as well as a more complex economy to facilitate the transfer of materials from the national to village levels. Both digester designs were assumed to be equally sophisticated for their operation, although the floating-dome digester again was thought to require a more complex economy because of its dependence on non-local goods and services (such as welding) for repair.

Cultural taboos or traditions are perhaps more important factors to consider for this technology than for most other small-scale energy systems because of the potential involvement with the handling of human or pig excreta, or of products produced from these raw materials. There are also important social factors to consider for alteration of traditional defecation and waste management practices in rural areas.

CONCLUSIONS

Anaerobic digesters are very complex technology systems that have the potential of interacting with many aspects of daily life in rural areas of developing countries. Assessment of the potential for an anaerobic digester in a given rural situation should include not only a judgment of the match between energy needs and energy resources via the digester, but also an assessment of the social and environmental fits.

To date, many introductions of this technology into rural areas of developing countries have been unsuccessful. We believe this is to a large extent due to a failure to examine critically the physical, social, and environmental resources (and limitations to their exploitation) available in rural areas, and how these resources are transformed by digesters into physical, social, and environmental tasks or services.

The application of the FLERT approach to anaerobic digestion systems in this study is an essential first step toward understanding how physical, social and environmental needs and resources in rural areas can be matched in specific situations by anaerobic digesters.

The FLERT approach provides a well-defined and replicative framework for examination of the resources exploited by digesters, and the products and coproducts they produce. The present application of the FLERT approach, limited as it was by the available database, provides an example of this newly-developed methodology, and sets the groundwork for more detailed studies of anaerobic digesters in the future.

The second step of matching rural needs with rural resources via anaerobic digesters will require a detailed examination of the resources and needs of the location for which a digester is being considered. This second step must include an analysis of the likely impact of the technology in the rural area, and include the effects of the introduction and use of a digester on both the users and nonusers of the technology.

Current designs of anaerobic digesters in use in south and southeast Asia and in the Pacific islands, vary considerably in the degree of exploitation of construction materials. These variations apply to both the types of resources required, and the quantity per unit of fuel produced. Certain types of anaerobic digesters, such as the floating-dome "Indian design" systems, which are in widespread use throughout the region, appear to be very inefficient in their exploitation of construction materials. Furthermore, the present heavy reliance of this digester design on steel for its gas collector, is not only hampering programs to promote this design, but also runs counter to the current advice (UNIDO 1978) that those energy technologies be emphasized that exploit locally available resources as much as possible.

Other designs of digesters, such as the fixed-dome underground anaerobic digesters commonplace in China, use construction materials much more effficiently (in terms of units of construction materials per unit of gas production), as well as being adaptable to using materials that commonly found in rural areas. The database on these types of digesters should improve as Chinese documents about anaerobic digesters are translated into other languages.

There is considerable interest in the region on the possible application of community-scale digesters that could meet the energy needs of even those persons in rural areas who do not control a sufficient quantity of raw materials (e.g. dung) to own a household-scale system. Although these community systems warrant the attention of rural development organizations, it is too early to determine how successful these systems might be in rural communities. However, it does seem likely that their applications will be limited to communities that possess the apparently essential qualities of a high level of community organization, cooperation, and "spirit."

It has been claimed that floating-dome community-scale digesters benefit from an economy of scale. However, this is documented only in the case of resources used to construct the digester plant itself, and is true only when comparisons are made to smaller digesters of the floating-dome design. Situations could exist where the use of resources (construction materials and labor) could actually be greater for the community-scale system than for the household-scale system, when the gas distribution subsystem, and the feedstock raw materials and digester residue management subsystems are included in the accounting.

In relation to the above discussion of economy of scale, the household-scale fixed-dome digester used in our analyses actually used construction materials more efficiently (in terms of a cubic meter of biogas produced) than did even the large community-scale version of the floating-dome digester (see Tables 2 and 16). It is entirely possible that household fixed-dome digesters (being at least as efficient in their use of resources as community floating-dome digesters) could be used in a community to the benefit of all households in the village, whether or not they own sufficient quantities of cattle. The basis for this arguement is similar to the one that forms the basis of community digesters--that the owners of cattle might be willing to "loan" their cattle dung for anaerobic digestion as long as they retain ownership of their share of the digester residue. Every household in the village would have its own underground fixed-dome digester. Those households not owning sufficient cattle would "borrow" dung from those households with sufficient cattle, and after digestion of the dung, would return dried or wet sludge to the households supplying the dung.

