MICHAEL PAUL STANGL Sludge Accumulation Rate in Pour-Flush Latrines

(Under the direction of John Briscoe, PhD.)

ABSTRACT

In 1983 the United Nations Development Programme Technology Advisory Group (UNDP/TAG) decided to sponsor a research project to investigate sludge accumulation rates in pour-flush waterseal latrines. A grant was given to the Department of Environmental Sciences and Engineering, School of Public Health, University of North Carolina at Chapel Hill, to conduct this project.

The project objectives were 1) to determine accumulation rates in a number of pour-flush latrines and 2) to try to explain how these rates had been affected by choice of pit design and local socio-cultural and environmental conditions.

A field study of pour-flush latrines was conducted in Patna and Singur, India. Sludge accumulation rates in thirty latrines were measured. Soil type, user population size, hydrogeological conditions and other factors thought to affect the accumulation rate were also evaluated. Specific tests were conducted to examine decomposition and drainage processes.

A large variation in sludge accumulation rates was observed. The "normal" range of accumulation rates was found to be between 0.010 and 0.060 m^3/capita-yr. The "average" accumulation rate was found to 0.025 m^3/capita-yr.

A theoretical model was developed to analyze the relationship between the sludge accumulation rate and design, socio-cultural and environmental factors. The model was designed to describe liquid loading and loss from a latrine.

Model evaluation indicated that the sludge accumulation rate is dependent on five factors - per capita loading rate, pit radius, amount of pit lining, soil hydraulic conductivity, and latrine age. Use of model accumulation rates led to better estimations of sludge accumulation than use of an "average" rate when the field data were examined.

Based on the conclusions drawn from the data analysis, recommendations have been made concerning latrine design in terms of 1) a practical guide for determination of pit capacity requirements, and 2) suggested changes in pit design in order to reduce sludge accumulation rates.

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PREFACE

A massive campaign to improve sanitation facilities in rural and urban communities across India is in progress. The pour-flush latrine has come to the forefront as the technology of choice in this effort. Pour-flush (PF) latrines are relatively inexpensive and are easy to construct and maintain. To date over 400,000 PF latrines have been built and many thousands more are planned.

Even though many pour-flush latrines are in use, much about their operation remains unknown. Latrine design guidelines have been mainly based on ad hoc observations. Limited research has been conducted to confirm these casual observations.

This report represents an attempt to document and explain differences in sludge accumulation rates based on a field study of pour-flush latrines in India. The objective is to develop information for improving procedures for designing pit latrines.

Many people and institutions have contributed to this research effort. First mention must go to Mr. A. K. Roy and the staff of UNDP/TAG India. Without their interest and support, the research on sludge accumulation rates would never have been started. The enthusiasm of UNDP/TAG India for the research was strong and much appreciated. Special mention must also be given to Mr. Geoffrey Read, Mr. Chris Schulz, and other members of UNDP/TAG Washington, who served as a liaison between UNDP/TAG India and the author.

The success of the field study phase of the research was dependent upon logistical support from Indian institutions. The author wishes to thank Mr. B. Patek, Director of Sulabh International, Patna, and Dr. K. J. Nath, Director, Public Health Engineering, All India Institute of Hygiene and Public Health, Calcutta, and their staffs for assistance in this area.

This report was produced as part of the requirements associated with the author's masters degree at the University of North Carolina at Chapel Hill. The author's work was guided by Dr. John Briscoe, Assistant Professor, in the Department of Environmental Sciences and Engineering, School of Public Health. The author wishes to thank Dr. Briscoe for his time and energy spent in lengthy discussions on the research. The author also would like to express his thanks to Dr. Briscoe for the confidence he showed in the author's work.

Assistance given by other members of the Department Environmental Sciences and Engineering staff is also acknowledged. Drs. F. Pfaender and J. Lamb served on the author's masters committee and in this capacity provided critical comments on the report. Their comments helped to clarify some of the main points made in the report. The informal assistance given by Dr. P. Singer and other faculty members is also appreciated.

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Michael P. Stangl

I. INTRODUCTION

1.1 Background

As part of its commitment to the United Nations International Drinking Water Supply and Sanitation Decade, the Government of India has adopted the goal of providing 80% of its urban population with hygienic sanitation facilities by the year 1991. Only 27% of the urban population (148 million people) had access to such facilities in 1981.

Initial cost estimates indicated that to provide conventional sewerage in urban areas would cost up to US$150 per capita (UNDP/TAG 1984). This level of investment was considered prohibitive as the annual per capita GNP in India in 1979 was US$190 (World Bank, 1981).

As a low cost alternative, the UNDP Technical Advisory Group's South Asia Office has promoted the use of pour-flush waterseal latrines. The initial cost of such a latrine for a typical family (5-10 persons) is between US$70 and 100. In addition to being low in cost, the pour flush latrine is relatively easy to install and maintain.

In a major policy shift, both state and central level government in India have adopted this on-site disposal technology as being an affordable and viable alternative to high cost sewerage. With TAG assistance, engineering and feasibility studies on the use of pour-flush latrines in 210 towns have been completed. Over 60,000 latrines have been constructed since the beginning of the UN Decade and many more are planned. Funding for sanitation projects utilizing pour-flush latrines has been provided by state and central government as well as by international organizations such as UNICEF and the World Bank.

1.2 Latrine Cost

For installation on the scale that is needed to meet India's goal, even the least expensive sanitation technology will require large amounts of investment. Every effort is being made to reduce the cost of pour-flush latrines to a minimum.

A breakdown of the costs of a typical latrine (for 5 users) as worked out by TAG South Asia Office is shown in Table 1.1. Approximately 15 percent of the cost is in the superstructure foundation, 15 percent in the flushing pan and trap, 50 percent in the leach pits and 20 percent in miscellaneous items.

1.3 Research Needed

One of the main determinants of the cost of a latrine is the expenditure required for the leaching pits. The costs of the leaching pits in turn depend on two factors: the pit capacity required, and the type of materials used to line the pit. The TAG South Asia office recommends the following equation for use in determining pit capacity requirements:

$$\text{Pit Capacity Required} = EF \times N \times PL$$

where:

EF = effective capacity factor (0.045 to 0.067 m^3/capita/yr)

N = user population size

PL = expected interval between pit emptying or closure

1.3.1 Sludge Accumulation Rate

The effective capacity factor suggested in the above equation is based upon the study of sludge accumulation rates in pour-flush latrines by TAG and a number of Indian research institutions. It represents the average rate of accumulation found in different investigations that have been conducted throughout India.

The results of the studies that have been undertaken to date are presented in Table 1.2. The variability in accumulation rates can be seen to be fairly small and it has been hypothesized that differences in the observed rates are due to differences in soil properties, water table conditions and other environmental factors. These hypotheses, however, have never been vigorously tested.

In light of the small variability of the observed accumulation rates at different sites, use of an average rate in pit design seems justified. However if the implications of even small differences in rates are fully considered (in terms of pit capacity requirements), the use of an average rate comes into question.

Two examples illustrate this point. If the lowest accumulation rate observed (0.037 m^3/capita/yr) is used to predict pit capacity requirements for a latrine designed for a five-member family, the pit size required turns out to be 0.56 m^3. If instead the largest value (0.066 m^3/capita/yr) is used, the pit size required is calculated to be 0.99 m^3. In these calculations a pit life of three years has been assumed.

How do these values compare to pit capacity requirements as predicted by using an effective capacity factor of 0.045 m^3/capita/yr (the TAG recommended value)? Using the same assumptions as before, standard pour-flush latrines built for use in the area where the ICMR study was conducted would be 31% oversized, while latrines built for use in the area where the AIIH&PH study was done would be 28% undersized.

1.4 Sludge Accumulation Rate (SAR) Project

Under the sponsorship of UNDP/TAG India a research program designed to study sludge accumulation rates in pour flush latrines was undertaken by the Department of

Environmental Sciences and Engineering, University of North Carolina at Chapel Hill.

1.4.1 Objectives

The objectives adopted for the sludge accumulation rate (SAR) project were:

1) to determine the sludge accumulation rates in thirty to forty-five operating pour-flush latrines.

2) to investigate the effect of socio-cultural, environmental and engineering parameters on rates of sludge accumulation; and

3) based on findings of the research done in association with Objectives 1 and 2, to develop a design equation that would provide better predictions of pit capacity requirements.

1.4.2 Funding

A total budget of $20,000 was allocated for the SAR project. In terms of project activities, 60% was allocated to research and development, and 40% to field work and data analysis.

1.4.3 Itinerary

The project was carried out in three phases.

Phase 1 (Chapel Hill, NC and Washington, DC, June-December 1983). A literature review was conducted of published and unpublished articles to identify socio-cultural, environmental and engineering parameters that could affect the rate of sludge accumulation in pour-flush latrines. Procedures and equipment were developed for the measurement of the parameters selected for study. Field testing of the procedures and equipment was conducted on pit latrines in rural North Carolina.

Phase 2 (India, January-May 1983). In collaboration with UNDP-TAG's South Asia office, a field study of pour-flush latrines was conducted at two different sites in India. One research site was in Patna, the capital of Bihar. Local support for the study at this site was provided by Sulabh International. The second research site was in Singur, a village 30 km northwest of Calcutta. Local support at this site was provided by the All India Institute of Hygiene and Public Health.

Phase 3 (Chapel Hill, NC, June 1984-October 1984). The final phase of the study was an analysis of the data from the field study phase of the project.

TABLE 1.1 Material and Labor Costs for the Construction of a Pour-flush Latrine for a Family of Five (Adapted from "Manual on the Design, Construction and Maintenance of Low-Cost Pour-flush Waterseal Latrines in India", TAG Technical Note Number 10).

ITEM	COST (US$)	PERCENTAGE OF TOTAL COST (%)
1. Foundation and plinth for superstructure		
a) Excavation	0.13	0.16
b) Cement concrete	1.61	2.03
c) Brickwork	7.24	9.15
d) Flooring	2.40	3.03
2. Flushing pan (materials and installation)	11.00	13.90
3. Twin leaching pits (materials and installation)	36.00	45.48
4. Miscellaneous		
a) Brick drain	7.80	9.85
b) Extra labor	2.70	3.41
c) Supervision costs	10.28	13.00
TOTAL	$79.16	100.00%

II. THEORY

2.1 Literature Review

A review of the sanitary engineering literature revealed that little published information was available on pit latrines. Most of the published studies have focused on the pollution aspects of latrine operation (IRCWD, 1980). No published material was found on sludge accumulation rates and how these rates might be affected by different socio-cultural and environmental conditions.

In light of this lack of information on latrines, it was decided that the best approach to designing an experiment to study accumulation rates was to have a thorough knowledge of the basic scientific principles that would govern the processes by which material accumulated in a pit.

2.2 Accumulation Processes

There are only two ways material can leave a latrine once it is deposited in a pit. One way is through decomposition and the other is through drainage.

2.2.1 Decomposition Process

A portion of the organic matter put into a pit latrine will be biologically degraded. Microorganisms will break

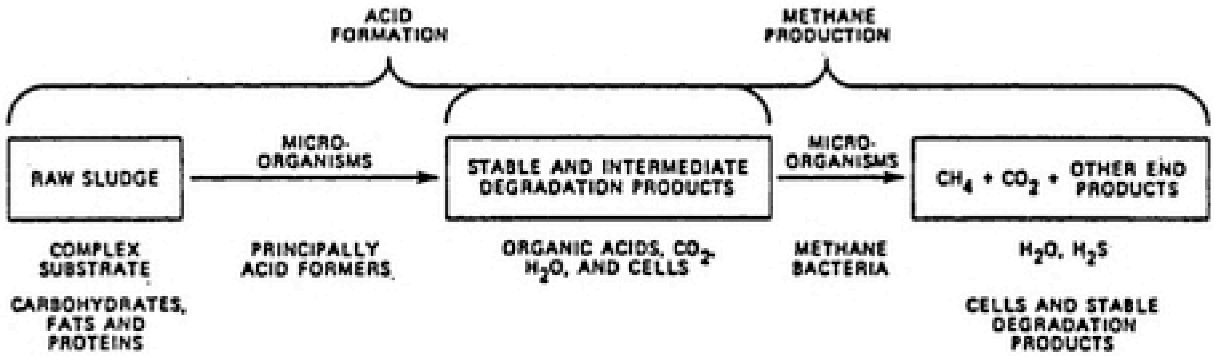


FIGURE 2.1

SUMMARY OF THE ANAEROBIC DIGESTION PROCESS down the complex organic compounds found in feces, urine and other wastes into simpler forms that can be used in cell metabolism and synthesis. While the organic matter that is converted to biomass will not affect the amount of sludge in a pit latrine, it is possible that some sludge reduction will occur due to the loss of liquid and gaseous by-products of cell metabolism.

It is expected that because of the relatively high concentration of organic matter in undiluted human wastes and because air is not artificially introduced into the sludge in a pit latrine, the primary type of microbial activity that will occur in a latrine will be anaerobic digestion.

Process Dynamics. Anaerobic digestion has been found to be a two-step process (McCarty, 1964). This is illustrated in Figure 2-1. In the first step, complex organic molecules of carbohydrates, proteins, and lipids are hydrolyzed to form simple alcohols and volatile acids. This step is often referred to as the liquefaction or acid formation phase of digestion.

The second step of digestion is gasification. In this step the alcohols and volatile acids formed in the liquefaction phase of digestion are converted to carbon dioxide, methane and other gaseous substances.

The bacteria responsible for the two steps - liquefaction and gasification - are different.

TABLE 2-1 BACTERIA OF ANAEROBIC DIGESTION (Metcalf and Eddy, 1979)

A. Non-Methanogenic (facultative and obligate anaerobes)

1. Clostridium spp.
2. Peptococcus anaerobus
3. Bifidobacterium spp.
4. Desulphovibrio spp.
5. Carynebacterium spp.
6. Lactobacillus
7. Actinomyces
8. Staphylococcus
9. Escherichia coli

B. Methanogenic (strict anaerobes)

1. Methanobacterium
2. Methanobacillus
3. Methanococcus
4. Methanosarcina

The microorganisms involved in the first step include both facultative and obligative anaerobes (see Table 2-1). They are highly adaptive and can function over a wide range of environmental conditions.

The methanogenic bacteria are involved in the transformation of the simple alcohols and volatile acids to methane and carbon dioxide gases. They are strict anaerobes. They cannot function in the presence of oxygen. In contrast to the bacteria responsible for liquefaction, the methanogenic bacteria are known for their sensitivity to environmental conditions.

In reference to the rate of digestion, it is the methanogenic bacteria which are critical (McCarty, 1964). Besides being the most sensitive to environmental conditions, they also have the slowest rate of metabolism. The rate-limiting or slowest step in digestion is therefore gasification.

ANAEROBIC DIGESTION PARAMETERS

Methanogenic bacteria are best known for their sensitivity to pH and temperature. Recent studies have also considered how these bacteria are affected by factors such as salt toxicity and composition. A general overview of how different factors are known to affect the anaerobic digestion process is provided in Table 2.2.A. A complete review of the literature on the anaerobic digestion process and associated parameters is provided in Appendix C.

2.2.2 Drainage Process

It can be assumed that solid materials will make up only 5-10% of the wastes that are put into a typical latrine (see Table 2.2.B). What happens to the remaining 90-95% of the wastes put into a latrine? The only way that this fraction (the liquid component) of the wastes can be reduced is through the process of drainage.

TABLE 2.2.A Anaerobic Digestion Parameters

Parameter	Operational Range
1. pH	6.6 to 7.6
2. Temperature	10^{o} to $60^{o}C$
3. C/N Ratio	16 to 35
4. Salt Toxicity	
a. Calcium	100 to 8,000 mg/l
b. Magnesium	75 to 3,000 mg/l
c. Potassium	200 to 12,000 mg/l
d. Sodium	100 to 8,000 mg/l

TABLE 2.2.B Solids Content of Night Soil (Feachem, et al, 1980)*

1. Faeces	
Total weight	250 gm
Moisture content	80 %
Solids input	50 gm
2. Urine	
Total weight	1200 gm
Moisture content	4 %
Solids input	48 gm
3. Anal cleansing	
Water	350 gm
4. Combined Night Soil	
Total weight	1800 gm
Moisture content	5 %
Solids input	98 gm

*Estimated per capita production

Process Dynamics

A. FORCES CAUSING LIQUID FLOW

Water movement through the soil can be explained in terms of energy levels (EPA, 1978). Water at any point in the soil has a certain amount of energy associated with it. Water will flow in the direction of lowest energy. That is, water will move from one position in the soil to another only if the energy level of the water at the second point is lower than the energy level of the water at its initial position.

The energy level or status of water at a position is referred to as its moisture potential (M). A moisture potential gradient indicates a difference in the energy level of water.

The moisture potential has two components. A portion of the moisture potential arises out of the forces of gravity acting on the water molecules. This creates what is known as a gravitational potential (h). The other component of the moisture potential is the matric potential (m). Inter- and intra-molecular forces are responsible for the creation of the matric potential. The sum of the water's gravitational and matric potential equals its moisture potential.

1) Gravitational Potential - The gravitational potential of water differs in reference to its relative vertical position. The force of gravity acts toward the center of

the earth. The gravitational potential gradient which exists between any two points in the soil is equal to,

Eqn 2.1

$$\text{GRAVITATIONAL POTENTIAL GRADIENT } (h) = (m)(g)(z)$$

where

m = mass of water (gm)

g = gravitational constant (cm/sec^2)

z = vertical distance between two points (cm)

A common convention is to consider the gravitational potential in terms of unit weight. The gravitational potential gradient on this basis is measured in units of length (cm).

2) Matric Potential - An attraction exists between water molecules and the surface molecules of the soil particles. This attraction is caused by adhesive forces. Water molecules are pulled in the direction of dry surface areas by these forces. These water molecules in turn pull on adjacent water molecules. This is due to intermolecular cohesive forces. The combination of adhesive and cohesive forces give rise to matric potential.

The amount of matric potential that is present in a given situation is a function of two factors - soil moisture content and type. As a general rule, the matric potential increases with decreasing moisture content (see Figure 2-2). This effect is most pronounced in sands and least seen in clays. Unlike gravitational potential, the matric potential cannot be determined through use of a sample equation based on physical constants and measureable quantities. Usually the matric potential of a soil is determined empirically. (A more detailed discussion of matric potential and its relationship to soil moisture content and type is provided in Appendix C.)

B. RESISTANCE OF SOIL TO GROUNDWATER FLOW

Just as important as the forces which cause water to move through the soil, are the resistances the flow encounters in its path. The resistance of the soil to flow can affect the amount and the direction of water movement.

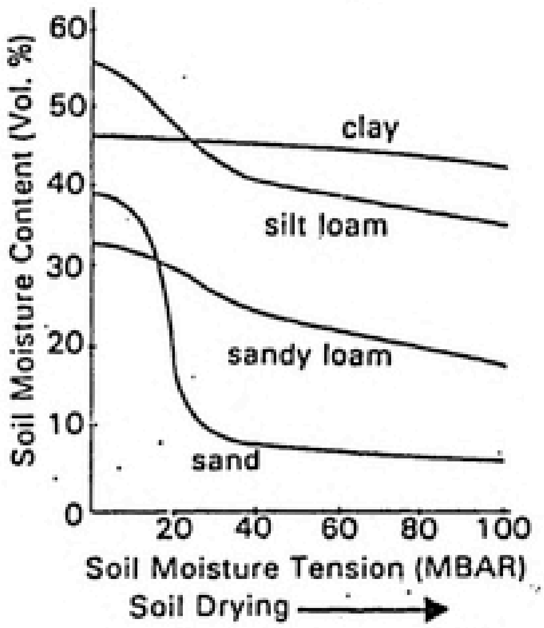
The traditional approach to accounting for a soil's resistance to water movement through it, has been to speak of the soil's ability to transmit water. To this end the concept of the hydraulic conductivity (k) has been developed.

The hydraulic conductivity differs in soils for a number of reasons. The hydraulic conductivity of a particular soil is a function of several physical factors. The porosity, particle size and distribution, shape of particles and arrangement all play a role in determining a soil's hydraulic conductivity (Todd, 1980). Values for some of these factors for soils are given in Tables 2.3 and 2.4.

Laboratory studies have been conducted in an effort to develop a means of predicting the hydraulic conductivity based upon one or more of the factors (porosity, etc.)

FIGURE 2.2

SOIL MOISTURE RETENTION FOR FOUR DIFFERENT SOIL TEXTURES



Matric Potential

The relationship between soil moisture content and matric potential (as measured in millibars of tension, Bouma, et al., 1972)

(Todd, 1980). The most successful studies in this area indicate a relationship can be shown between conductivity and particle diameter in the form of,

<u>Eqn 2.2</u>

$$k = f_s f \quad d^2$$

where

k = hydraulic conductivity (cm/day)

f_s = grain or pore shape factor

f = porosity factor

d = characteristic grain diameter

Extension of the laboratory research to suggest field measurements to predict hydraulic conductivity has been limited. This is due to the large number of factors which influence a soil's conductivity. It has been found very difficult to replicate in-situ soil conditions in a laboratory.

In general, instead of trying to predict hydraulic conductivity from the soil characteristics, it has been recommended k be measured in-situ when possible. Several methods are available in the literature for in-situ measurement of the hydraulic conductivity of a soil (Black, 1965).

C. DESCRIPTIVE EQUATION

In 1856, Henry Darcy developed an expression describing the flow of water through porous media (Todd, 1980). The expression takes into account the forces causing water to

Material	Particle Size, mm
Clay	<0.004
Silt	0.004–0.062
Very fine sand	0.062–0.125
Fine sand	0.125–0.25
Medium sand	0.25–0.5
Coarse sand	0.5–1.0
Very coarse sand	1.0–2.0
Very fine gravel	2.0–4.0
Fine gravel	4.0–8.0
Medium gravel	8.0–16.0
Coarse gravel	16.0–32.0
Very coarse gravel	32.0–64.0

Table 2.3
Soil classification based on particle size
(Morris and Johnson, 1967)

Material	Porosity, Percent	Material	Porosity, Percent
Gravel, coarse	28*	Loess	49
Gravel, medium	32*	Peat	92
Gravel, fine	34*	Schist	38
Sand, coarse	39	Siltstone	35
Sand, medium	39	Claystone	43
Sand, fine	43	Shale	6
Silt	46	Till, predominantly silt	34
Clay	42	Till, predominantly sand	31
Sandstone, fine-grained	33	Tuff	41
Sandstone, medium-grained	37	Basalt	17
Limestone	30	Gabbro, weathered	43
Dolomite	26	Granite, weathered	45
Dune sand	45		

*These values are for repacked samples; all others are undisturbed.

Table 2.4
Representative values of porosity
(Morris and Johnson, 1967)

move and the ability of a soil to transmit this water. Equation 2.3 has become known as Darcy's Law,

Eqn 2.3

$$Q = -k\ A\ (dH/dz)$$

where,

Q = volumetric flow rate (cm^3/day)

k = hydraulic conductivity (cm/day)

A = flow area (cm^2)

dH/dz = hydraulic gradient (dimensionless)

The negative sign indicates that water will flow in the direction of decreasing hydraulic gradient.

Darcy's law was initially applied to flow of water through saturated soil. In such a case the matric potential is equal to zero and the hydraulic gradient is due only to gravitational potential. With slight modification Darcy's law can be used to describe flow in unsaturated soils as well,

Eqn 2.4

$$Q = -k\ A\ (dM/dz)$$

where,

dM/dz = moisture potential gradient

In this interpretation of Darcy's law, the hydraulic gradient in Eqn 2.3 is replaced by the moisture potential. The moisture potential as was shown earlier consists of both the gravitational and matric potentials.

Darcy's law ties together the concepts of a force or forces pushing water through a soil and the resistance encountered against this flow. By evaluating the parameters on the right-hand side of Eqn 2.4, it is possible to predict the rate of drainage of water through soil.

D. SPECIAL CONSIDERATIONS

Clogging

In situations similar to that which is expected to be found in a pit latrine a phenomenon known as clogging occurs. Clogging is the process of a soil losing its ability to transmit water when saturated for long periods of time.

The mechanism(s) leading to a soil becoming clogged have not been well described. The phenomenon is thought to be the result of several physical, chemical, and biological factors. Most of the research that has been conducted on clogging has been associated with trying to find ways of improving septic tank operation.

Clogging Mechanism

Clogging is usually thought of as a two or three step process (Kristian, 1981). This is illustrated in Figure 2.3. The first decrease in the soil absorptive capacity comes as air is entrapped in the soil pores when a soil is first loaded with liquid. This air is quickly used up by

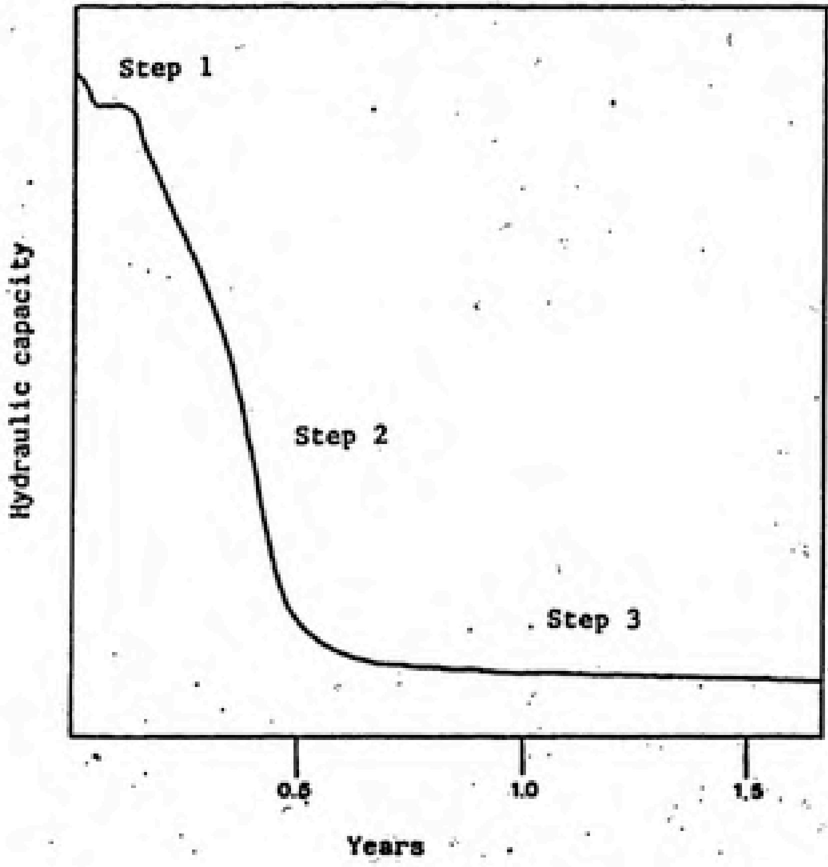


Figure 2.3 Loss of hydraulic capacity with time (Kristian, 1981)

aerobic organisms and the soil environment turns anaerobic (McGauhey, 1964).

The change from aerobic to anaerobic conditions signals the start of the second phase of clogging. During this phase a gradual decrease in the soil's hydraulic conductivity occurs due to two factors. One is the formation of a biological slime in and on the soil's pores. This slime has been found to contain a high concentration of polysaccharides and polyuronides (Mitchell and Nevo, 1964) indicating that rather than actual cellular material, this slime represents waste products of microbiological activity.

The second factor contributing to the loss of hydraulic conductivity is thought to be chemical in nature (McGauhey, 1964). Under anaerobic conditions soluble sulfide compounds have a tendency to precipitate from solution. Such precipitates, especially iron sulfide (FeS), have been found in soils that were clogged.

The third and final phase in clogging is when an equilibrium is reached. Complete loss of soil hydraulic conductivity seldom occurs with some pore space always remaining open (Kristiansen, 1981).

Sludge Dewaterability

In assessing loss of liquid from a pit latrine, a second phenomenon that has to be considered is dewaterability, which describes the the ability of a sludge to give up water. Most sludges do not do this easily.

There are two different ways of looking at the dewaterability of sludge. One view is to consider that a sludge somehow "holds onto" its water. This has been the traditional approach in the sanitary engineering field (Valdius, 1979). This has led to development of a test to determine how much negative pressure is required to remove water from a sludge. Typical values for the specific resistance of a sludge are shown in Table 2.5 (EPA, 1974).

A second way of considering the dewaterability is to consider that the sludge represents a compressible type of soil. If this is done, then the same nomenclature and concepts used in soil mechanics can be applied to sludge dewaterability. This approach to explaining the mechanism of sludge dewaterability is fairly new and still being tested.

It is difficult to predict what influence the dewaterability of the sludge in a latrine will have on the accumulation rate. Most of the work that has been done on dewaterability has focused on the use of a vacuum device to remove water from sludge. In the case of a latrine, the only driving force is gravity. It is known that for any sludge, its dewaterability can be affected by many factors, including particle surface charge and hydration, particle size, compressibility, sludge temperature, ratio of volatile solids to fixed solids, sludge pH, and septicity. How the

Table 2.5

SPECIFIC RESISTANCE OF VARIOUS TYPE SLUDGES
(EPA, 1974)

Type Sludge	Specific Resistance (sec^2/g)
Raw	$10\text{-}30 \times 10^9$
Raw (coagulated)	$3\text{-}10 \times 10^7$
Digested	$3\text{-}30 \times 10^9$
Digested (coagulated)	$2\text{-}20 \times 10^7$
Activated	$4\text{-}12 \times 10^9$

dewaterability of a particular sludge will be affected by one or more of these parameters is presently largely unknown.

III. FIELD STUDY METHODOLOGY

3.1 Site Selection

The research sites of Patna and Singur were selected by the TAG South Asia office. Background information on the research sites is provided in Table 3.1. Latrine types constructed in Patna and Singur are shown in Figure 3.1.

3.2 Work Schedule

Approximately six weeks was spent at each of the research sites. Four weeks of this time was devoted to the study of individual latrines and two weeks to assessment of local soil and hydrogeological conditions.

3.3 Latrine Examinations

A protocol was developed for the examination of each latrine over a two day period. The procedures followed on each day are discussed in the same order as they were performed.

3.3.1 Description of Pit Contents

A plexiglas sampling tube was used to take a vertical section of the material in a pit. This tube was lowered gently into the pit contents until the base of the pit was reached. A vacuum was then created in the upper portion of

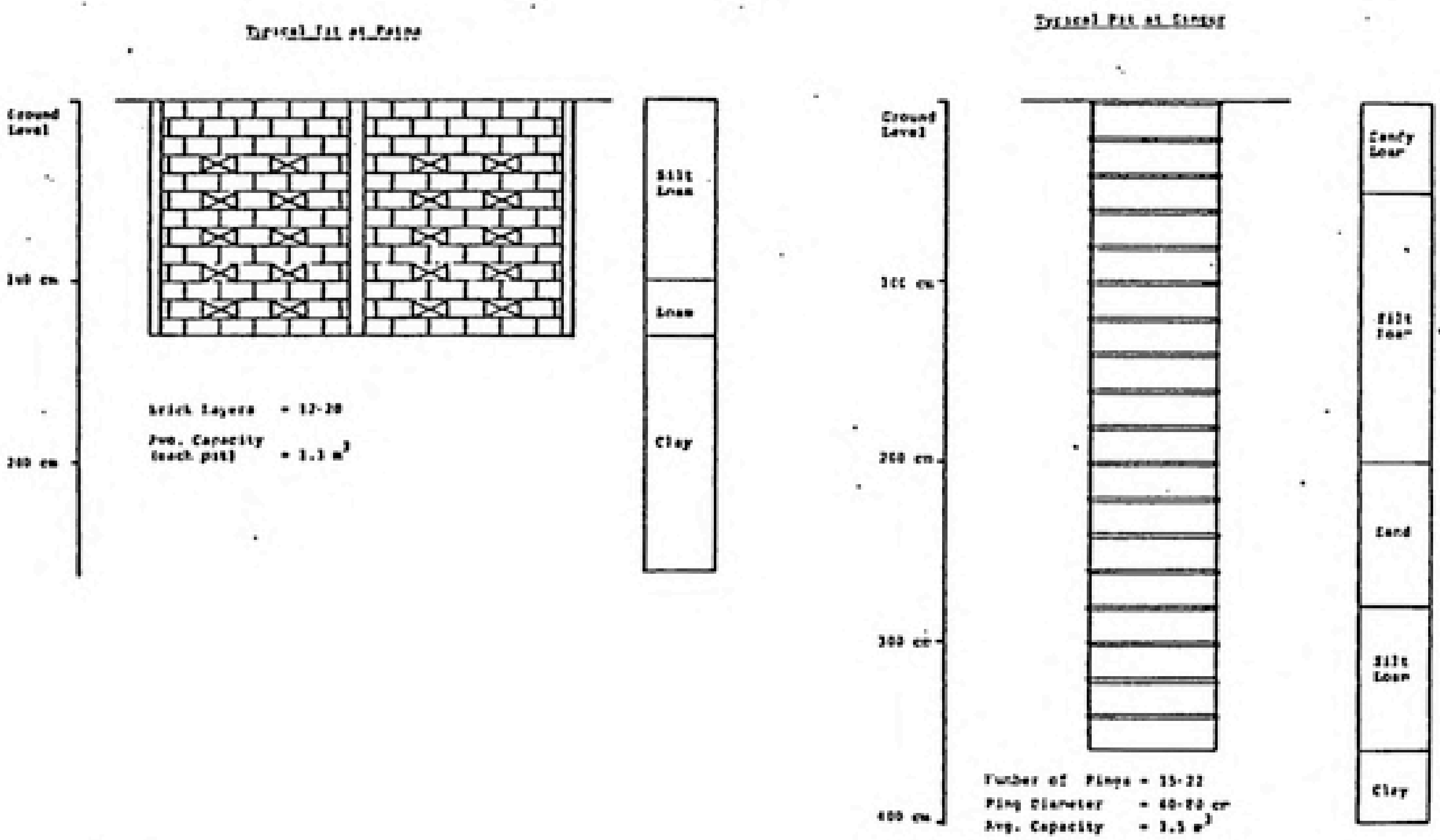


Figure 3.1. Pit Designs at Patna and Singur

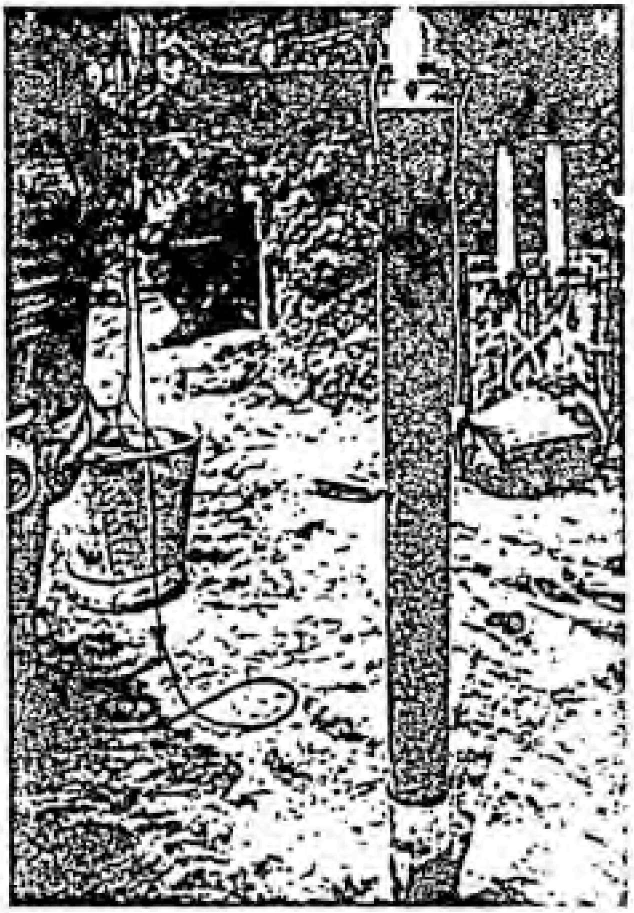


Figure 3.2
Sample of Pit Contents

Figure 3.3
Gas
Production
Test in Progress

the tube with a hand pump. While maintaining the vacuum, the sampling tube was lifted out of the pit and sealed. A sketch of the sample was made to record the different layers (scum, supernatant and sludge) seen in the pit.

3.3.2 Gas Production Test

The sampling tube (with sample) was connected to a gas manometer. The cumulative amount of gas produced was then measured every thirty minutes for a four to six hour period. During the test, the sampling tube was kept in the pit to maintain a constant temperature in the sample. The accuracy of the gas volume measurement was ± 2.0 cc.

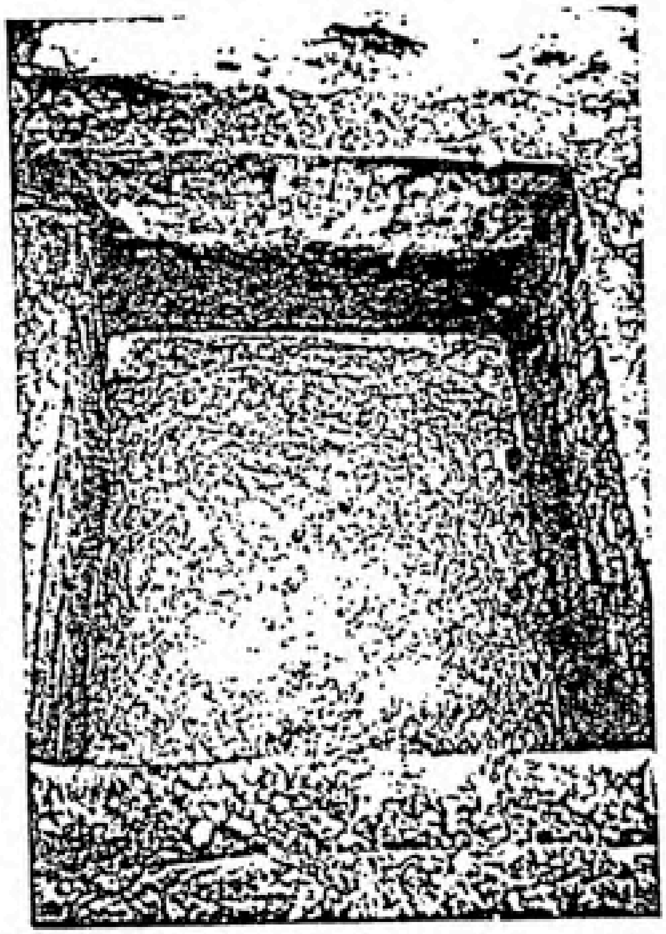
3.3.3 In-situ Measurements of Sludge Characteristics

Three characteristics of the pit contents were measured in-situ with portable field equipment. These were pH, temperature, and dissolved oxygen concentration. All measurements were made at mid-depth of the pit contents. The pH was determined within ± 0.1 pH units. The dissolved oxygen concentration and temperature were determined to within ± 0.01 mg/l and $\pm 0.1^{\circ}C$, respectively.

3.3.4 Pit Description

A rough sketch of the pit under study was made. This sketch included the type of lining and the dimensions of the pit as well as a record of the level of sludge in the pit at the time of inspection.

Figure 3.4



Typical Pit in Patna

3.3.5 Sample Collection for Laboratory Analysis

To achieve a representative sample, material was drawn from three different points in a pit. The procedure used to take these samples was the same as that previously described. The three samples of sludge were mixed in a bucket and a portion of the homogeneous material that resulted from this mixing was then taken for analysis. A list of the constituents analyzed in the laboratory is provided in Table 3.2. (In Patna, the laboratory analysis was conducted by the Public Health Institute of Bihar, and, in Singur, by the All India Institute of Hygiene and Public Health in Calcutta.)

Figure 3.5
Typical Pit Latrine
in Singur

Figure 3.6
Drainage Test in Progress

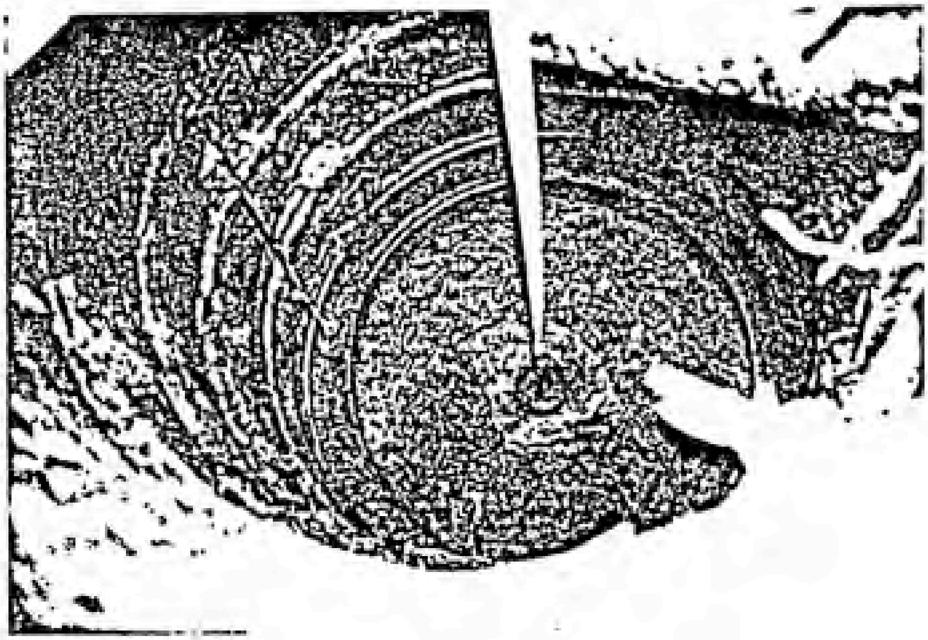


Table 3.2 Laboratory Analysis of Pit Contents

1. Total solids (at 105°C)
2. Volatile solids (at 550°C)
3. Fixed solids (at 550°C)
4. Chemical oxygen demand
5. Nitrogen (organic and ammonia)
6. Phosphorus (total)
7. Chloride (total)
8. Specific gravity

3.3.6 Drainage Rate Measurement

The drainage rate from the pit was determined by monitoring the drop in the surface level of the pit contents throughout a period during which the pit was not in use. In shallow pits (0-150 cm) a meter stick was used to measure the pit content level relative to ground level. In deep pits (>150 cm) it was often not possible to reach the pit content level with a meter stick. In this case, a float connected to an aluminum rod was placed into the pit. The rod extended from the float to the top of the pit. As the surface level changed, the float and rod would drop. The change in the position of the rod through time was used to measure the drainage rate. The cumulative decrease in the surface level was appraised every thirty minutes for a period of seven to nine hours.

3.3.7 User Survey

A survey was conducted to determine how the pit latrine was used by its owners. The head of the household was approached by the project team and asked to spend thirty to sixty minutes answering a questionnaire. To verify the answers given by the head of the household, a second household member was also interviewed when possible.

The user survey was designed to address three issues:

1) demographic data - number, age, sex, and occupation of people who had used the latrine over an extended period (one month or more);

2) pit latrine history - dates of construction and emptying, and record of any modifications to the pit; and

3) maintenance practices - substances used in cleaning, amounts and frequency of application.

3.3.8 Soil Log

A site within five meters of the pit was chosen for sampling. Using a hand auger with a two inch bit, soil samples were taken every fifty centimeters from ground level to a depth of one meter below the pit base. A record was made of soil color, moisture and texture. The groundwater level, if encountered, was noted. Soil color was identified according to the Munsell Color Code. A rough estimate was made of soil moisture by the feel of the soil. The soil was classified into one of three categories - dry, moist and saturated. Soil texture (clay, silt, sand) was analyzed by the touch method.

3.4 Area Tests

After the pit latrine examinations were completed, assessment of soil properties at the study site was conducted. This testing was necessary because 1) there was a need to confirm the soil type analysis that had been done in association with the soil logs; and 2) measurement of the soil's hydraulic conductivity had not yet been done. A description of the methods and materials used in these analyses follows.

3.4.1 Soil Type (Particle Size Analysis)

Soil samples were taken at three different locations at each research site. A complete vertical profile was taken at each location (samples taken at 50 cm intervals up to depth of 250 cm at Patna, and up to a depth of 400 cm in Singur). A particle size analysis on each of the samples taken was performed. ASTM Standard No. 422 was followed in this analysis.

3.4.2 Soil Hydraulic Conductivity Assessment

As with the soil samples, testing of the hydraulic conductivity was conducted at three different locations at each site. The hydraulic conductivity of each soil stratum, as identified in the soil type analysis, was measured.

A modified version of the Inversed Auger Hole Method (Kessler, 1974) was followed in measurement of hydraulic conductivities. This method is very simple: A hole is bored into the soil stratum to be tested, filled with water and then the rate of water loss measured. In the field study, the hole was lined with a perforated PVC pipe to prevent hole collapse. The method as described in the literature does not include the use of such a pipe.

3.5 Work Summary

A total of thirty (equally divided between Patna and Singur) latrines were examined during the twelve-week duration of the field study. A list of the data gathered on the individual latrines and for each research site is given in Table 3.2.

TABLE 3.1 Site Description

	PATNA	SINGUR
Pit Design		
Number of pits	double	single
Shape	rectangular	circular
Capacity	1-2 m^3	1-2 m^3
Pit lining	honey-combed brick	tile rings
Depth	1-2 m	3-4 m
Environmental Conditions		
Location	Bihar	West Bengal
Rainfall (annual)	1100 mm	1582 mm
Temperature (avg. monthly)	17-32°C	20-31°C
Soil type	silty loam mixed with sand layers	sandy loam
Maximum ground water level	Within 1 m of surface in monsoon	unknown
Cultural Conditions		
Community setting	urban	rural
User population		
- Predominant religion	Sikhism	Hinduism
- Employment	service, small business	farming
- Number of users per latrine	3-7	8-10
Housing		
- Type	single family units in government housing scheme	multifamily compounds
- Water supply	in-house connection with municipal waterworks	village wells and rainwater catchment ponds
- Electricity	present	absent

TABLE 3.3 A Summary of Data Gathered on Individual Latrines and at Each Research Site

INDIVIDUAL LATRINE EXAMINATIONS

Pit Design
- Shape
- Width and length (rectangular pits)
- Diameter (circular pits)
- Depth
- Lining (type and amount)

Pit Conditions
- Age
- Number
- Capacity filled
- Soil type

Sludge Characteristics
- Total solids
- Volatile solids
- Chemical oxygen demand
- Nitrogen (ammonia and organic)
- Phosphorus (total as P_2O_5)
- Chloride (total)
- pH
- Temperature
- Specific gravity

Specific Tests
- Gas production rate
- In-situ drainage rate

Latrine History
- Date of construction
- Date(s) pit filled
- Date(s) pit emptied

Demographic Data
- Present number of users
- Past number of users
- Age of users
- Sex of users
- Occupation of users

(TABLE 3.3 continued)

AREA INFORMATION

Soil Properties
- Hydraulic conductivity
- Particle size analysis
- Bulk density
- Moisture
- Cation exchange capacity
- Color identification (Munsell Color Guide)

Hydrological Conditions
- Present groundwater level
- Annual fluctuation (high and low)

Climatic Conditions (Five year period)
- Temperature (monthly average)
- Rainfall (monthly average)

IV. RESULTS

4.1 Sludge Accumulation Rates (SAR)

The overall sludge accumulation rates observed in the Patna latrines are presented in Table 4.1. These rates are referred to as "overall" rates because they are based upon sludge accumulation (in both pits) and person-years of usage over the entire period of latrine operation.