Data about the biogas yield per unit of raw materials inputs are inadequate for assessing the resource requirements for operating a digester. In part, this inadequacy is due to the methods of reporting data in much of the current literature, and the inherent variation in the quality of feedstock raw materials in different locations. For example, our estimate of the number of cattle needed to supply dung to produce sufficient biogas for the cooking requirements of a family of five varied by a factor of seven.

There were also major discrepancies in the literature concerning the fertilizer or soil conditioning value of digester sludge, in comparison with untreated wastes or commercial fertilizers. Deficiencies in experimental design and reporting have created uncertainty as to the validity of past reports about the potential improvement of the fertilizer value of animal wastes when they are anaerobically digested.

Biogas, although of low density and requiring special resources for distribution, is a fairly versatile fuel that can be used to power a number of task-performing technologies in rural areas. Cooking appears to be one of the most important potential applications for biogas, although it has been suggested that biogas might be used more appropriately for other purposes (Bhatia and Niamir 1979).

The use of dung-based biogas for cooking rather than dung cakes appears to be a theoretically more efficient use of the dung resource, and a given quantity of dung can perform more of this task via biogas than via direct combustion. However, this relationship remains to be documented with empirical measurements. The anaerobic digester route also appears to favor nitrogen conservation, however, as is true for using biogas as an alternative fuel, other tradeoffs must also be considered. For example, what are the differences in terms of labor required by a householder to perform various tasks before and after the introduction of an anaerobic digester?

In summary anaerobic digestion technologies have considerable possibilities for providing needs in rural areas of developing countries. However, there are many possible pitfalls and tradeoffs in introducing digesters among rural households and communities. The complexity of this technology could result in unforeseen problems that might jeopardize the success of digesters, causing their abandonment, or perhaps causing hardship among nonusers. Considerably more attention should be given to social, resource, and environmental studies to better understand the interactions of anaerobic digesters with rural areas. Inclusion of economics and shadow prices also could help in the evaluation of alternative anaerobic digestion technologies.

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NO. 74

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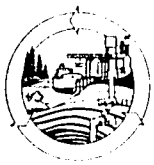
THE EAST-WEST RESOURCE SYSTEMS INSTITUTE is directed to the overall goal of understanding how nations can maintain adequate, equitable, and reliable access to resources. The institute consists of a broad study of three interrelated programs: Food Systems, Energy Systems, and Raw Materials Systems.

International research groups are collaborating with RSI staff to analyze and conduct research on these systems. A series of databases and information exchange facilities is now being developed to support their studies. On an interdisciplinary basis, the various teams will explore these problems stressing their interrelationships in both local and international terms in the Asian and Pacific region.

Food Systems conducts research on the institutional and policy aspects of improving food security in the Asia-Pacific region; examines the complex interactions of administrative, technological, and social issues involved in developing food systems in marginal areas; and explores alternate food systems with special emphasis on: food and the city, food systems based on water environments, and institutional and policy aspects of biological nitrogen fixation.

Energy Systems provides analyses of the vulnerabilities of nations to disruptions in the flow of fuels; collects and analyzes data on energy supply, demand, and flows, especially those in rural areas; evaluates alternative development policies on a variety of energy systems; and develops energy indexing methodologies and information exchange both within and among nations.



Raw Materials Systems is concerned with the identification and evaluation of policy and strategy options that will benefit nations from the exploration and development of their mineral resource potential. The main research areas are: mineral assessment for national planning, innovative government-transnational company arrangements, uncertainties in future commodity trade, and case histories of mineral projects.

THE EAST-WEST CENTER—officially known as the Center for Cultural and Technical Interchange Between East and West—is a national educational institution established in Hawaii by the U.S. Congress in 1960 to promote better relations and understanding between the United States and the nations of Asia and the Pacific through cooperative study, training, and research. The Center is administered by a public, nonprofit corporation whose international Board of Governors consists of distinguished scholars, business leaders, and public servants.

Each year more than 1,500 men and women from many nations and cultures participate in Center programs that seek cooperative solutions to problems of mutual consequence to East and West. Working with the Center's multidisciplinary and multicultural staff, participants include visiting scholars and researchers; leaders and professionals from the academic, government, and business communities; and graduate degree students, most of whom are enrolled at the University of Hawaii. For each Center participant from the United States, two participants are sought from the Asian and Pacific area.

Center programs are conducted by institutes addressing problems of communication, culture learning, environment and policy, population, and resource systems. A limited number of "open" grants are available to degree scholars and research fellows whose academic interests are not encompassed by institute programs.

The U.S. Congress provides basic funding for Center programs and a variety of awards to participants. Because of the cooperative nature of Center programs, financial support and cost-sharing are also provided by Asian and Pacific governments, regional agencies, private enterprise, and foundations. The Center is on land adjacent to and provided by the University of Hawaii.

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