The range of SAR values seen in the Patna latrines was between 0.016 and 0.055 m^3/person-year. The overall SAR mean was 0.034 m^3/person-year, with a standard deviation of $\pm$0.012. The median value was 0.031 m^3/person-year.

Latrines 4, 11, and 12 were not considered to be "normal" latrines in terms of either their design and/or operation. Because of this, their SAR values were not included in the calculation of the rate statistics.

There were different specific reasons for not considering the results from Latrines 4, 11, and 12. A water tap drain ran close to Latrine 4. At the time of the study, water was not entering the latrine's pit from the drain but it appeared that this had happened in the past. An unusually high accumulation rate was estimated to have occurred in the latrine and this was taken to be confirmation of the suspicion that drainage water had entered the latrine.

The data from Latrine 11 was excluded from the rate statistics because there was a large difference between the design of the leaching pits of Latrine 11 and that seen in the leaching of the other Patna latrines. The leaching pits of Latrine 11 were lined with solid brick and were circular in shape. All of the other latrines in Patna were built with rectangular pits lined with honeycombed brick.

Each Patna latrine was built with two pits, and, in normal use, one pit was to be completely filled before switching to the second pit. In Latrine 12, both pits of the latrine had been used but not as called for in the latrine design. In this latrine the owner had decided to switch pits before the first pit was completely filled. The amount of sludge present in the older pit could be measured but it was impossible to judge how much volume reduction had occurred due to the loss of liquid and the settling of the pit contents since the time the pit was last used. The accumulation rate shown in Table 4.1 is based upon the sludge volume found in the older pit at the time of the study.

TABLE 4.1 Patna Sludge Accumulation Rates (overall)

LATRINE NUMBER	PIT CAPACITY FILLED (M^3)	AMOUNT OF USAGE (PERSON-YEARS)	ACCUMULATION RATE (M^3/PERS-YR)
1	2.367	57.2	0.041
2	2.934	116.1	0.025
3	1.275	27.9	0.045
4	1.735	20.3	[0.085]
5	1.236	33.4	0.037
6	1.641	101.9	0.016
7	2.131	67.5	0.031
8	1.103	23.1	0.047
9	1.096	33.7	0.032
10	1.099	55.6	0.019
11	0.770	39.1	[0.019]
12	1.550	124.9	[0.012]
13	3.237	121.9	0.026
14	0.465	8.4	0.055
15	4.064	140.3	0.028

Rate Statistics	Mean	0.034
	Std. deviation	0.012
	Median	0.031

Rates in [] not included in statistical analysis. See discussion of results.

4.1.2 Patna Latrines ("Old" and "Operating" Pit Rates)

In addition to looking at overall rates, individual pit SAR rates in the Patna latrines were examined (see Tables 4.2 and 4.3). Pits were labeled "operating" or "old" depending on their status at the time of the study. "Operating" pits were defined as the pits in current use, while "old" pits were defined as pits which had become full and been put out of service. At the time the study was conducted, one pit had been filled and the second was being used in most of the Patna latrines.

The range of SAR "operating" pit rates was from 0.013 and 0.184 m^3/person-year. The "operating SAR mean was calculated to be 0.047 m^3/person-year with a standard deviation of ±0.027. The median value was slightly below the mean, at 0.043 m^3/person-year.

The SAR values observed in the "old" pits ranged from 0.013 to 0.052 m^3/person-year. The "old" pit SAR mean was found to be 0.026 m^3/person-year with a standard deviation of 0.017. The median SAR for the "old" pits was determined to be 0.018 m^3/person-year.

Because of construction mistakes and/or lack of information, "old" and "operating" rates could not be determined in five of the twelve "good" Patna latrines. In some of the latrines (nos. 5, 13, and 15), the leaching pits had been interconnected either through the pit wall or with a pipe. In this case it was not possible to distinguish "old from "operating" pits because fresh excreta was flowing

TABLE 4.2 Patna Sludge Accumulation Rates (in operating pits)

LATRINE NUMBER	PIT CAPACITY FILLED (M^3)	AMOUNT OF USAGE (PERSON-YEARS)	SAR(MSD) (M^3/PERS-YR)
1	1.053	32.1	0.032
2	0.794	7.6	0.104
6	0.521	15.7	0.033
7	0.886	17.5	0.050
8	0.531	12.3	0.043
10	0.520	12.0	0.043
12	0.775	56.9	0.013
14	0.465	8.4	0.055

Rate Statistics	Mean	0.047
	Std. deviation	0.027
	Median	0.043

TABLE 4.3 Patna Sludge Accumulation Rates (in old pits)

LATRINE NUMBER		PIT CAPACITY FILLED (M^3)	AMOUNT OF USAGE (PERSON-YEARS)	ACCUMULATION RATE (M^3/PERS-YR)
1		1.314	25.1	0.052
2	A	1.070	57.1	0.018
	B	1.070	51.4	0.020
6	A	0.560	41.2	0.013
	B	0.560	45.0	0.012
7		1.245	50.0	0.024
8		0.572	10.8	0.052
10		0.579	43.6	0.013
12		n/a	n/a	n/a
14		n/a	n/a	n/a

Rate Statistics	Mean	0.026
	Std. deviation	0.017
	Median	0.018

into both pits. In Latrines 3 and 9, the owners were unsure of the date when one pit had become full and the second started.

4.1.3 Singur (Overall Rates)

There was only one set of accumulation rates for the Singur latrines as these latrines were constructed with only one pit. The accumulation rates for the Singur latrines represent the total volume of sludge accumulation divided by the number of person-years of usage over the entire period of a latrine operation.

The overall sludge accumulation rates determined for the Singur latrines are presented in Table 4.4. The range of SAR values was from 0.011 to 0.057 m^3/person-year. The mean SAR was 0.029 m^3/person-year with a standard deviation of $\pm$0.017. The median SAR was found to be 0.022 m^3/person-year.

The sludge accumulation rates determined for Latrines 9, 12, and 14 were not considered to be representative and have not been included in the calculation of the rate statistics. There are different reasons for rejection of the data. In Latrine 9, the drainage pipe from the squatting plate to the pit had broken and, hence, every time the latrine was flushed, both excreta and earth were washed into the pit.

In the case of Latrine 12, it was not possible to determine the depth of the pit. Two different measurements of the pit depth were recorded, neither of which seemed

TABLE 4.4 Singur Sludge Accumulation Rates (overall)

LATRINE NUMBER	PIT CAPACITY FILLED (M^3)	AMOUNT OF USAGE (PERSON-YEARS)	ACCUMULATION RATE (M^3/PERS-YR)
1	0.367	16.0	0.022
2	0.676	16.0	0.042
3	0.903	15.6	0.057
4	0.233	20.9	0.011
5	0.834	71.0	0.011
6	0.693	37.7	0.018
7	0.795	39.4	0.020
8	1.071	19.7	0.054
9	0.419	29.0	[0.052]
10	0.396	18.4	0.021
11	1.465	29.8	0.049
12	1.684	19.5	[0.086]
13	1.789	79.7	0.022
14	0.347	55.3	[0.006]
15	0.454	22.0	0.020

Rate Statistics	Mean	0.029
	Std. deviation	0.017
	Median	0.022

Rates in [] not included in statistical analysis. See discussion of results.

accurate when accumulation rates were calculated based on their values.

An extremely low accumulation rate was found in Latrine 14. No clear explanation could be found for the low SAR value and it has been rejected mainly due to the large difference between its value and the SAR mean.

4.1.4 Experimental Error in SAR Value Measurements

There were three factors used to determine the sludge accumulation rate in a given latrine. These were 1) the volume of accumulated sludge, 2) the number of people using the latrine on a regular basis, and 3) the time or period of latrine use by these people. The latter two factors were multiplied together to provide the amount of latrine usage (person-years).

Sludge volume error

The precision in the measurement of sludge accumulation in a pit was taken to be $\pm$ 2.5 cm in any one direction. For example, the volume of sludge in Patna Latrine 7 was determined to be 0.886 m^3. This volume was based upon a pit width, and length of 87 and 98 cm, respectively. The sludge thickness was measured to be 104 cm. Within the degree of precision used in the measuring the various factors, the actual volume could have been anywhere between 0.819 and 0.958 m^3.

Latrine usage error

Unlike the measurement of sludge accumulation, which could be based upon some sort of objective standard, the amount of latrine usage had to be determined with a user survey which by its nature was a subjective instrument. To account for possible experimental error in the estimation of the amount of latrine usage it was assumed that the greater the age of a latrine, the greater the chance of obtaining inaccurate user information. With this in mind, a progressive scale of error with age was set up. In this system, the amount of usage as reported by the latrine owners was assumed to be off by 10%, 20%, and 30% in latrines which had been in operation from 0 to 2 years, 2 to 4 years, and 4 or more years, respectively.

Combined error

Based on the assumptions made, it was possible to prepare tables of "worst" case accumulation rates to examine how much variability in these rates might have been due solely to experimental error. This information is provided in Table 4.5 and Table 4.6 for the Patna "operating" pits and Singur latrines.

In these tables, the experimental error in the fourth and fifth columns represents two different situations. In the preparation of the "negative" column, it was assumed that sludge accumulation had been overestimated and the amount of usage underestimated. The resulting sludge

TABLE 4.5 Patna Sludge Accumulation Rates (in operating pits)
Possible Experimental Error

LATRINE NUMBER	PIT AGE (YEARS)	SAR (MSD) (M^3/PERS-YEAR)	EXPERIMENTAL NEGATIVE	ERROR (%) POSITIVE
1	4.6	0.032	-27.5	51.4
2	1.1	0.104	-14.8	18.4
6	1.2	0.033	-15.8	19.7
7	1.8	0.050	-14.6	18.2
8	3.2	0.043	-22.7	34.6
10	3.0	0.043	-22.8	34.7
12	5.1	0.013	-28.5	53.4
14	2.3	0.055	-22.9	34.9

The "negative" experimental error represents the case in which the volume of sludge was assumed to have been underestimated and the amount of usage overestimated. The opposite situation was assumed in the case of the "positive" error.

TABLE 4.6 Singur Latrines Accumulation Rates
Possible Experimental Error

LATRINE NUMBER	PIT AGE (YEARS)	SAR (MSD) (M^3/PERS-YEAR)	EXPERIMENTAL NEGATIVE	ERROR (%) POSITIVE
1	8.3	0.022	-35.3	67.6
2	8.3	0.042	-35.3	67.6
3	8.3	0.057	-35.3	67.6
4	8.3	0.011	-36.6	70.5
5	8.3	0.011	-35.3	67.6
6	8.2	0.018	-34.4	65.6
7	8.2	0.020	-33.9	64.6
8	8.1	0.054	-34.4	65.6
10	8.3	0.021	-33.6	63.9
11	8.3	0.049	-31.5	59.5
13	8.1	0.022	-33.6	63.9
15	8.2	0.020	-35.3	67.6

The "negative" experimental error represents the case in which the volume of sludge was assumed to have been underestimated and the amount of usage overestimated. The opposite situation was assumed in the case of the "positive" error.

accumulation rate would naturally be smaller than the originally calculated rate. The opposite approach was taken in the "positive" column, where it was assumed sludge accumulation had been underestimated and the amount of usage, overestimated.

The range of possible experimental error in most of the accumulation rates can be seen to be significant. The most extreme case in Patna was in Latrine 12 in which the possible error ranged from -29 to +55 percent. In the Singur latrines there was less variability in the error because the latrines were approximately the same age. The error calculations indicated that the Singur SAR values could have been off by -30 to +70 percent.

4.1.5 Other Accumulation Rates

In most of the latrines examined in Patna and Singur, three distinct layers of material were seen in the pits. These layers corresponded with those that are typically found in a sludge digestor, i.e., scum, supernatant, and sludge. Following traditional practice in the discussion of latrine operation, the accumulation rates presented in Tables 4.1 through 4.6 have been based upon the volume of all material found in a pit. For comparative purposes, "sludge" accumulation rates based solely on the volume of the bottom solids layer found in the pits are provided in Appendix A.

TABLE 4.7 Sludge Characteristics

ITEM	PATNA RANGE	PATNA MEAN	SINGUR RANGE	SINGUR MEAN
Chemical Composition				
Solids, total (gm/kg)				
-fixed	2-54	24.0	40-94	76.9
-volatile	3-222	67.0	12-448	136.9
Chemical oxygen demand (gm/kg)	5-460	182.0	28-122	72.6
Nitrogen (gm/kg)				
Organic (as NH_3-N)	0.1-0.9	0.2	2.4-5.5	3.8
Ammonia (as NH_3-N)	0.1-0.5	0.2	0.7-2.1	1.5
Phosphorus, Total (as P_2O_5, gm/kg)	0.1-6.8	1.7	1.9-5.6	3.4
pH	6.3-7.9	7.1	6.7-7.7	7.0
Physical Characteristics				
Temperature (^oC)	16-24	20.1	24-31	27.7
Specific Gravity	0.99-1.09	1.02	1.01-1.41	1.1

4.2 Decomposition Process

4.2.1 Sludge Characteristics

The range and mean values of the chemical composition of the sludge found in the latrines examined are provided in Table 4.7. The typical sludge was 10% solids and 90% moisture by weight. The solid faction consisted, on the average, of 20% organic and 80% inorganic matter. The concentrations of the different solid components (total, volatile, nitrogen, and phosphorous) found in the Patna samples were generally lower than those of the same components in the Singur samples. The mean value of chemical oxygen demand (COD) in the Patna samples (mean COD-182.0 gm/kg) was, however, higher than that of the Singur samples (mean COD-72.6 gm/kg).

A complete set of the laboratory results for each sludge sample taken is provided in Appendix A. In general, the variability seen in the composition data was great. Because such large variability was not expected, control experiments to evaluate data variability due to sampling technique and analytical error were not conducted.

Because of the unusually large data variation, the sludge composition data was considered to be of limited usefulness. It is presented here to serve as a data base for future studies. Methods for determining sampling and analytical errors are suggested in the discussion chapter of the report.

4.2.2 Gas Production Rates

Evidence of microbial conversion of solid organic waste to gaseous products was seen in each of the latrines examined. Gas was collected from all the sludge samples at rates of between 0.002 to 3.014 liter/hr/kg volatile solids.

Gas production rates from each sample are provided in Appendix A. There was little consistency in the gas production data. It is not know whether this is because the sampling technique was unsatisfactory or the volatile solids analyses were incorrect. The problems encountered in the sludge composition analysis have already been mentioned. Methods of improving the gas production measurement and assessing the sampling variability are also considered later in the report in the discussion chapter.

The large degree of variability found in both the gas production and sludge composition data precluded the analysis which was planned of the possible relationships between gas production rates and physical/chemical parameters.

4.3 Drainage Process

4.3.1 Soil Properties

The soil particle size analyses confirmed the geological information which was known about the Patna and Singur areas before the study was begun. In Patna the upper soil stratum was a sandy loam, followed by a clay layer beginning at a depth of about one meter. In Singur, the solid consisted of a silt loam intermixed with layers of sand. The sand layers were the result of the movement of an ancient riverbed through the area. A complete set of the soil particle size analysis is provided in Appendix A.

Testing of the hydraulic conductivity in the different solid layers indicated that the conductivity of the soils surrounding the Patna latrines was lower than that of the soils surrounding the Singur latrines. Individual "equivalent" hydraulic conductivities were calculated for soil around each latrine based on Eqn. 4.1.

Equation 4.1
Equivalent Soil Hydraulic Conductivity
(Todd, 1980)

$$k\text{-eqiv} = \frac{ki \times zi}{zi}$$

where k-eqiv = equivalent hydraulic conductivity, (m/day),
ki = hydraulic conductivity in soil stratum, i, (m/day),
zi = horizontal thickness of soil stratum, i, (m).

The average equivalent hydraulic conductivity found for soil surrounding the Patna latrines was 0.59 m/day. The average equivalent hydraulic conductivity found for the Singur latrines was 1.16 m/day. The hydraulic conductivity values measured in the different soil strata and individual equivalent conductivities are presented in Appendix A.

4.3.1 Drainage Rate

Typical drainage curves observed in the latrines examined in Patna and Singur can be seen in Figure 4.1. The general pattern found was one in which fairly rapid liquid

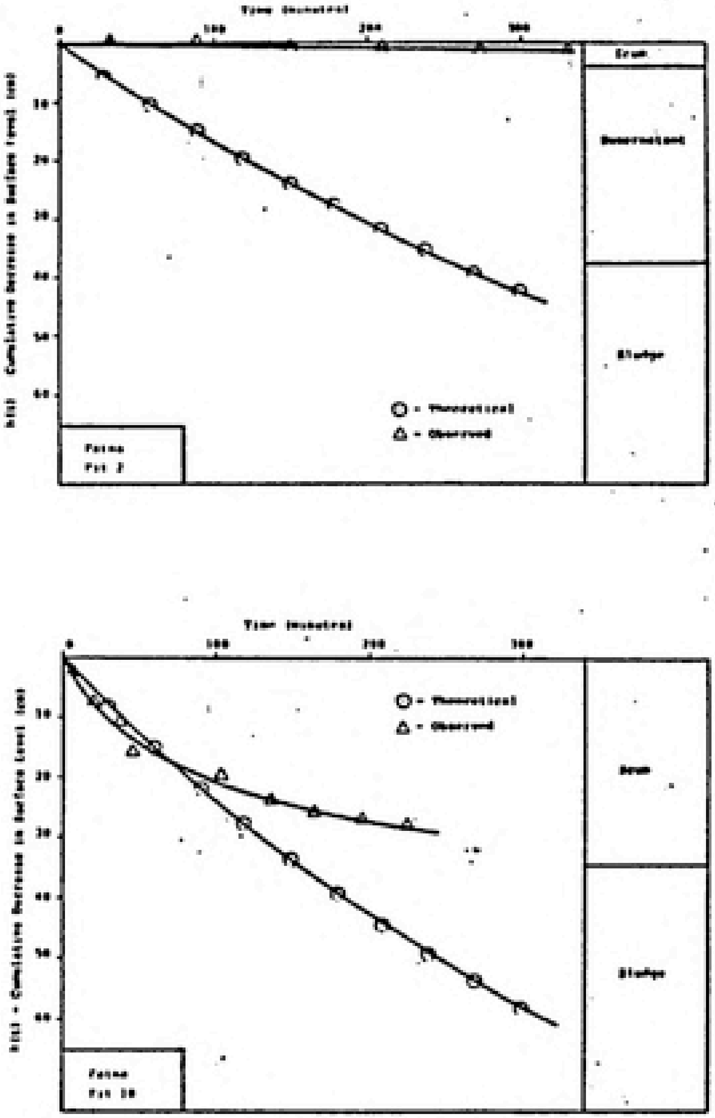


Figure 4.1 Typical drainage curves in Patna and Singur latrines

loss occurred in the first two hours of observation, followed by little or no drainage after that time. Included on the graphs is a theoretical curve of liquid loss based on the use k-eqiv values in Darcy's law.

To obtain a quantitative sense of what such drainage patterns meant in terms of liquid loss, "effective" hydraulic conductivities for each latrine were calculated based on Eqn. 4.2.

Equation 4.2
"Effective" Hydraulic Conductivity
(Auger hole method [Kessler, 1974])

$$k\text{-eff} = \frac{r \times \text{In}(h(t_i) + r/2) - \text{In}(h(t_n) + r/2)}{t_n - t_i}$$

where k-eff = "effective" hydraulic conductivity (m/day),
r = pit radius (m),
h(t) = height of liquid in pit at time, t (m),
t_i = initial time,
t_n = final time.

In general, the "effective" hydraulic conductivities were lower than "equivalent" conductivities found in the surrounding soil. The average k-eff in the Patna latrines was 0.14 m/day compared to a k-eqiv mean of 0.59 m/day. In the Singur latrines the average k-eff was 0.01 m/day. The k-eqiv value for these latrines was 1.16 m/day.

A very wide range "effective" hydraulic conductivity values were found. In some latrines there was up to a thirty centimeter drop in the sludge surface level during the testing period and in other latrines there was no change at all. Because of the large degree of variability the k-eff values, these results were regarded with some skepticism.

For future reference the "effective" hydraulic conductivity values are provided in Appendix A. The usefulness of the data as far as predicting the relationship drainage rate and soil properties was thought to be somewhat limited because of the large variability in the data.

V. DISCUSSION

5.1 Sludge Accumulation Rates

5.1.1 SAR Data Variability and Sample Size

The first objective of the SAR project called for the determination of sludge accumulation rates in a number of pour-flush latrines. Implicit in this objective was a desire to establish the "average" and range of accumulation rates that can be expected in these latrines.

A summary table of the accumulation rate statistics is provided in Table 5.1. In general, the different data sets are characterized by high standard deviations. It was surprising to find such a large degree of variability in the accumulation rate data. Since the range in a small sample of a population is less than would be found in the population as a whole, this implies that a very wide range of accumulation rates is possible.

If discussion is limited to consideration of the overall Patna and Singur data sets, the "normal" range of accumulation rates appears to be from 0.010 to 0.060 m^3/pers-yr. This range represents approximately from two to three standard deviations either side of the Patna

Table 5.1 Summary of sludge accumulation rate statistics

Data Set	Data Pts.	Range of SAR values*	Median	Mean ± S.D.
Patna				
a) overall	12	0.016-0.055	0.031	0.034±0.012
b) "old"	8	0.012-0.052	0.018	0.026±0.017
c) "operating"	8	0.013-0.014	0.043	0.047±0.043
Singur				
a) overall	12	0.011-0.057	0.022	0.029±0.017

*All rate statistices expressed in terms of m^3/pers-yr.
SAR = sludge accumulation rate
S.D. = standard deviation

Figure 5.1A

Distribution of sludge accumulation rate data in Patna latrines

SAR mean
X= 0.034 m3/cap-yr

Std. Deviation
SD= 0.012

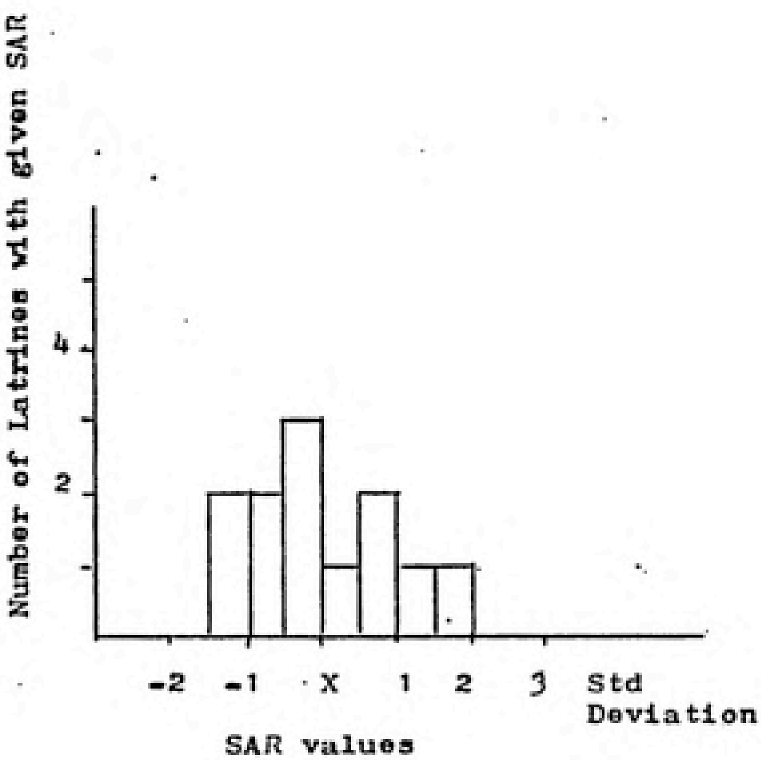
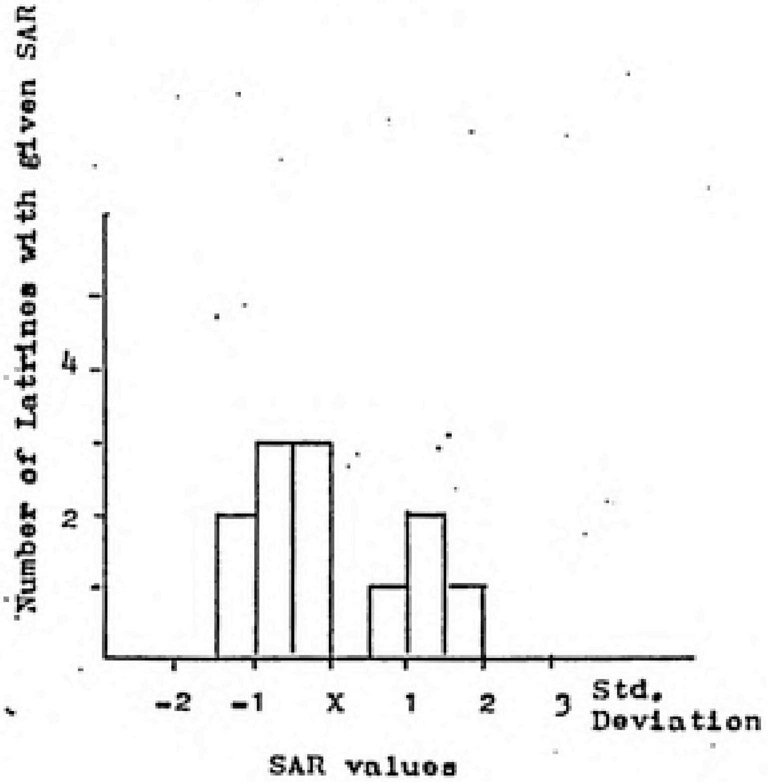


Figure 5.1B

Distribution of sludge accumulation rate data in Singur latrines

SAR mean
X=0.029 m3/cap-yr

Std. Deviation
SD=0.017



and Singur rate means. (This range also covers the accumulation rates found in other studies.)

In trying to determine the true mean accumulation rate, it was necessary to see if the data are normally distributed. Histograms for the Patna and Singur rates were prepared and these are presented in Figures 5.1A and 5.1B. The rate data was found not to have a normal distribution. In both Patna and the Singur, the data was skewed in the lower direction.

Because of the predominance of lower SAR values, use of the Patna and Singur SAR means to identify the "average" rate was not justified. Rather, a better measure of the central tendency was thought to be the median. In general, use of the median reduces the effect of extreme values in trying to identify the central tendency. This appeared to be the best approach in handling the accumulation rate data.

The median SAR values found in the Patna and Singur latrines were 0.031 and 0.022 m^3/pers-year, respectively. Considering both median values, the "average" accumulation rate in pour-flush latrines appears to be approximately 0.025 m^3/pers-yr.

5.1.2 Comparison of SAR "Average" Rate to UNDP/TAG "Effective" Capacity Factor

The "average" accumulation rate of 0.025 m^3/pers-yr. found in Patna and Singur is below both the "effective" capacity factor currently recommended (UNDP, 1984) for dry conditions (0.045 m^3/pers-yr) and for wet conditions (0.066 m^3/pers-yr).

5.1.3 Experimental Error in SAR Values

The large degree of data variability raised concerns about the amount of experimental error in accumulation rate determinations. This concern generated an attempt to predict the experimental error in the rates.

Predictions of the experimental error associated with the accumulation rate determinations explained only a small portion of the data variability. In the Patna latrines, the experimental errors were, at most, fifty percent (see Table 4.5) of the measured rates. In the Singur latrines the maximum experimental error was predicted to be approximately seventy percent of the measured rates (see Table 4.6). Such experimental errors alone could not explain the three- to eightfold difference in accumulation rates that was observed within the individual data sets.

The technique used to assess the experimental error in the rate determinations is not considered to be entirely adequate. The main reason this is said is because there is no way of knowing whether the assumptions made in association with usage error are correct or not (see Section 4.1.4). Ideally, there should be an objective means of assessing the error in this factor. How this might done is discussed later in the report in a section of "Improvements in Experimental Design."

5.2 Sludge Accumulation Rate: Relationship to Pit Design, Socio-economic and Environmental Factors

5.2.1 Latrine Model

To achieve the study objective of determining the influence of different design and environmental factors on the sludge accumulation rate it was necessary to develop a framework for the data analysis. To this end a mathematical model, based upon theoretical considerations was developed to describe the accumulation process.

5.2.2 Model Derivation

a) Materials Balance

To begin with, it was assumed that the level of solids reduction in a latrine would be high, i.e., eighty to ninety percent. As human excreta contains five to ten percent solids, this assumption meant that the accumulated volume of solids would be relatively small and therefore could be ignored.

The focus of the model development then became how to describe liquid accumulation in a latrine. Two processes had to be considered; liquid input or loading by the latrine users and liquid loss through drainage. In terms of a simple material balance;

Equation 5.1

Materials balance for a pit latrine

Liquid Accumulation at time, t+ t	=	Liquid Accumulation at time, t	+	Liquid Input in time, t	-	Liquid loss through drainage in time, t

b) Description of Drainage Losses

Assuming that the per capita loading rate would be constant, the question of interest then became how to best describe the rate of liquid loss or drainage. Darcy's Law was used for this purpose;

Equation 5.2

Darcy's Law

$$Q = k \times A \times dh/dl$$

where, Q = drainage rate (volume/time),
k = soil hydraulic conductivity (length/time),
A = flow area (length x length),
$\frac{dh}{dl}$ = hydraulic gradiant (unitless).

c) Assumptions

The interpretation of what soil hydraulic conductivity, flow area, and hydraulic gradient to use in Darcy's Law was based on the following series of assumptions.

1) Hydraulic conductivity, k-eff: the literature review had indicated that in septic tanks, it was quite common for a biological slime or clogging layer to build up on the liquid-soil interfaces of such systems. Studies of the clogging phenomena indicated that this layer grew very quickly and was very impermeable.

In the development of the model it was assumed that a clogging layer would be formed on the sidewalls and base of a pit. It was also assumed that the hydraulic conductivity of this layer would be much lower than that of the surrounding soil. To denote this difference it was decided that the hydraulic conductivity used in the model would have been identified as an "effective" hydraulic conductivity.

2) Flow area, A (t): In a latrine there are two directions through which liquid can flow from the pit -- horizontally through the pit sidewalls or vertically through the pit base. In the model it was assumed that flow would occur primarily in the horizontal direction. There are two reasons for this assumption. Latrines are normally built upon a firm base, i.e., clay or rock, both of which have low permeabilities. Secondly, over time a layer of solids tends to build up on the base of a pit. Experience has shown this layer to be both compact and impermeable.

Another factor which had to be taken into consideration was the presence of pit lining in latrines. To compensate for the loss of flow area due to pit lining, a term, Y, known as the "drainage ratio," was developed. This term is equal to the ratio of the unlined sidewall to total sidewall area.

Based on the assumption that liquid loss would occur primarily through the pit walls, the flow area for a latrine was defined as follows:

e) Material Balance

Having adopted a means of estimating liquid losses it was possible to write a more precise materials balance

Equation 5.5

Modified materials balance for a pit latrine

$$VOL_{t + \ t} = VOL_t + (NX) \ t - Q(t) \ t$$

where VOL = volume of sludge accumulated in pit at time, t, or t + t,
N = number of people using latrine,
X = per capita loading rate (volume/time),
t = change in time or period of latrine use (time),
Q(t) = drainage rate at time, t (volume/time). or (k-eff)(Y)(2 r)(h(t)).

By placing VOLt on the left hand side, and dividing through by time, Equation 5.5 was put into a form which was more recognizable:

Equation 5.6

$$\frac{VOL_{t + \ t} - VOL_t}{t} = (NX) - (k\text{-}eff)(Y)(2 \ r)(h(t))$$

Taking the limit of Equation 5.6 as t -- 0, yielded,

Equation 5.7

$$\frac{dVOL}{dt} = (NX) - (k\text{-}eff)(Y)(2 \ r)(h(t))$$

After further manipulation, Equation 5.7 was put into the form of the differential equation:

Equation 5.8

$$\frac{dh(t)}{dt} = \frac{(NX)}{r^2} - \frac{(2Y)(k\text{-eff})(h(t))}{r}$$

Equation 5.8 was solved by the separation of variables technique and then integrated to provide a formula for the prediction of the sludge height in a pit at any time, t.

Equation 5.9

$$h(t) = \frac{C1}{C2} \times (\exp^{C2t} - 1)$$

where $C1 = \frac{NX}{r^2}$ $\qquad C2 = -\frac{2Y(k\text{-eff})}{r}$

The final step in the model derivation was the conversion of Equation 5.9 into a form that could be used for the prediction of sludge accumulation rates. This was done by multiplying both sides of the equation by the factor, $r^2/(N \times t)$. The results of this manipulation are shown in Equation 5.10.

5.2.3 SAR (MODEL) Presentation

Equation 5.10

Sludge Accumulation Rate Model (for circular pits)

$$\text{SAR (MODEL)} = \left[-\frac{(X)(r)}{(2Y)(k\text{-eff})(t)}\right]\left[\exp(-(2Y)(k\text{-eff})(t)/(r))-1\right]$$

where SAR(MODEL) = predicted sludge accumulation rate (volume/capita x time))
x = per capita loading rate (volume/time),
r = pit radius (length)
Y = drainage ratio (unitless),
k-eff = "effective" hydraulic conductivity (length/time),
t = pit age (time).

A similar model for the prediction of accumulation rates in rectangular pits was also developed, with all parameters being the same as in Equation 5.10 except l and w which represent the pit length and width.

Equation 5.11

Sludge Accumulation Rate Model (for rectangular pits)

$$\mathrm{SAR}_{(MODEL)} = \left[-\frac{-(X)(l \times w)}{(2Y)(k\text{-}eff)(t)}\right] \times \left[\exp\left(\frac{-(2Y)(k\text{-}eff)(l + w)(t)}{(l \times w)}\right) - 1\right]$$

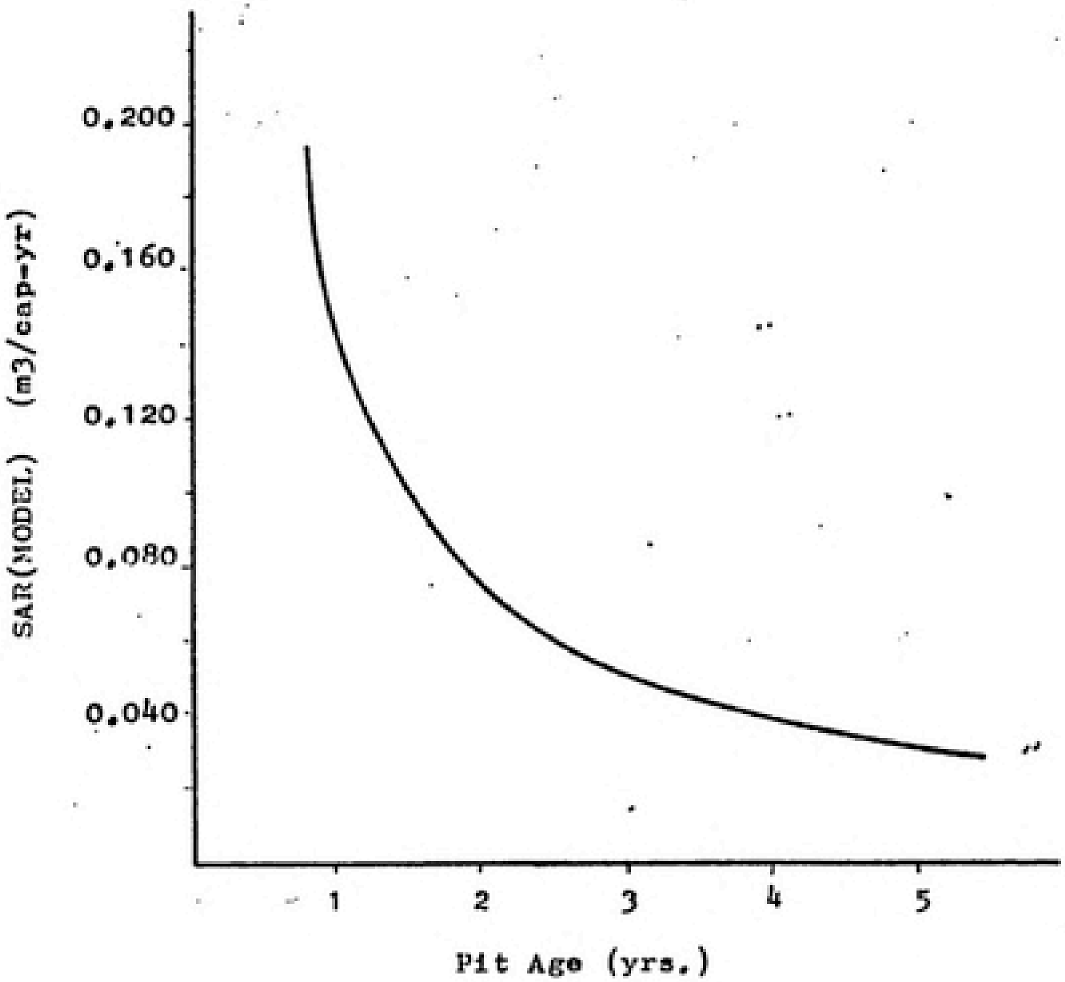
5.3 Model Interpretation

Having developed the model, the first question asked was, "What does the model suggest about the effect of different factors on SARs?"

According to the model, there are five parameters which could affect the sludge accumulation rate -- "effective" hydraulic conductivity, per capita loading rate, pit radius, drainage ratio, and age. To examine what effect each of these parameters had on the predicted sludge accumulation rates, a number of different situations were considered.

Figure 5.2A

Sludge accumulation rate as predicted by model versus pit age

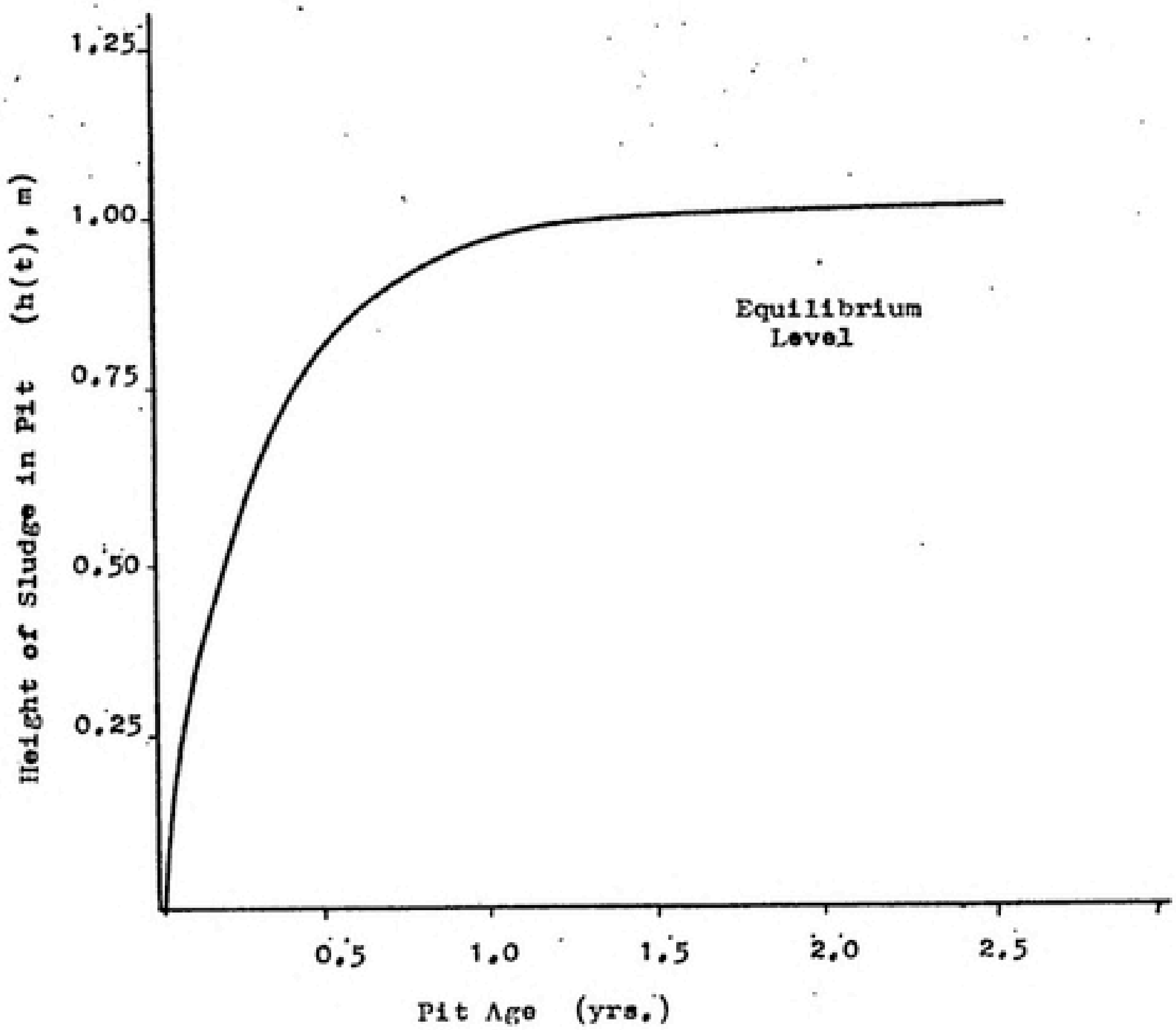


Constants

Xs= 1.5 l/cap/day
Y= 0.03
r= 0.50 m
k-eff = 0.08 m/day

Figure 5.2B

Sludge height versus pit age



Constants

X= 1,5 l/cap/day
Y= 0,03
r= 0,50 m
k-eff= 0,08 m/day
N= 5 capita

5.3.1 SAR(MODEL) vs. Time

The most influential parameter in the model was found to be time. Its importance lies in its position in the model's exponential term. In latrines which have been used for relatively short periods (0-3 years), the exponential term is large enough to have an effect on the sludge accumulation rate. As time increases, however, the exponent approaches zero and the accumulation rate becomes almost constant. This phenomenon is illustrated in Figure 5.2A, where sludge accumulation rate [SAR(MODEL)] versus pit age has been plotted.

To understand the physical meaning of the SAR(MODEL) - time relationship, one must look at what happens to h(t), the height of sludge in a pit, through time. The latter relationship has been plotted in Figure 5.2B.

What is seen in a graph of h(t) versus time is a sharp rise in h(t) during the first year of latrine operation. During this period, the rate of loading is greater than the rate of loss and, hence, a net increase in sludge accumulation occurs.

By the end of the first year, the sludge height (h(t)) reaches an "equilibrium" level. This level is the point, as represented by Equation 5.12, where the rate of liquid loss equals the rate of liquid loading.

Equation 5.12

Liquid Loading		Liquid Loss

$$XN = (k\text{-}eff)(A)(t) = (k\text{-}eff)(Y)(2\ \ r)h(t)$$

where
- X = per capita loading rate (m^3/cap/day),
- N = user population size (capita),
- $k\text{-}eff$ = "effective" hydraulic conductivity (m/day),
- $A(t)$ = flow area at any time, t (m^2),
- Y = drainage ratio (unitless),
- r = pit radius (m),
- $h(t)$ = height of sludge in pit at time, t (m).

Given a certain value of k-eff, the sludge height will increase until the size of the flow area is large enough to allow liquid losses to equal liquid input. After this point, the model indicates that there will be no further increase in the sludge height. This means the volume of sludge also does not change.

5.3.2 SAR(MODEL) vs. Pit Radius

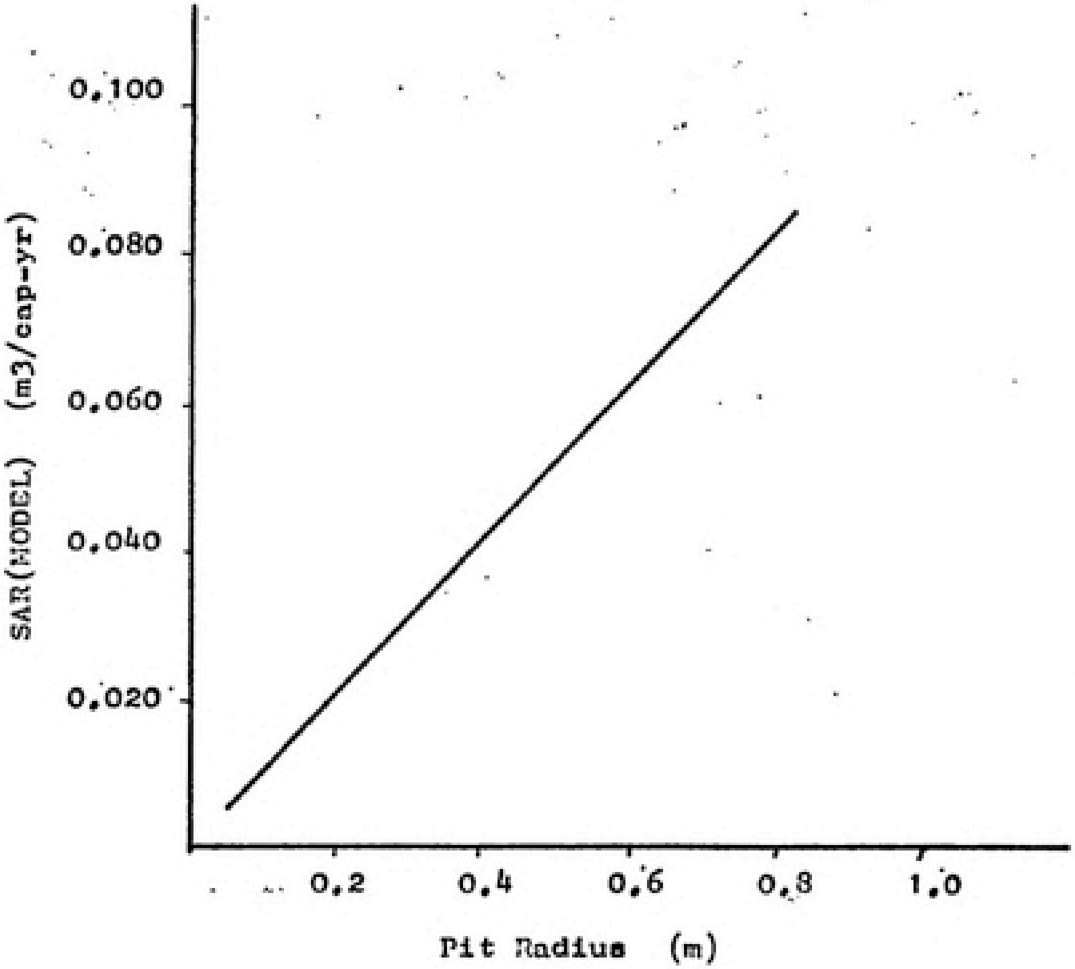
The relationship between SAR(MODEL) and pit radius is plotted in Figure 5.3. What was found was a linear increase in SAR(MODEL) as the pit radius increases. This is so because pit radius is in the numerator of the model's first term.

Table 5.2 Effect of Changing Pit Radius on SAR(MODEL)

Change in Radius	Net Effect Height h(t)	Flow Area (2 r)(h(t))	Volume (r^2)(h(t))	SAR(MODEL)
1.increase	decrease	no effect	increase	increase
2.decrease	increase	no effect	decrease	decrease

Figure 5.3

Sludge accumulation rate as predicted by model versus pit radius



Constants

X= 1.5 l/cap/day
Y= 0.03
t= 3 yrs.
k-eff= 0.08 m/day

Model simulations show a small difference in the relative effect of pit radius on sludge accumulation rates when different pit ages were assumed (see Figure 5.4). The reason for this was attributed to the position of the radius in the exponential term of the model. As with time, the value of the exponent, as determined by the pit radius and other factors, affects the SAR(MODEL) values in the early stages of latrine operation.

5.3.3 SAR(MODEL) vs. Drainage Ratio

The simulations of the relationship between SAR(MODEL) and the drainage ratio indicated that small changes in the ratio could have significant effects on the accumulation rate.

A plot of SAR(MODEL) vs. drainage ratio is provided in Figure 5.5. The decrease in SAR(MODEL) with increasing drainage ratio reflects the fact that less flow area is required when the number of openings/unit area increases in the pit lining.

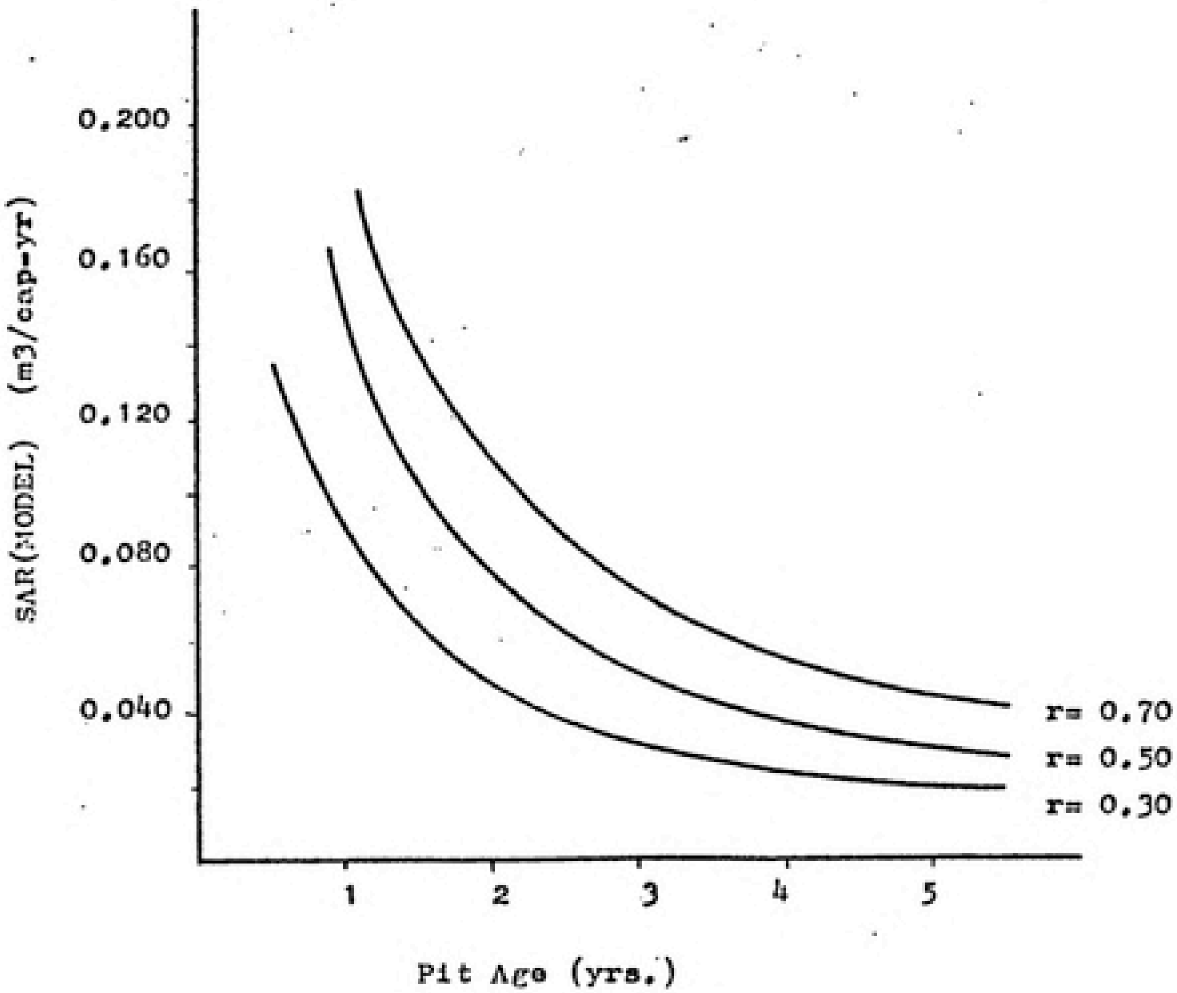
As in the case of pit radius, a difference was noted in the relative effect of the drainage ratio on SAR(MODEL) when different pit ages were assumed (see Figure 5.6). Here again the difference was attributed to the position of the ratio in the exponential term of the model.

5.3.4 SAR(MODEL) vs. Per Capita Loading Rate

The relationship between SAR(MODEL) and the per capita loading rate is shown in Figure 5.7. As is obvious from the

Figure 5.4

Sludge Accumulation rate as predicted by model versus pit age (different pit radii)

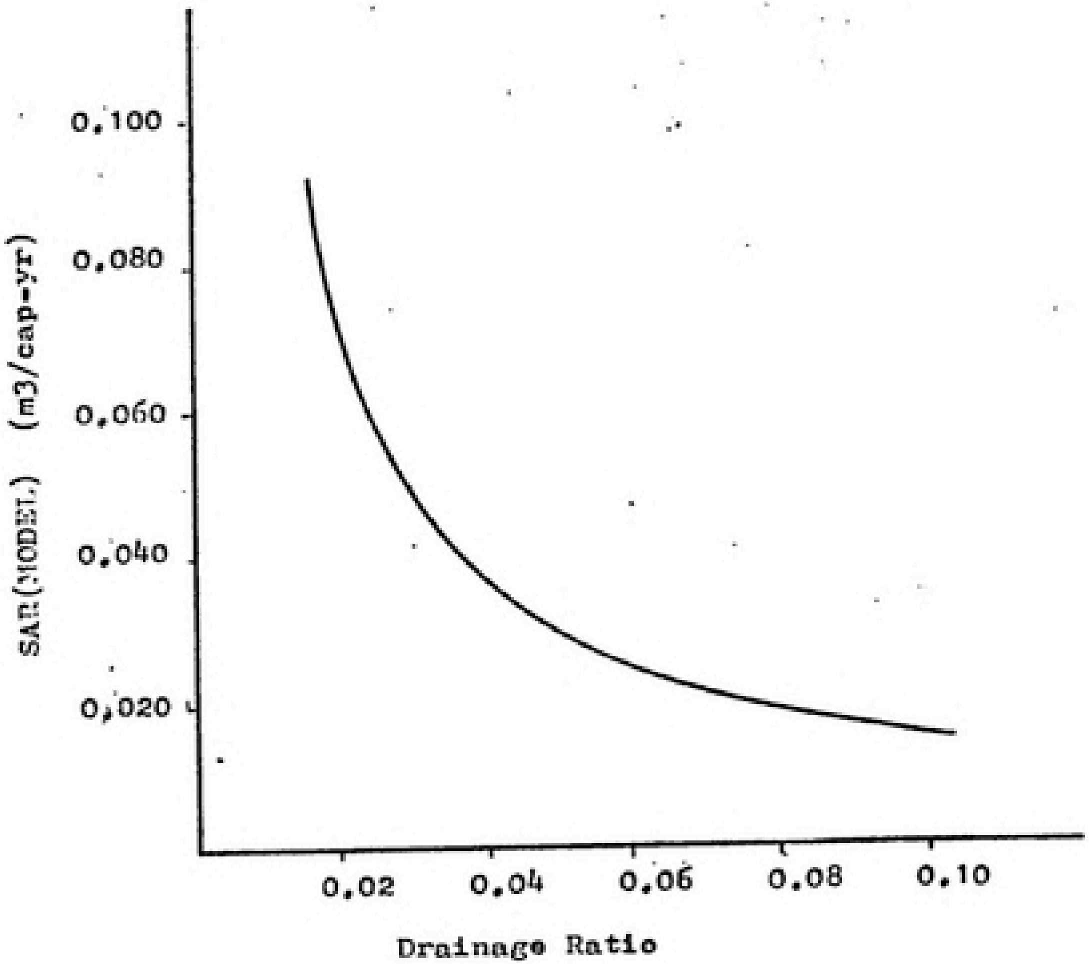


Constants

X= 1.5 1/cap/day
Y= 0.03
k-eff= 0.08 m/day

Figure 5.5

Sludge accumulation rate as predicted by model versus drainage ratio

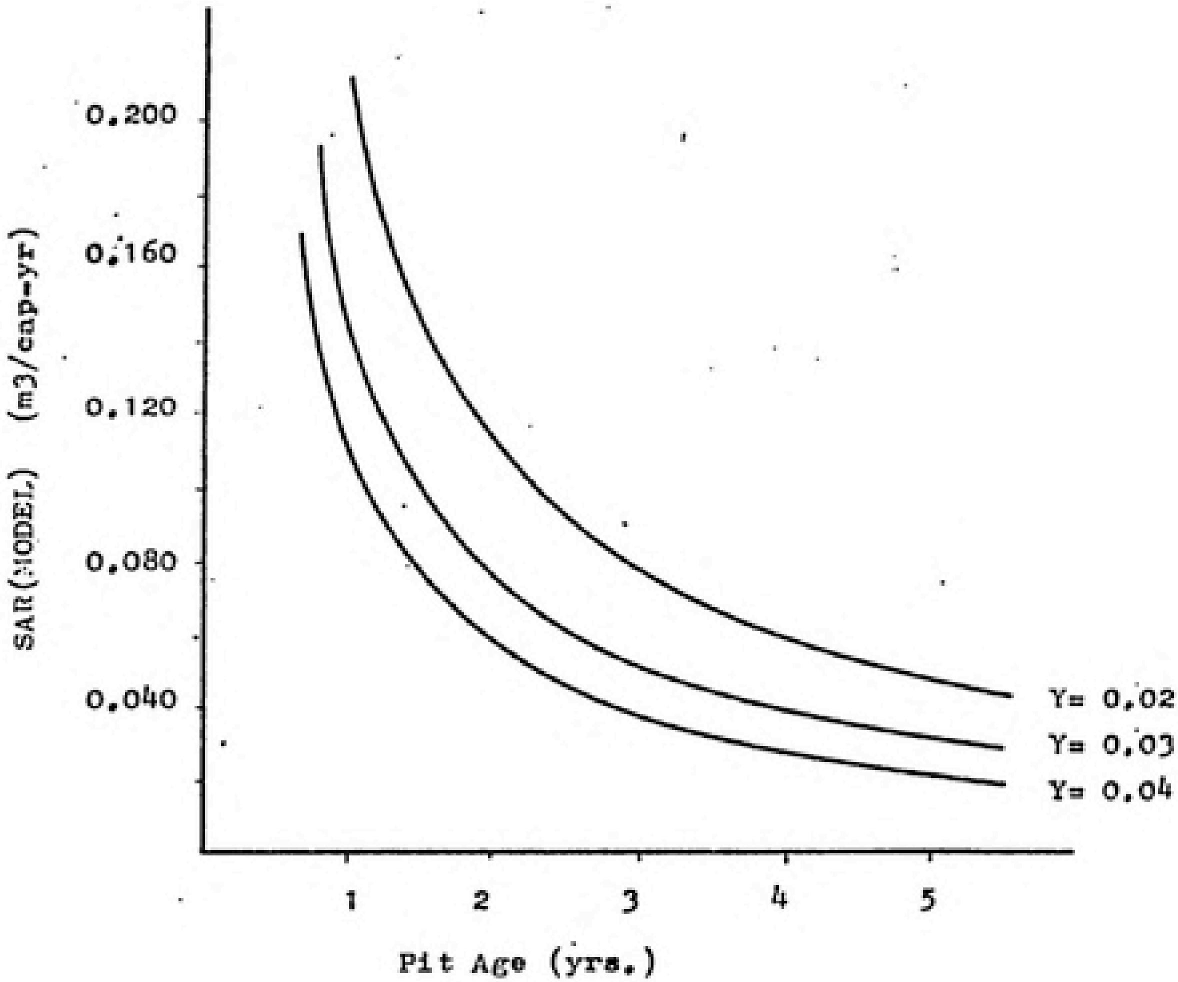


Constants

X= 1.5 l/cap/day
r= 0.50 m
t= 3 yrs,
k-eff= 0.08 m/day

Figure 5.6

Sludge accumulation rate as predicted by model versus pit age (different drainage ratio)

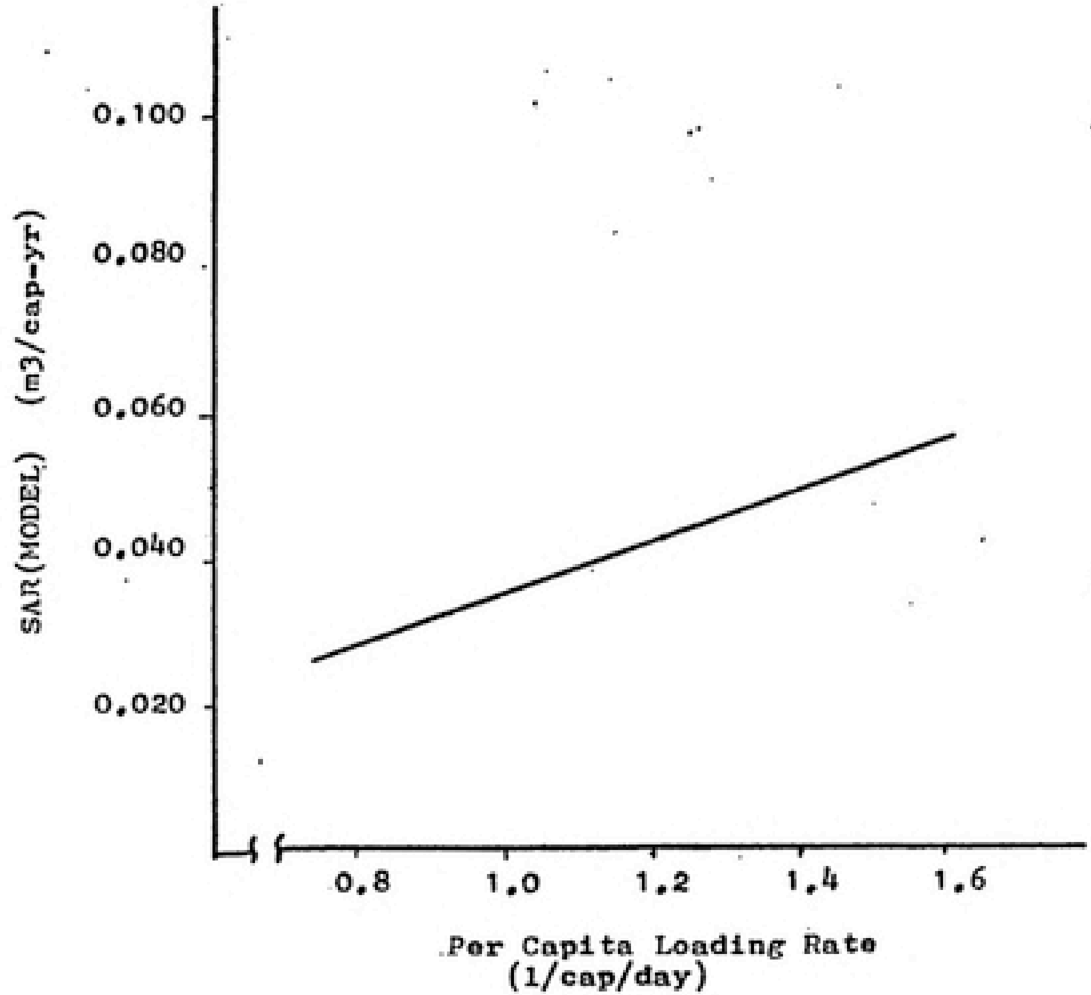


Constants

X= 1.5 l/cap/day
r= 0.50 m
k-eff= 0.08 m/day

Figure 5.7

Sludge accumulation rate as predicted by model versus per capita loading rate



Constants

Y= 0.03
r= 0.50 m
t= 3 yrs.
k-eff= 0.08 m/day

model formulation, SAR(MODEL) increases linearly with the loading rate.

5.3.5 SAR(MODEL) vs. "Effective" Hydraulic Conductivity

In the model the "effective" hydraulic conductivity represents the permeability of the clogging layer that has been assumed to form in all latrines. It has also been assumed that the value of k-eff would be the same in all latrines.

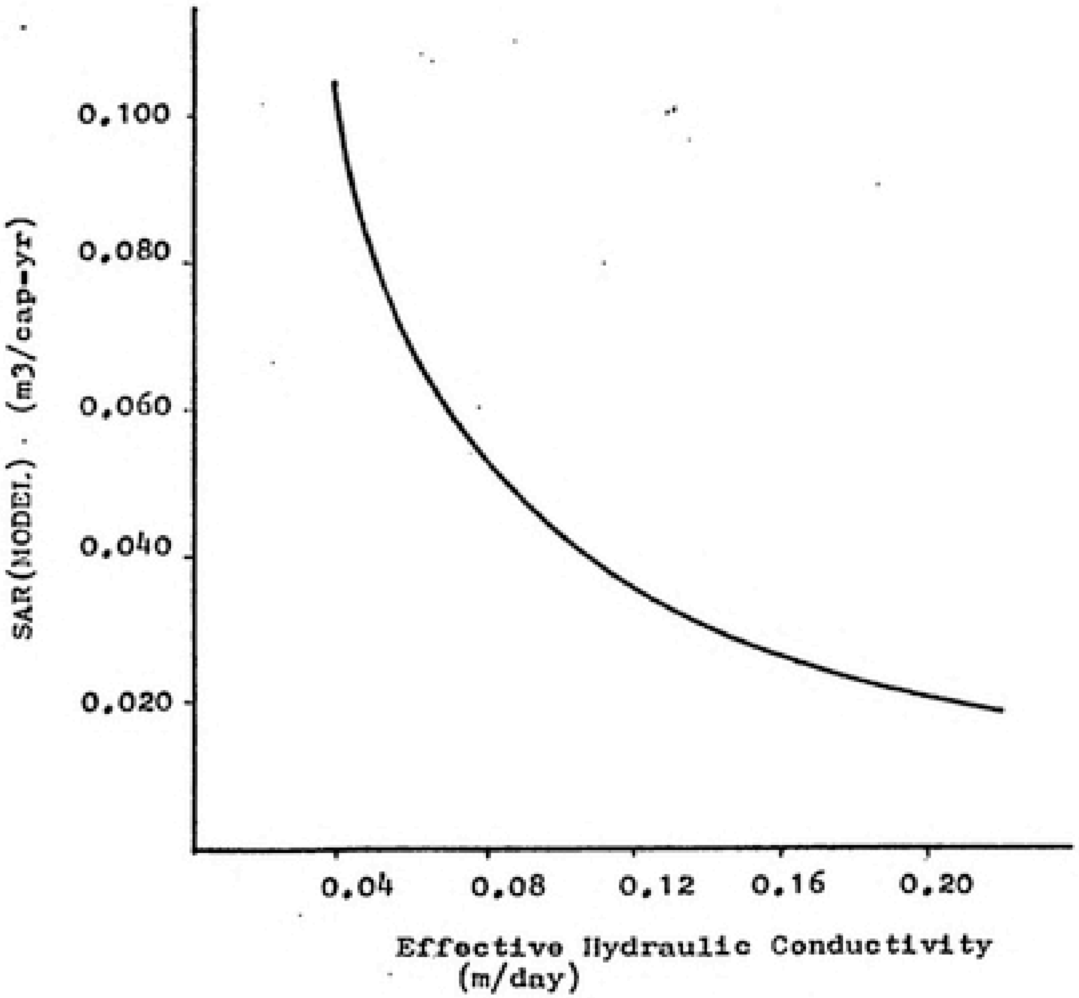
Despite the assumption that k-eff is a constant, the relationship between SAR(MODEL) and k-eff was examined. Since k-eff and the drainage ratio enter into the model in the same way, the effects are identical. As can be seen in Figure 5.8, the value of SAR(MODEL) decreases exponentially as k-eff increases.

The higher the k-eff of the clogging layer, the more liquid which can pass from the pit per unit of flow area. With high values of k-eff, less flow area is required and, hence, lower accumulation rates are predicted.

Because k-eff is in the exponential term of the model, the relative effect of k-eff on SAR(MODEL) values changes with time. This is illustrated in Figure 5.9.

Figure 5.8

Sludge accumulation rate as predicted by model versus "effective" hydraulic conductivity

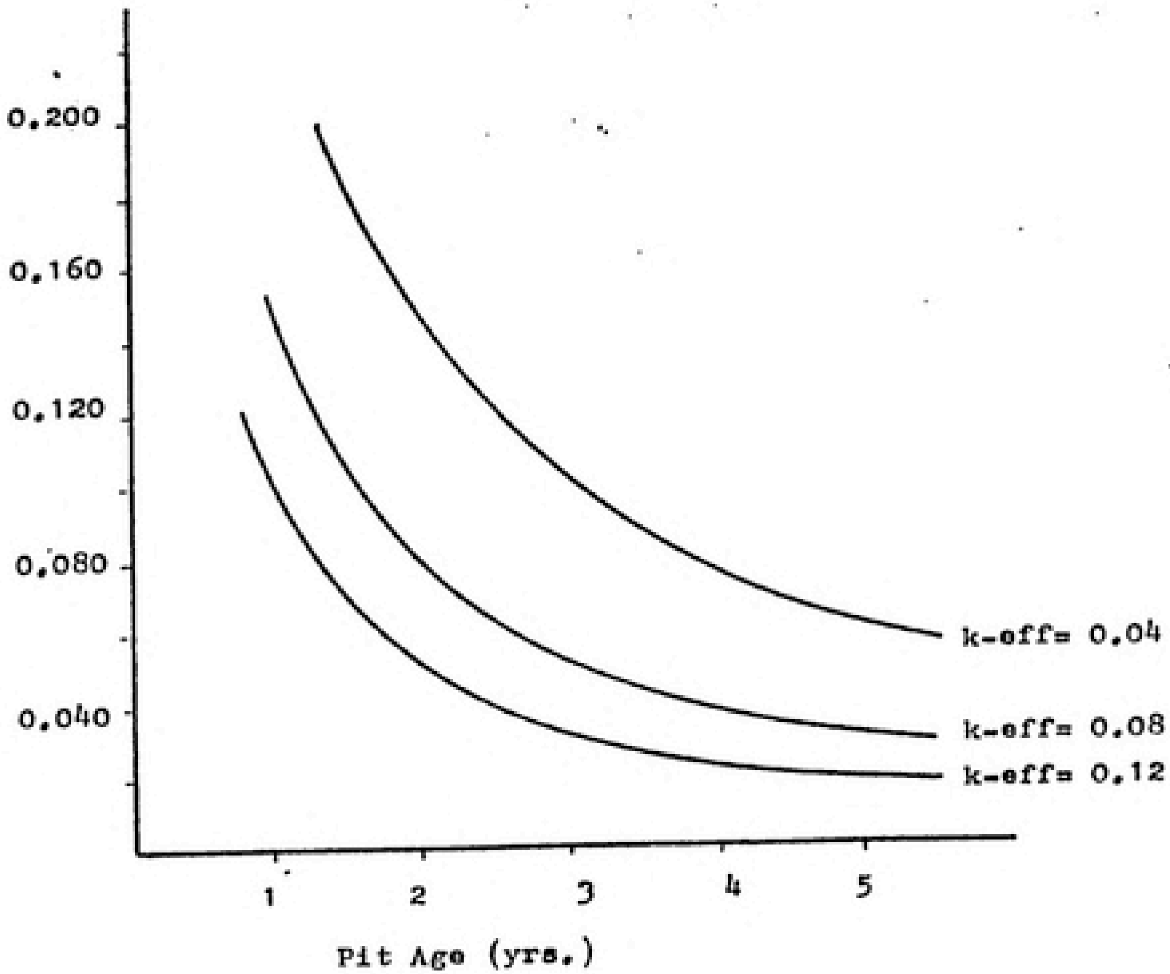


Constants

X= 1.5 1/cap/day
Y= 0.03
t= 3 yrs.
r= 0.50 m

Figure 5.9

Sludge accumulation rate as predicted by model versus pit age (different "effective" hydraulic conductivities)



Constants

X= 1.5 l/cap/day
Y= 0.03
r= 0.50 m

5.4 Parameter Estimation

Having developed a theoretical model of the relationship between the sludge accumulation rate and different design and environmental factors, the logical next question to ask is, "Do the latrines perform as predicted by the model?" This question is addressed by comparing the predicted accumulation rates with those measured in the Patna and Singur latrines. The calculation of SAR(MODEL) values for each latrine depended in turn on having values for each of the parameters in the model.

All of the parameters in the model, except the "effective" hydraulic conductivity (k-eff), represented quantities that could be determined from the field data. An attempt to measure k-eff values directly in the field had failed and the value of this parameter had to be estimated indirectly.

A "sum of squares" method was used to find the best estimate of the "effective" hydraulic conductivity. This method involved the calculation of the summation,

Equation 5.13

k-eff Estimation

$$\sum_{i=1}^{n} \left(SAR(MSD)_i - SAR(MODEL)_i\right)^2$$

where, $SAR(MSD)_i$ = measured sludge accumulation rate, in latrine, i (m^3/cap/yr),

$SAR(MODEL)_i$ = sludge accumulation rate predicted by model in latrine, i (m^3/cap/yr),

n = total number of Patna "old" pits,

over a range of hydraulic conductivity values. The best estimate of k-eff was taken to be the hydraulic conductivity such that the summation was minimized.

There was some debate about which sludge accumulation rates to use in estimation procedure for k-eff. There were three data sets that could have been drawn upon -- those of the Patna "old" and "operating" pits and Singur latrines.

No matter which data set was chosen, the set used to estimate k-eff would become "biased" for later use in testing the model. There was a strong desire to use the Patna "operating" pits in the model evaluation because they offered a chance to examine the effect of time on accumulation rates. Similarly, there was a desire to save the Singur data for the model evaluation in order that the two different styles of latrines could be compared. In the end, then, it was decided to use the Patna "old" pit rate in the k-eff estimation procedure.

Using the Patna "old" pit accumulation rates and parameters (l, w, Y, and t), a range of k-eff values from 0.01 to 1.0 m/day was examined. The minimum "sum of squares" value was found to occur at a k-eff value of 0.08 m/day. This value was taken to represent the hydraulic conductivity of the clogging layer assumed to exist in latrines.

5.5 Model Evaluation

5.5.1 Evaluation Technique

Two questions were asked in the model evaluation;

1) how closely did the model's prediction of sludge accumulation rates match those found in the Patna and Singur latrines; and,

2) did the use of the model's SAR predictions in the UNDP/TAG design equation lead to a more accurate estimate of pit capacity requirements than the use of an "average" accumulation rate?

a) SAR(MODEL) Predictions

To answer the first question, model "predicted" accumulation rates [SAR(MODEL)] were calculated for each of the Patna and Singur latrines. These rates were then compared to the actual accumulation rates [SAR(MSD)].

Based on the experimental error associated with the SAR(MSD) values (see Tables 4.5 and 4.6), it was decided that SAR(MODEL) values within ± 50% of the measured rates would be considered valid.

The percentage error in each rate estimate was calculated according to Equation 5.14;

Equation 5.14

SAR(MODEL) Error

$$\text{Percentage Error (\%)} = \frac{\text{SAR(MODEL)} - \text{SAR(MSD)}}{\text{SAR(MSD)}} \times 100$$

b) Comparison of Model and "Average" Rate Equation

To answer the second question, a "sum of squares" error estimation method was used. First, for each latrine, the volume of sludge accumulation as predicted by the model [VOL(MODEL)] and "average" rate equation [VOL(AVG)] were calculated (see Table 5.3). This was followed by the computation of an error term for each latrine and then a summation of total error in both the VOL(MODEL) and VOL(AVG) estimates.

A summary of the "sum of squares" error estimation method is provided in Table 5.4.

5.5.2 Results of Model Evaluation

a) Patna Latrines

<u>SAR(MODEL) Predictions:</u>

The percentage error in estimated accumulation rates in Patna latrines are presented in Table 5.5. Both positive and negative errors were observed indicating that the model both overestimated and underestimated actual accumulation rates. In terms of deviation from zero, the minimum and maximum errors observed were Latrine 8 (-11.6%) and Latrine 16 (+48.4%).

The SAR(MODEL) estimates for the Patna latrines were considered to be accurate within the prescribed degree of error. All of the SAR(MODEL) values were less than fifty percent off of the measured accumulation rates, with the

Table 5.3 Sludge Accumulation Equations

I. Model
$$VOL(MODEL) = SAR(MODEL) \times N \times PL$$

II. "Average" Rate Equation
$$VOL(AVG) = SAR(AVG) \times N \times PL$$

VOL(MODEL)	=	model predicted sludge accumulation (m^3).
VOL(AVG)	=	"average" rate equation predicted sludge accumulation (m^3),
SAR(MODEL)	=	sludge accumulation rate predicted by model, (m^3/capita-yr,),
SAR(AVG)	=	average sludge accumulation rate, (m^3/capita-yr.),
N	=	user population size (capita),
PL	=	period of latrine use (yrs.).

Table 5.4 Error Summations

I.
$$\sum_{i=1}^{n} VOL(MSD_i) - VOL(MODEL_i))^2$$

II.
$$\sum_{i=1}^{n} (VOL(MSD_i) - VOL(AVG_i))^2$$

$VOL(MSD)_i$	=	measured sludge accumulation (m^3),
$VOL(MODEL_i)$	=	model predicted sludge accumulation (m^3),
$VOL(AVG_i)$	=	"average" rate equation predicted sludge accumulation (m^3),
n	=	number of latrines in data set.

Table 5.5 Patna "Operating" Pits: Percentage Error in Model Predictions of Sludge Accumulation Rates

LATRINE NUMBER	SAR(MODEL) (M^3/PERS-YR.)	SAR(MSD) (M^3/PERS-YR.)	PERCENTAGE ERROR (%)
1	0.028	0.032	-12.5
2	0.132	0.104	26.9
6	0.049	0.033	48.4
7	0.062	0.050	24.0
8	0.038	0.043	-11.6
10	0.029	0.043	-32.5
12	0.019	0.013	46.1
14	0.065	0.055	18.1

$$\text{Percentage error} = \frac{\text{SAR(MODEL)} - \text{SAR(MSD)}}{\text{SAR(MSD)}} \times 100$$

majority of the estimates being good within plus or minus thirty percent.

Comparison of Model and "Average" Rate Equations:

There was a large difference between the model's summation value (SUM=0.3) and that of the "average" rate equation (SUM=4.1). Such a large difference in error summations indicated that the use of the SAR(MODEL) values led to much better estimates of pit capacity requirements than the use of the "average" rate. This finding confirmed the model's ability to accurately predict accumulation rates in the Patna latrines.

b) Singur Latrines

SAR(MODEL) Predictions:

The percentage error in the accumulation rate estimations for the Singur latrines are presented in Table 5.6. Again both positive and negative errors were observed. In terms of deviation from zero, the minimum and maximum errors were found in Latrine 1 (+9.0%) and Latrine 5 (+118.1%).

Contrary to the results found using the Patna data, the Singur SAR(MODEL) errors indicated that the model did not produce accurate rate estimates. SAR(MODEL) predictions in two latrine (4 and 5), were particularly bad, being off by more than one hundred percent.

Table 5.6 Singur Latrines: Percentage Error in Model Predictions of Sludge Accumulation Rates

LATRINE NUMBER	SAR(MODEL) (M^3/PERS-YR.)	SAR(MSD) (M^3/PERS-YR.)	PERCENTAGE ERROR (%)
1	0.024	0.022	9.0
4	0.022	0.011	100.0
5	0.024	0.011	118.1
6	0.027	0.018	50.0
7	0.028	0.020	40.0
8	0.027	0.054	-50.0
10	0.028	0.021	33.3
11	0.036	0.049	-26.5
15	0.025	0.020	25.0

Latrines 2, 3, and 13 were not considered in the analysis because two ring sizes were used in the pits of these latrines.

$$\text{Percentage error} = \frac{\text{SAR(MODEL)} - \text{SAR(MSD)}}{\text{SAR(MSD)}} \times 100$$

Comparison of Model and "Average" Rate Equations:

Error summations for the model's [VOL(MODEL)] and "average" rate equation's [VOL(AVG)] predictions of sludge accumulation were calculated. The average rate used to calculate the VOL(AVG) values was 0.029 m^3/pers-yr (the Singur mean rate).

There was relatively little difference found between the two error summations, with that of VOL(MODEL) being SUM=1.6 and that of VOL(AVG) being SUM=2.1. Because there was only slight difference in the error summation values, it can only be said that the use of the SAR(MODEL) values produced equivalent estimates of pit capacity requirements to those that resulted from the use of the "average" rate.

5.6 Model Validity and Possible Improvements

5.6.1 Summary of Model Evaluation

The evaluation indicated that the model could be used to predict the effects of different design and environmental parameters on accumulation rates in the Patna latrines. The model's SAR predictions were fairly accurate, and provided better estimates of pit capacity requirements than the use of an "average" accumulation rate.

The analysis of the Singur data did not lead to results as clear as those found with Patna data. In the Singur latrines, error in the model's SAR predictions proved to be unacceptable. The model only provided estimates of pit capacity requirements equal to what would have been found if the "average" rate had been used.

5.6.2 Remaining Questions

The use of the model led to accurate predictions of SAR values in the Patna latrines but not in the Singur latrines. What conclusion could be drawn when the model worked in one case but not another?

The final step in the data analysis was to ask why the model was able to accurately predict accumulation rates in the Patna latrines but not in the Singur latrines? By looking at this question it was hoped the strengths and weaknesses of the model would become evident, and, hence, a final judgement could be made on its utility.

5.6.3 Possible Reasons for Differences in Patna and Singur Results

There were three possible reasons why the model's predictions of sludge accumulation in the Patna latrines were better than its predictions in Singur latrines;

1) Model bad, data good:

One possible reason for the difference in the Patna and Singur results might lie in the exclusion of a design or environmental factor which affected sludge accumulation in the Singur latrines but not in the Patna latrines.

One such factor was thought to be groundwater penetration of the Singur latrines. During the period of the field study, the groundwater table was well below both the Patna and Singur latrines. Through questioning local residents this was found to always be the case in Patna but not so in Singur.

Following up the residents' observations, records of annual groundwater level fluctuation were examined at the All India Institute for Hygiene and Public Health research station at Singur. The information available indicated that the groundwater table moved quite a bit in a normal year. In the rainy season the groundwater table often came to within one meter of the surface, while later, during the dry season, the groundwater table could drop to a level of as much as six meters below the surface.

What effect the rise of the groundwater table into a latrine might have on the accumulation rate is not clear and needs further study. In any case, the point is that such a factor might have caused the model's predictions to be off in the case of the Singur latrines but not have affected the predictions for the Patna latrines.

2) Model good, data bad:

In the evaluation, two of the model parameters were assumed to have the same values in both Patna and Singur. A standard per capita loading rate of X-1.5 l/cap/day was assumed for all users. An "effective" hydraulic conductivity of k-eff=0.08 m/day was assumed in all latrines.

There is reason to believe that the per capita loading rate at the two sites could have actually been different. The per capita loading rate was probably higher in Patna than in Singur due to differences in community settings. The Patna research site was in an urban area. The Singur site was in a rural area. In Patna, the residents had to use their latrines. There was no alternative. In Singur, the residents may have used their latrines in the morning, but it is very unlikely that the latrines were used when the people were working on their farms during the rest of the day.

A standard per capita loading rate had to be assumed because there was not local data available. The ideal situation would be to have such information before starting a study of sludge accumulation rates. The important point is that the model's predictions of accumulation rates in the Singur latrines may be poor because the per capita loading rate in these latrines was overestimated. In this case the failure of the model would not have been because it was inappropriate, but rather because of bad input data.

3) Model good, data different:

One of the primary reasons that the model's predictions of sludge accumulation in the Patna latrines were better than those of the "average" rate equation was because the model was able to more accurately predict sludge accumulation in latrines of relatively young and old age. This is illustrated in Figures 5.10 and 5.11.

Looking solely at the Patna data there seemed to be the possibility that the main strength of the model was in its ability to predict the sludge accumulation rate-time relationship. It was not possible to confirm or deny this possibility with the Singur data because all of the latrines examined in Singur were of the same age.

An earlier study of sludge accumulation rates in Singur latrines had looked at the SAR-time relationship. This study had been conducted over a nine-year period (1972-81) by the Public Health Engineering Department of the All India Institute of Hygiene and Public Health.

In the AIIH&PH study are presented in Figure 5.12 where sludge accumulation rate versus time has to be plotted. On this graph the individual points represent the accumulation rates in each of nine latrines at the time when they were completely filled and could no longer be used.

Interestingly, the SAR-time relationship found by the AIIH&PH researchers is the same as predicted by the model (see Figure 5.2A) -- i.e., an exponential decline in accumulation rates with pit age.

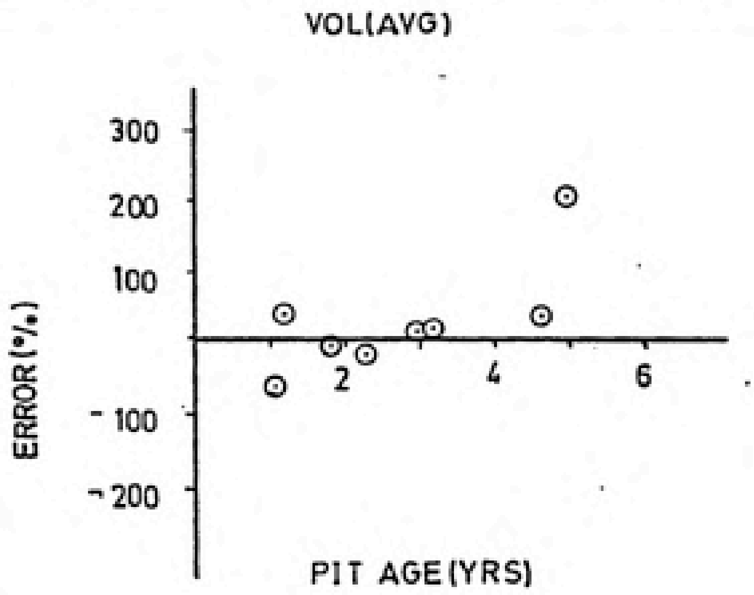


__Figure 5.10__ Percentage error (%) in "average" rate equation's predictions of sludge accumulation versus pit age.

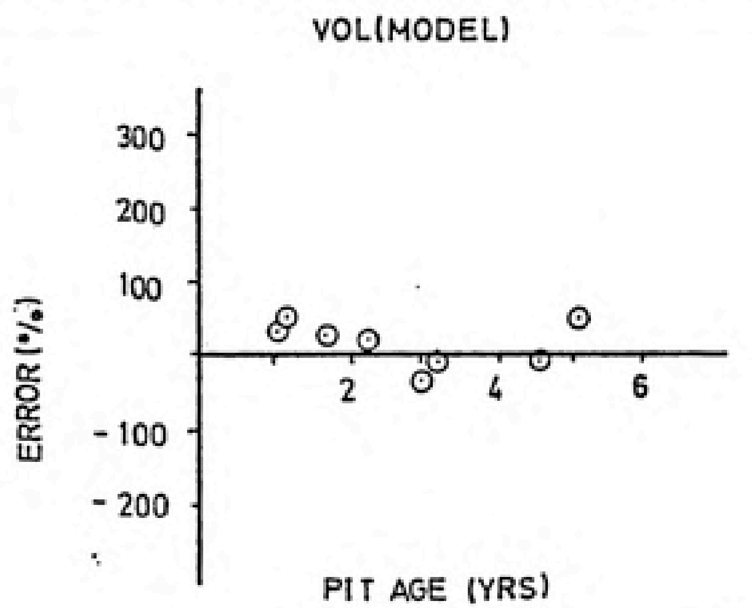
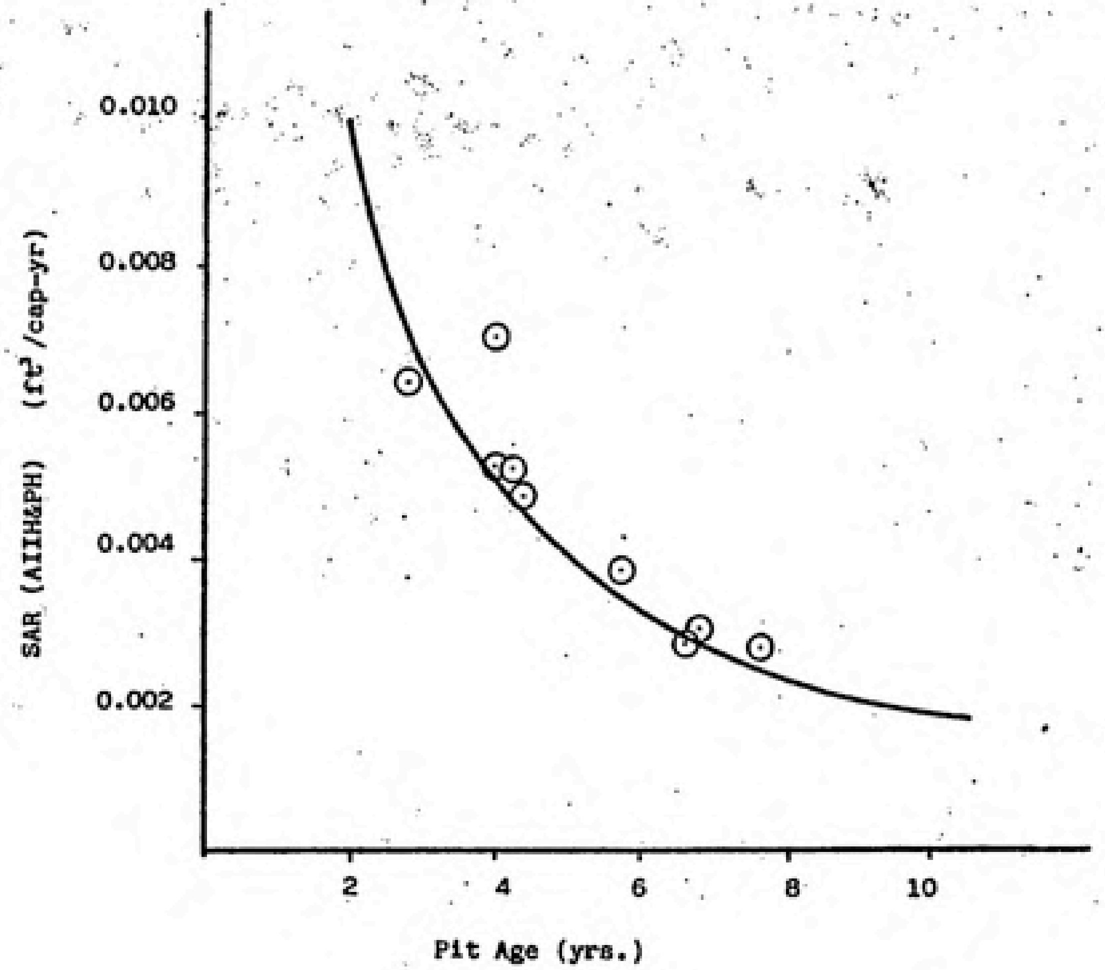


__Figure 5.11__ Percentage error (%) in model's predictions of sludge accumulation versus pit age.

Figure 5.12

Sludge Accumulation rate versus Pit Age (AIIH&PH Report)



Equation 5.15

SAR-Time Relationship Found by AIIH&PH

$$\text{Rate} = \frac{1}{47.5 \times (t)^{1.03}}$$

where, Rate = rate of filling of sludge accumulation rate (cft./cap-yr)
t = pit age (yrs).

5.7 Summary of SAR Relationship to Pit Design and Socio-economic and Environmental Factors

A theoretical model developed to examine the relationship between the sludge accumulation rate and design and environmental factors indicated that the SAR in any given latrine will be determined by five different factors -- per capita loading rate, "effective" hydraulic conductivity, and pit radius, drainage ratio, and age. Can this model be accepted?

Points in favor of model acceptance:

1. Model was able to accurately predict accumulation rates within ± 50% of actual rates in latrines (Patna only).
2. Use of model predicted accumulation rates led to estimates of pit capacity requirements as good as or better than an "average" rate (Singur and Patna).
3. Sludge accumulation rate - time relationship predicted by model agrees with that found in present and previous studies on latrines.

Points against model acceptance:

1. Model evaluation based on a limited amount of data [Patna (N=8), Singur (N=9)].

2. Model may not consider all design and environmental factors that affect accumulation rates (Singur).

The points in favor of the model outweigh the points against it which suggests the model should be accepted. The main strength of the model lies in its ability to predict sludge accumulation rates in latrines over time. Its main weakness may lie in the fact that it does not take into account the effect of hydrological changes (i.e., groundwater penetration) on sludge accumulation rates.

5.8 Improvement of Experiment Design

5.8.1 Data Categories

Because of the objectives of the project, two types of data were collected. One category of data consisted of information on sludge accumulation rates, latrine design, and environmental and socio-economic conditions. The second category consisted of the data on solids decomposition and drainage processes.

5.8.2 Sludge Accumulation Rate Data

There were three pieces of information which were used to estimate the sludge accumulation rate in a latrine. These were the use population size, latrine age, and sludge volume.

a) User population size

The most likely source of error in the accumulation rates was in the assessment of the user population size. The head of each household was interviewed and asked to name all of the people who had stayed in the house and had used the latrine from the date of latrine construction. Each person's name, occupation, date of birth, and entry or exit from the household were recorded. When possible, this information was confirmed by talking with a second household member.

Several lessons were learned in trying to gather the user information. First, the proper procedure for investigating a latrine is to conduct the user survey first, and then, later, to measure the amount of sludge accumulation. If good user information is not available then it makes no sense to continue the study of a latrine. If one begins by measuring the sludge accumulation, and later finds out the accurate user information can not be obtained, a lot of time is wasted.

Another issue is movement of people in and out of households. Every effort should be made to study latrines in areas where the households are fairly stable. Worker's quarters, military housing schemes, refugee camps, and other sites where there is a frequent shift in population should be avoided. The best situation is one in which the family owns the house in which it lives.

Many times latrines are present but people do not use them. Before a research site is selected, every effort should be made to find out the local residents' attitudes toward latrine usage. It is very difficult to assess the correct user population size when people report regular use of a latrine when in reality the use is not regular. Studies should only be conducted in areas where there is strong evidence of latrine usage by all members of the community.

Finally, because the user population size is such a crucial factor and so difficult to estimate objectively, it is recommended that independent testing should be conducted to 1) confirm the user information gathered by the research team, and 2) to provide an estimate of error in the latrine owner's reply to the user survey. The independent testing would not have to be done in every household where a latrine was studied. Only one out of five or ten households would be interviewed a second time.

b) Latrine Age

In the present study, the household owners were asked when their latrines had been built. This information was confirmed by checking the records of the institutes that had constructed the latrines. For the most part, the date on record agreed with that given by the household owners.

The type of situation in which the latrine age can be confirmed by some sort of official record is ideal. When selecting a research site, it is recommended that areas should be considered where latrines have been constructed in association with public health and community development projects. If this is done, then the likelihood of obtaining records of latrine installation become much higher.

One particular problem encountered in the present study was that of determining the date of pit change-over in dual-pit latrines. All of the change-overs had been made by the latrine owners and therefore it was necessary to rely on the owner's memory for this information. It is recommended in future studies that dual-pit latrines be studied early in their operation, before pit change-over has been made. This would eliminate reliance on the owner's memory for determination of pit age.

c) Sludge Volume

Measurement of sludge volume was a relatively straightforward matter. The sludge level and pit depth were measured to determine the sludge thickness. The pit length by width (rectangular pits) or diameter (circular pits) was measured to determine the cross-sectional area. Multiplying the sludge thickness by area provided the sludge volume. All measurements were made by using a measuring tape. A steel rod was used to find the pit base.

One thing which made it easy to determine the pit depth in the Patna and Singur latrines was the fact that the sidewalls of each pit were completely lined. If unlined latrines are to be examined, then the best procedure is to take a minimum of three depth measurements at different points in a pit. Unusual findings should be rechecked. Again, construction records are helpful if available.

5.8.3 Decomposition Process Data

a) Sludge Composition

It was hoped that differences in gas production rates could be correlated with chemical and physical differences in the sludge samples. It was also hoped that the amount of solids reduction in different chemical constituents could be examined. Unfortunately, this was not possible. An unusually large degree of variation was found in the laboratory results, thus bringing their validity into question.

There are two possible reasons why the laboratory results showed so much variation. First, the sampling technique might have been faulty. In the present study, sludge was taken from three different points in a pit, this sludge was mixed, and the resulting sample was analyzed. To check whether this procedure is adequate or not, it is recommended that in future studies individual sludge samples be analyzed and these results be compared to the results found in a mixed sample.

The second possibility is that the chemical analyses were poorly done. The sludge samples were taken to local laboratories for analyses. It was requested that the samples be analyzed by APHA standard methods. It was assumed that the laboratories were of high quality and that analytical problems would not be encountered. This may have been an incorrect assumption. In future studies, it is recommended that,

1) selected replicate samples be sent for analyses. Triplicate samples of the selected sludge should be sent for analyses to check the precision of a laboratory's work. Attention should be paid to the precision of each of the methods used in the sludge analysis.

2) Spiked samples be sent for analyses. Samples of a known concentration should be given to a laboratory to assess the accuracy of its work. Spiked samples containing all chemical constituents which are to e analyzed by the laboratory should be provided so that the accuracy in each analytical method will be known.

b) Gas Production Test

The gas production test, if conducted properly, could provide useful information on the relationship between the solids decomposition rate and physical and chemical conditions in a latrine.

In the present study, the gas production test was a secondary concern and, hence, probably was not given as much attention as required for good results. For future studies it is recommended that,

1) replicate tests of the samples taken for the same pit should be performed. This would provide an idea of the amount of experimental error in the testing procedure.

2) The conditions under which the test is performed should be as controlled as possible. One problem which occurred in the present study was that a change in the ambient air temperature sometimes affected the test results. This problem could be eliminated by insulating the sampling tube and gas collection apparatus.

3) Accurate equipment should be used to measure gas production. In particular, the manometer used in the present study was fairly crude. With better equipment, better test results should be observed.

5.8.4 Drainage Process

a) Soil properties

Two types of soil properties were examined in the study -- soil texture and hydraulic conductivity. ASTM standard methods for particle size analysis were used to determine soil texture. The inversed auger hole method was used to determine soil hydraulic conductivity.

For future studies it is recommended that ASTM standards continue to be followed in the analysis of soil texture. ASTM methods are well documented and recognized throughout the world. Most agricultural research stations perform ASTM soil particle size analyses on a routine basis.

The inversed auger hole method (often called the falling head percolation test) for finding a soil's hydraulic conductivity is also well known. However, unlike the soil texture analysis, the inversed auger hole method often does not provide consistent results.

In future studies it is recommended that the inversed auger hold method be used. Despite its lack of precision and accuracy, it is the quickest and least expensive means of assessing hydraulic conductivity. Other, more accurate, methods are available (Kessler and Oosterboan, 1974) for situations where more time and money are available.

b) Drainage rate

In the study, the rate of liquid loss from a latrine was measured over a six to eight hour period. It was hoped that both a qualitative and quantitative sense of "normal" drainage could be obtained from this test.

The results of the drainage test were mixed. In some latrines, the surface level of the pit contents dropped by as much as thirty centimeters during the time of observation. In other latrines, there was no drop at all. There appeared to be an "equilibrium" level above which drainage would occur and below which it would not.

It is recommended that in future studies this test not be repeated. There appears to be no practical way of determining the "equilibrium" level other than to observe a latrine over a one day period. Once the "equilibrium" level is identified, the drainage rate can be monitored for comparative purposes. This would require that a latrine be observed for a second day, and this is considered to be impractical in terms of user inconvenience.

VI. CONCLUSIONS

6.1 Sludge Accumulation Rates

1. <u>The "normal range of sludge accumulation rates in pour-flush latrines is between 0.010 and 0.060 m^3/person-yr</u>.

   Based on:

   a) Sludge accumulation rate range observed in present study of Patna and Singur latrines.

   b) Sludge accumulation rate range observed in previous latrine studies.

2. <u>The "average" rate of sludge accumulation in pour-flush latrines is 0.025 m^3/person-yr</u>.

   Based on:

   a) Median and mean accumulation rates found in Patna latrines (N=12), which were 0.031 and 0.034 m^3/person-year, respectively.

   b) Median and mean accumulation rates found in Singur latrines (N=12), which were 0.022 and 0.029 m^3/person-year, respectively.

6.2 Sludge Accumulation Rate Relationship to Design, Environmental and Socio-economic Factors

1. <u>The sludge accumulation rate declines exponentially with time</u>.

   Based on:

   a) Sludge accumulation rate-time relationship observed in Patna latrines.

   b) Sludge accumulation rate-time relationship observed in previous studies.

2. The main factors which affect the sludge accumulation rate are per capita loading rate, pit dimensions (radius in circular pits, length and width in rectangular pits), and amount of pit lining.

Based on:

a) Parameters which according to theoretical considerations will affect the rate of liquid loss from a latrine.

b) Use of a model based on these parameters led to accurate predictions of sludge accumulation rates as observed in Patna and Singur latrines.

3. Soil type has no affect on the sludge accumulation rate.

a) Engineering literature indicates that clogging phenomenon will occur in any soil (sand, silt, or clay) which is saturated for long periods of time.

b) In the present study, a model based on the assumption that clogging had occurred accurately predicted sludge accumulation rates observed in latrines situated in different soil types.

VII. DESIGN RECOMMENDATIONS

7.1 Design Guidelines

7.1.1 Effective Capacity Factor versus Time Graphs

Use of the model developed in the SAR project provides a new means of assessing pit capacity requirements for pour-flush latrines. Instead of using an "average" accumulation rate, it becomes possible to predict effective capacity factors for individual latrines based on choice of pit design, environment, and expected operational period.

For practical purposes, three graphs have been prepared depicting the effective capacity factor-time relationship for design of latrines for five, ten, and fifteen-user families (see Figures 7.1-3).

To prepare the EF-time graphs it was necessary to make certain assumptions concerning pit design. Based on recommendations made in the "Manual on the Design, Construction, and Maintenance of Low-Cost Pour-Flush Waterseal Latrines in India," issued by UNDP/TAG (World Bank, 1984), pit diameters of different sizes were used for three user groups. The suggested diameters for five, ten, and fifteen users were 1.0 m, 1.2 m, and 1.4 m, respectively.

A value for ratio of unlined to total pit sidewall area (i.e., drainage ratio, Y) also had to be assumed. The value used in the preparation of the EF-time graph, Y=0.03, is based upon the brick-spacing pattern seen in the Patna latrines.

7.1.2 Examples of Assessment of Pit Capacity Requirements

Three examples have been worked out to illustrate how the EF-time graphs can be used to predict pit capacity requirements.

In Example A, a latrine for a small family is to be built. To start with, a "Pit Capacity Requirement" form is filled out (see following page). On this form, the expected number of users is reported.

Finding that there are five family members, the latrine designer must then decide on the pit's operational period. This period could depend upon a number of factors -- the availability of municipal pit emptying services, the cost of emptying, etc. In the case of Example A, a pit life of three years is decided upon.

Knowing the user population size and pit operational period it is possible to utilize the EF-time graphs. Because the user size is five, Figure 7.1 is used. Finding the EF factor is simply a matter of locating the operational

Example A: Assessment of pit capacity requirements for a five-user family

Pour-Flush Latrine (Dual Pit) Pit Capacity Requirements

I. Latrine Owner
Name: Harry Kumar
Address: Connaught Circus, New Delhi

II. Latrine Usage Information

a) Number of people in household (N) = 5 (capita)
b) Anticipated period before pit switch-over or emptying (PL) = 3 (years)
c) Effective capacity factor (EF) = 0.047 (m^3/pers-yr.)
Five-user family (Figure 7.1)
d) Pit diameter (PD) = 1.0 (m)
Five-user family (PD=1.0 m)

III. Pit Design

a) Pit capacity requirements (PCR)

Effective volume per pit = 0.047 (EF) x 5 (N) x 3 (PL) = 0.71 (m^3)

b) Pit depth required

Pit depth = 1.27 x 0.71 (PCR)/1.0 (PD^2) = 0.90 (m)

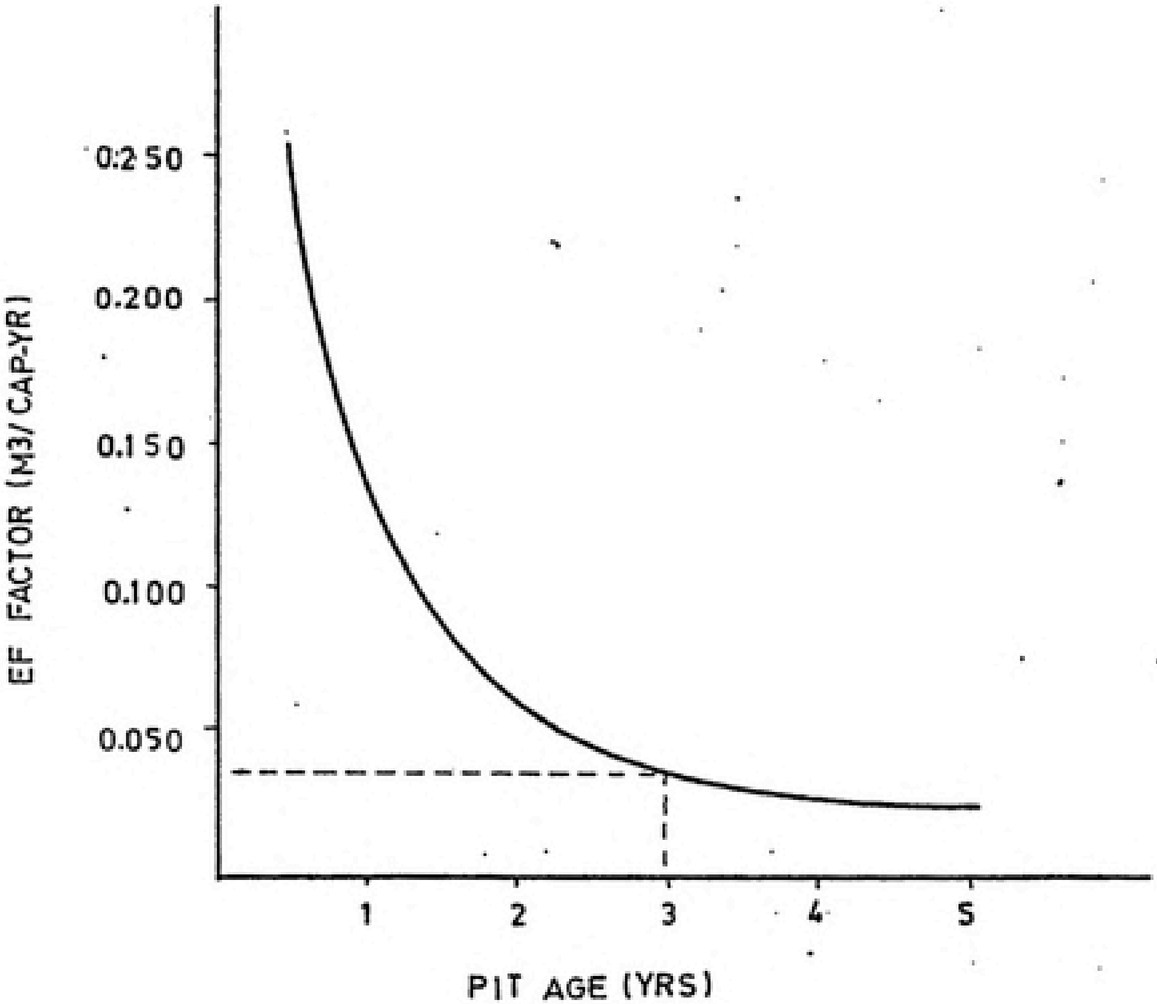


Figure 7.1 "Effective" Capacity Factor - Time Curve for Five-user Family

Situation: Latrine designed for three years of use before pit change-over or emptying.

Constants: X=1.5 l/cap/day
Y=0.03
r=0.45 m
k-eff=0.08 m/day

period (Pit Age) on the x-axis, following this line to the curve, and then reading corresponding EF factor from the y-axis.

Pit Capacity Required = EF x PL x N

where EF = effective capacity factor, 0.047 m^3/pers-yr. (from Figure 7.1 at pit age equal to three years),
N = user population size, five,
PL = pit operational period, three years.

In Example A, the pit capacity required turns out to be 0.71 m^3. Examples B and C illustrate use of the EF-time graphs in ten and fifteen user family situations.

7.2 Way of Reducing Sludge Accumulation Rates

In the interpretation of the model (Section 5.3), the effect of different parameters on the sludge accumulation rate were considered. From this information, practical means of reducing sludge accumulation rates can be suggested.

7.2.1 Reduction of Clogging Effect

According to the study results, one means of increasing drainage from a latrine would be to reduce or eliminate the microbial clogging of the walls and base of a pit. This might be achieved by lining the outside of a pit with an envelope of gravel as illustrated in Figure 7.4.

Example B: Assessment of pit capacity requirements for a ten-user family

Pour-Flush Latrine (Dual Pit) Pit Capacity Requirements

I. Latrine Owner
Name: R. J. Singh
Address: Independence Ave., Patna

II. Latrine Usage Information

a) Number of people in household (N) = 10 (capita)
b) Anticipated period before pit switch-over or emptying (PL) = 2 (years)
c) Effective capacity factor (EF) = 0.093 (m^3/pers-yr.)
Ten-user family (Figure 7.2)
d) Pit diameter (PD) = 1.2 (m)
Ten-user family (PD=1.2 m)

III. Pit Design

a) Pit capacity requirements (PCR)

Effective volume per pit = 0.093 (EF) x 10 (N) x 2 (PL) = 1.86 (m^3)

b) Pit depth required

Pit depth = 1.27 x 1.86 (PCR)/1.2 (PD^2) = 1.64 (m)

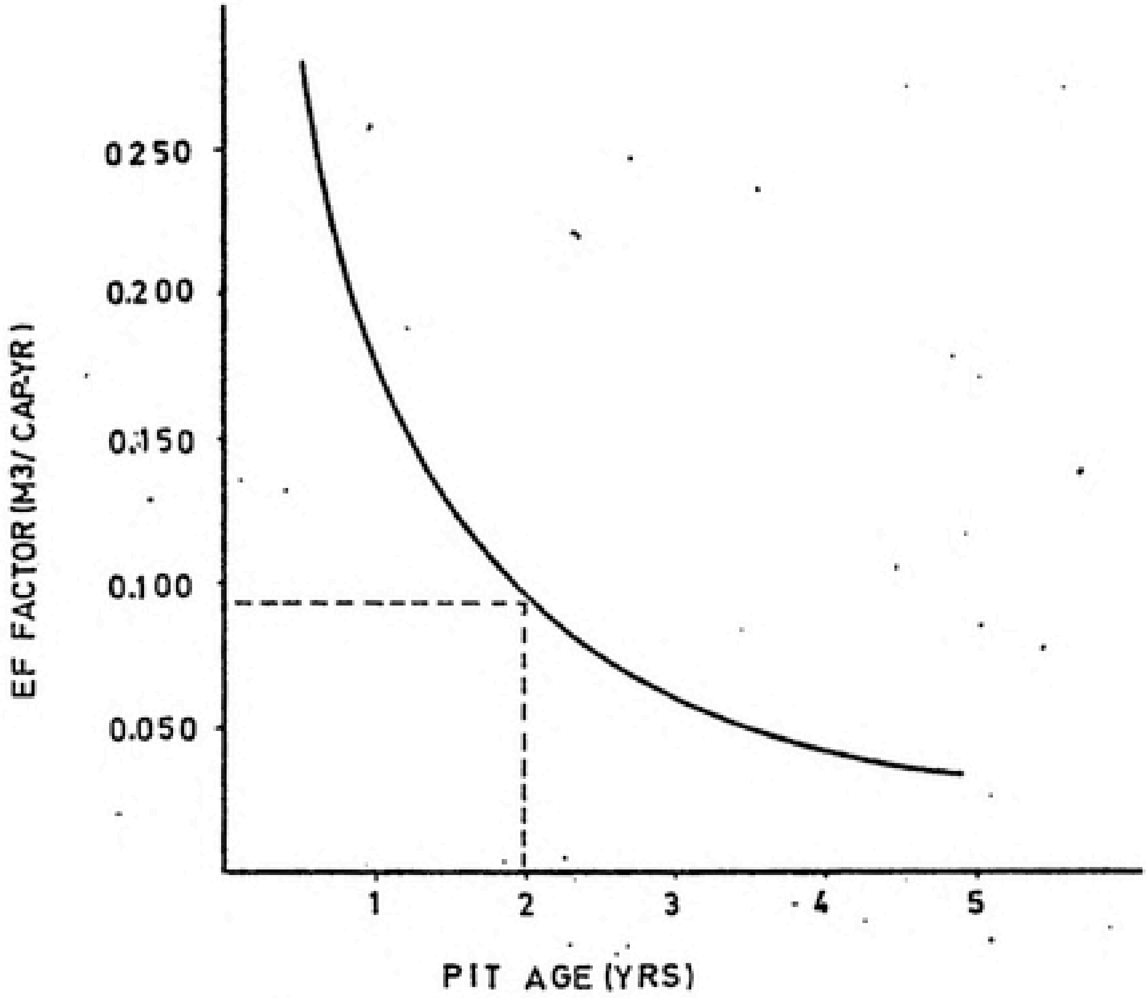


Figure 7.2 "Effective" Capacity Factor - Time Curve for Ten-user Family

Situation: Latrine designed for two years of use before pit change-over or emptying.

Constants:

Y=0.03
r=0.60m
k-eff=0.08 m/day

Example C: Assessment of pit capacity requirements for a fifteen-user family

Pour-Flush Latrine (Dual Pit) Pit Capacity Requirements

I. Latrine Owner
Name: S. W. Rao
Address: Madras Road, Calcutta

II. Latrine Usage Information

a) Number of people in household (N) = 15 (capita)
b) Anticipated period before pit switch-over or emptying (PL) = 4 (years)
c) Effective capacity factor (EF) = 0.055 (m^3/pers-yr.)
Fifteen-user family (Figure 7.3)
d) Pit diameter (PD) = 1.4 (m)
Fifteen-user family (PD=1.4 m)

III. Pit Design

a) Pit capacity requirements (PCR)

Effective volume per pit = 0.055 (EF) x 15 (N) x 4 (PL) = 2.14 (m^3)

b) Pit depth required

Pit depth = 1.27 x 0.71 (PCR)/1.0 (PD^2) = 0.90 (m)

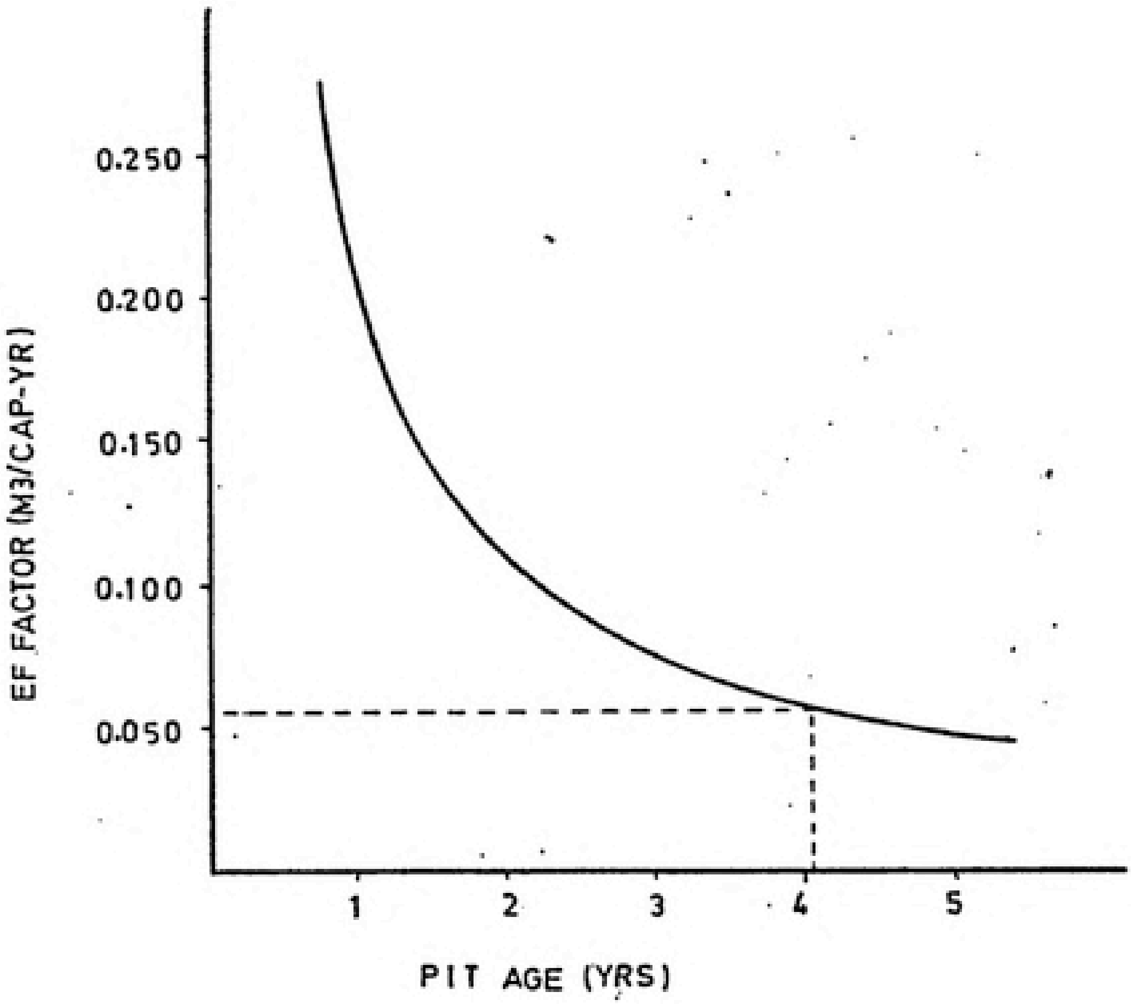


Figure 7.3 "Effective" Capacity Factor - Time Curve for Fifteen-user Family.

Situation: Latrine designed for four years of use before pit change-over or emptying.

Constants: X=1.5 l/cap/day
Y=0.03
r=0.70 m
k-eff=0.08 m/day

General Form

Pour-Flush Latrine (Dual Pit) Pit Capacity Requirements

I. Latrine Owner
Name: ______________________________
Address: ____________________________
____

II. Latrine Usage Information

a) Number of people in household (N) = ____ (capita)
b) Anticipated period before pit switch-over or emptying (PL) = ____ (years)
c) Effective capacity factor (EF) = ____ (m^3/pers-yr.)
Five-user family (Figure 7.1)
Ten-user family (Figure 7.2)
Fifteen-user family (Figure 7.3)
d) Pit diameter (PD) = ____ (m)
Five-user family (PD = 1.0 m)
Ten-user family (PD = 1.2 m)
Fifteen-user family (PD = 1.4 m)

III. Pit Design

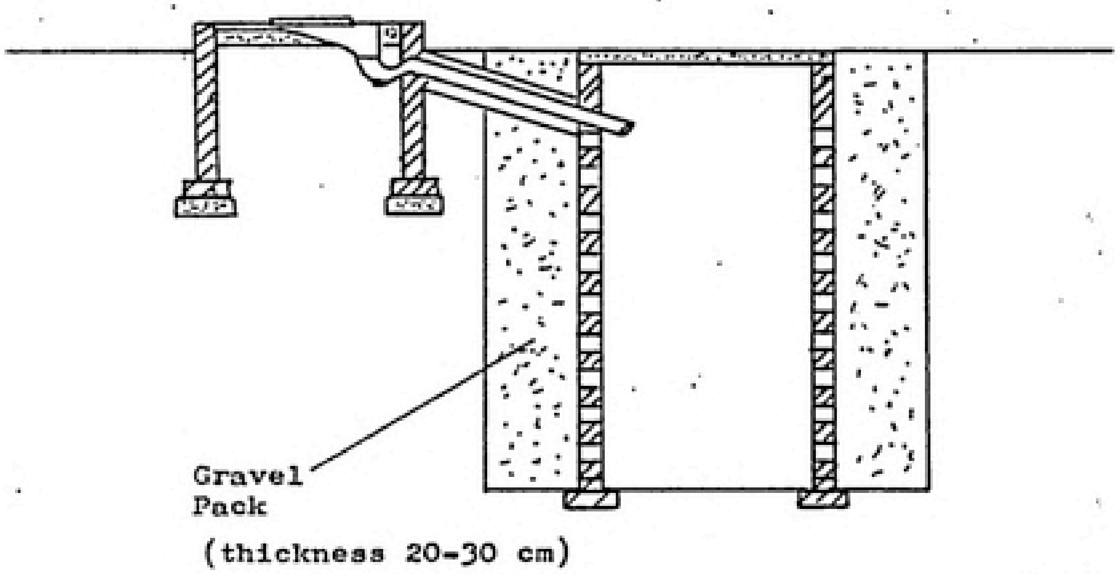
a) Pit capacity requirements (PCR)

Effective volume per pit = ____ (EF) x ___ (N) x ___ (PL) = ___ (m^3)

b) Pit depth required

Pit depth = 1.27 x ____ (PCR)/____ (PD^2) = ____ (m)

Figure 7.4 Pour-flush latrine lined with gravel to reduce sludge accumulation.



7.2.2 Increasing Drainage Ratio

Another way of increasing drainage from a latrine would be to increase the ratio of unlined to total pit sidewall area. This could be done by changing the brick spacing pattern in pits which are honey-combed, or perforating the rings used in tile lined pits.

7.2.3 Proper Operation of Dual-Pit Latrines

Many of the dual-pit latrines studied in Patna were not operating as designed. In particular, both pits were connected in several of these latrines. Operation of the latrines in this fashion can lead to higher accumulation rates because there is no "rest" period in a pit's operation. Studies on clogging indicate that one means of reducing the clogging effect is to expose the clogging layer to dry, aerobic conditions. This can only occur if one pit is operated at a time.

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Appendix 2

Experimental Data

General Description of Pit Latrines: Patna

PIT NO.	DATE OF CONSTRUCTION*	DESIGN OF PITS	PIT CAPACITY (m^3)	TYPE OF PIT LINING
1	JAN 76	DUAL	2.6280	Honey-combed brick
2	MAY 75	"	2.1408	"
3	JAN 76	"	2.2248	"
4	JAN 76	"	2.4280	"
5	JAN 80	"	1.3106	"
6	JUNE 75	"	1.1204	"
7	JUNE 76	"	2.4894	"
8	SEPT 76	"	1.1446	"
9	MAY 76	"	1.2750	"
10	MAY 76	"	1.1576	"
11	DEC 78	"	5.2000	"
12	MARCH 71	"	5.6434	"
13	FEB 73	"	6.4746	"
14	NOV 81	"	1.6786	"
15	JULY 71**	"	2.0322	"

*Date of construction or first use

**Emptied once in May 1983

General Description of Pit Latrines: Singur

PIT NO.	DATE OF CONSTRUCTION*	DESIGN OF PITS	PIT CAPACITY (m^3)	TYPE OF PIT LINING
1	FEB 76	SINGLE	1.591	Inter-locking tile rings
2	FEB 76	"	1.4072	"
3	FEB 76	"	1.4902	"
4	FEB 76	"	0.8198	"
5	FEB 76	"	0.9358	"
6	FEB 76	"	1.1945	"
7	FEB 76	"	1.2638	"
8	MARCH 76	"	1.1580	"
9	MARCH 76	"	1.2776	"
10	JAN 76	"	1.1814	"
11	JAN 72	"	2.8464	"
12	JAN 76	"	2.5544	"
13	MARCH 76	"	1.9742	"
14	JAN 76	"	1.5008	"
15	FEB 76	"	1.4862	"

Patna
Pit Design Data

Latrine Number	Length (cm)	Width (cm)	Depth (cm)	Drainage Ratio
1	118	96	116	0.028
2	97	89	124	0.038
3	98	88	129	0.028
4	97	84	149	0.021
5	71	65	142	0.022
6	74	67	113	0.058
7	93	87	146	0.040
8	73	70	112	0.029
9	75	68	125	0.048
10	72	67	120	0.038
11	(dia.=180cm)		138	—
12	152	102	203	0.059
13	164	84	233	0.019
14	81	81	128	0.025
15	94	94	115	0.013

Singur
Pit Design

Latrine Number	Radius (cm)	Depth (cm)	Ring Height (cm)
1	30	394	14
2	30/35	394	14
3	30/35	405	14
4	27	358	18
5	30	331	19
6	32	360	20
7	34	348	20
8	32	349	15
9	32	332	14
10	35	387	17
11	44	468	15
12	44	428	15
13	33/35	254	15
14	35	400	20
15	30	390	20

The drainage ratio in the Singur latrines was assumed to equal 0.0125 based upon a ring height of 18 cm with a 0.25 cm gap between rings.

Patna
Latrine Useage Data

Latrine Number	Pit Age (years)	Wt. Average Users	Operation Status
1A	3.50	7.0	full
1B	4.59	7.0	in use
2A	4.00	14.0	full
2B	3.67	14.0	full
2C	1.00	7.0	in use
3A&B	8.00	3.5	in use
4A&B	8.00	2.5	in use
5A&B	4.00	8.4	in use
6A	4.50	10.0	full
6B	3.17	13.0	full
6C	1.17	13.4	in use
7A	6.00	8.2	full
7B	1.75	10.0	in use
8A	4.33	2.5	full
8B	3.16	3.9	in use
9A&B	7.40	4.6	in use
10A	4.84	9.0	full
10B	3.00	4.0	in use
11A&B	6.00	6.5	in use
12A	8.00	12.0	partially full
12B	5.00	11.2	in use
13A&B	11.00	11.1	in use
14A	2.33	3.6	in use
15A&B	12.00	11.0	in use

Singur
Latrine Useage Data

Latrine Number	Pit Age (years)	Wt. Average Users	Operation Status
1	8.25	2.0	in use
2	8.25	2.0	in use
3	7.00	2.0	in use
4	8.25	3.1	in use
5	8.25	8.9	in use
6	8.16	4.5	in use
7	8.16	4.9	in use
8	8.00	2.5	in use
9	8.00	3.6	in use
10	8.25	2.2	in use
11	8.25	3.6	in use
12	8.25	2.4	in use
13	8.00	9.9	in use
14	8.25	6.7	in use
15	8.16	2.0	in use

Sludge and Total Accumulation Rates
(m^3/capita/yr)

LATRINE	PATNA "OPERATING PITS" SLUDGE	PATNA "OPERATING PITS" TOTAL	SINGUR SLUDGE	SINGUR TOTAL
1	0.022	0.033	0.019	0.022
2	0.063	0.105	0.039	0.042
3			0.051	0.057
4			0.009	0.011
5			0.011	0.012
6	0.014	0.033	0.010	0.024
7	0.037	0.050	0.017	0.020
8	0.034	0.041	0.054	0.054
9				
10	0.031	0.043	0.021	0.021
11				
12	0.006	0.013	0.074	0.086
13				
14	0.027	0.050	0.006	0.021
15			0.015	0.021

TABLE SR-2 Solid and COD Reduction

Item	PATNA (N=14) Mean ± SD	SINGUR (N=14) Mean ± SD
Loss of total solids (%)		88.25 ± 8.3784.77 ± 12.18
Loss of organic (volatile) solids	87.48 ± 10.08	86.06 ± 12.83
Loss of inorganic (fixed) solids	90.79 ± 7.61	81.70 ± 15.01
Loss of nitrogen (%)	99.23 ± 0.92	94.26 ± 2.93
Loss of phosphorus (%)	95.64 ± 4.61	95.17 ± 2.66
Loss of COD (%)	55.24 ± 37.80	89.41 ± 6.69

PUBLIC HEALTH INSTITUTE, PATNA

NAME OF PROJECT: Sludge Accumulation Study

Reports of Chemical Analysis Nature of Sample-Sludge

SAMPLE NO	DATE OF COLLECTION	TOTAL SOLID gm/kg	TOTAL VOLATILE SOLID gm/kg	CHLORIDE mg/kg	COD gm/kg	TOTAL NITROGEN AS NH_3-N gm/kg	AMMONIA NITROGEN AS NH_3-N gm/kg	ORGANIC NITROGEN AS NH_3-N gm/kg	TOTAL PHOS AS P_2O_5 gm/kg
1	11-2-84	94.54	48.93	0.800	252.6	0.276	0.155	0.121	2.000
2	11-2-84	4.62	3.22	0.016	5.7	0.015	0.008	0.015	0.600
3	13-2-84	89.64	75.31	0.640	144.6	0.233	0.120	0.113	1.000
4	14-2-84	96.36	55.39	0.340	152.4	0.215	0.120	0.095	0.801
5	14-2-84	103.69	86.43	0.940	275.0	0.215	0.103	0.112	2.610
6	17-2-84	90.67	68.40	0.346	152.6	0.240	0.120	0.120	3.210
7	22-2-84	87.10	40.67	0.530	144.8	0.216	0.120	0.096	4.608
8	22-2-84	115.13	60.79	0.340	355.2	0.336	0.240	0.096	6.791
9	24-2-84	90.77	86.53	0.076	125.6	0.264	0.120	0.144	3.125
10	24-2-84	245.40	222.80	0.107	175.8	0.286	0.144	0.144	0.667
11	2-3-84	31.68	17.15	0.192	193.6	0.252	0.093	0.156	0.232
12	2-3-84	89.68	78.53	0.675	332.0	0.986	0.538	0.448	0.053
13	7-3-84	100.72	75.45	0.580	67.2	1.037	0.140	0.897	0.202
14	8-3-84	140.78	91.31	1.000	460.0	0.672	0.299	0.373	0.077
15A	9-3-84	4.20	2.36	0.240	6.1	0.263	0.053	0.210	0.058
15B	9-3-84	71.00	59.64	0.240	73.6	0.560	0.280	0.280	0.511

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ALL INDIA INSTITUTE OF HYGIENE & PUBLIC HEALTH
110, CHITTARANJAN AVENUE, CALCUTTA - 73

NAME OF THE PROJECT : SLUDGE ACCUMULATION STUDY

INVESTIGATOR - UNDP CONSULTANT :

REPORTS OF CHEMICAL ANALYSIS

NATURE OF SAMPLE - SLUDGE

Sample No. (Pit)	Date of collection	Specific Gravity	Total solid gm/kg at 105°C	Total volatile solid - gm/kg at 500°C	Non-filtrable solid gm/kg at 105°C	Volatile non filtrable solid gm/kg at 500°C	Chloride mg/kg	C.O.D. gm/kg	Total Nitrogen as NH_3-N gm/kg	Ammonia Nitrogen as NH_3-N gm/kg	Organic Nitrogen as NH_3-N gm/kg	Total Phosphate as P_2O_5 gm/kg
1.	30.3.84	1.12	200.16	140.60	165.60	126.00	230	71.5	6.069	.773	5.296	4.125
2.	30.3.84	1.18	294.40	192.60	262.20	175.00	240	32.0	4.011	1.489	2.522	3.088
3.	30.3.84	1.04	63.20	26.00	58.60	21.50	420	70.0	3.885	1.100	2.785	1.925
4.	30.3.84	1.10	230.00	132.60	220.00	122.00	270	122.0	7.096	2.036	5.060	5.635
5.	07.4.84	1.04	51.10	17.00	41.00	37.00	430	98.0	5.880	1.860	4.000	3.223
6.	07.4.84	1.01	42.50	11.75	37.50	10.50	290	112.0	7.012	2.120	4.892	4.418
7.	07.4.84	1.08	152.40	106.40	135.20	101.80	490	28.0	3.520	1.110	2.410	2.536
8.	07.4.84	1.04	79.58	28.70	75.00	27.50	190	42.0	4.175	0.650	3.525	3.110
9.	07.4.84	1.41	512.28	447.96	495.00	431.30	320	36.0	3.850	1.188	2.662	2.624
10.	07.4.84	1.21	321.40	253.60	287.10	248.20	320	34.0	4.165	0.990	3.175	1.855
11.	12.4.84	1.03	203.78	95.70	157.20	85.50	420	90.0	5.560	1.775	3.785	3.619
12.	12.4.84	1.13	511.40	297.60	369.90	250.00	440	100.00	6.960	2.050	4.910	4.825
13.	12.4.84	1.25	284.00	185.30	210.00	170.00	170	62.0	5.020	1.990	3.030	3.112
14.	12.4.84	1.07	196.50	69.00	136.00	61.00	350	52.0	4.576	0.776	3.800	2.665
15.	12.4.84	1.05	64.88	47.00	51.10	41.00	185	110.0	7.690	2.125	5.565	4.835

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Physical/Chemical Characteristics of Pit Contents: Patna

PIT NO	pH	TEMP (°C)	MOISTURE (%)	COD/N	DO (mg/l)
1	6.3	-	89.56	918.5	-
2	6.9	-	78.96	262.0	-
3	6.5	-	90.15	920.6	-
4	7.5	16.6	89.34	705.6	0.02
5	7.9	18.6	88.43	1273.1	0.06
6	7.1	22.6	90.03	633.2	0.15
7	7.0	23.8	90.46	670.4	-
8	6.5	21.0	86.99	970.5	0.15
9	6.9	17.3	90.02	475.8	0.11
10	6.8	17.7	67.48	610.4	0.09
11	-	19.9	96.73	777.5	0.16
12	7.4	21.5	90.15	336.7	0.12
13	7.4	23.3	88.80	64.9	0.14
14	6.6	22.3	83.62	684.5	0.06
15A	7.4	17.8	92.36	41.8	0.11
15B	7.6	18.2	99.52	131.4	0.15
MEAN	7.1	20.1	88.27	592.3	0.11
SD	±0.5	±2.5	±7.17	±352.7	±0.05

Physical/Chemical Characteristics of Pit Contents: Singur

PIT NO	pH	TEMP (^{o}C)	MOISTURE (%)	COD/N	DO (mg/l)
1	7.0	26.7	79.9	11.78	0.14
2	7.5	24.5	70.6	7.98	0.22
3	6.8	23.6	93.7	18.02	0.11
4	6.9	27.4	77.0	17.19	0.09
5	6.7	30.9	94.9	16.67	0.07
6	6.8	29.1	95.8	15.97	0.10
7	7.0	28.4	84.8	7.95	0.10
8	7.0	29.2	92.0	10.06	0.09
9	7.3	29.6	48.8	9.35	0.10
10	6.7	27.3	67.9	8.16	0.14
11	7.1	28.5	79.6	16.19	0.08
12	7.1	29.2	48.9	14.37	0.08
13	7.0	28.3	71.6	16.33	0.14
14	7.2	26.8	80.4	11.36	0.11
15	7.7	26.7	93.5	14.30	0.12
MEAN	7.1	27.7	78.6	13.05	0.11
SD	±0.3	±1.9	±15.2	±3.69	±0.04

Solids Reduction Data - Patna

LATRINE	TOTAL SOLIDS LOADED (KG)	LATRINE	TOTAL SOLIDS ACCM. (KG)	LATRINE	TOTAL SOLIDS REDUCTION(%)
1	1155.00	1	101.30	1	91.20
2	273.00	2	3.70	2	98.60
3	1008.00	3	14.90	3	98.50
4	9.00	4	51.10	4	-468.00
5	1152.00	5	134.50	5	88.30
6	466.00	6	47.90	6	89.70
7	780.00	7	78.50	7	89.90
8	456.00	8	62.20	8	86.30
9	297.00	9	48.10	9	83.70
10	432.00	10	130.10	10	69.80
11	150.00	11	12.30	11	91.70
12	2196.00	12	42.30	12	98.00
13	4428.00	13	321.80	13	92.70
14	336.00	14	66.00	14	80.30
15	330.00	15	76.82	15	76.82

LATRINE	VOLATILE SOLID LOADED (KG)	LATRINE	VOLATILE SOLID ACCM. (KG)	LATRINE	VOLATILE SOLID REDUCTION(%)
1	808.50	1	52.40	1	93.50
2	191.10	2	2.60	2	98.60
3	705.60	3	12.50	3	98.20
4	6.30	4	29.40	4	-367.10
5	806.40	5	112.10	5	86.00
6	327.60	6	36.20	6	88.90
7	546.00	7	36.60	7	93.20
8	319.20	8	32.80	8	89.60
9	207.90	9	45.80	9	77.90
10	302.40	10	118.10	10	60.90
11	105.00	11	6.70	11	93.60
12	1537.20	12	37.00	12	97.50
13	3099.60	13	241.00	13	92.20
14	235.20	14	42.80	14	81.70
15	231.00	15	62.40	15	73.00

LATRINE	FIXED SOLIDS LOADED (KG)	LATRINE	FIXED SOLIDS ACCM. (KG)	LATRINE	FIXED SOLIDS REDUCTION(%)
1	346.50	1	48.90	1	85.80
2	81.90	2	1.10	2	98.60
3	302.40	3	2.30	3	99.20
4	2.70	4	21.70	4	-706.10
5	345.60	5	22.40	5	93.50
6	140.40	6	11.70	6	91.60
7	234.00	7	41.80	7	82.10
8	136.80	8	29.30	8	78.50
9	89.10	9	2.20	9	97.40
10	129.60	10	11.90	10	90.70
11	45.00	11	5.60	11	87.30
12	658.80	12	5.20	12	99.20
13	1328.40	13	80.70	13	93.90
14	100.80	14	23.20	14	76.90
15	99.00	15	14.00	15	96.40

Solids Reduction Data - Patna

LATRINE	COD LOADED (KG)	LATRINE	COD ACCM. (KG)	LATRINE	COD REDUCTION(%)
1	577.50	1	270.80	1	53.00
2	136.50	2	4.50	2	96.60
3	504.00	3	24.10	3	95.20
4	4.50	4	80.90	4	-1699.30
5	576.00	5	356.90	5	38.00
6	234.00	6	80.70	6	65.40
7	390.00	7	130.50	7	66.50
8	228.00	8	192.10	8	15.70
9	148.50	9	66.50	9	55.10
10	216.00	10	93.20	10	56.80
11	75.00	11	75.60	11	-0.90
12	1098.00	12	156.70	12	85.70
13	2214.00	13	214.70	13	90.30
14	168.00	14	215.90	14	-28.50
15	165.00	15	80.50	15	84.50

LATRINE	NITROGEN LOADED (KG)	LATRINE	NITROGEN ACCM. (KG)	LATRINE	NITROGEN REDUCTION(%)
1	78.37	1	0.29	1	99.63
2	14.28	2	0.01	2	99.93
3	50.00	3	0.03	3	99.94
4	0.60	4	0.11	4	81.86
5	77.14	5	0.27	5	99.65
6	30.76	6	0.12	6	99.61
7	52.77	7	0.19	7	99.64
8	31.57	8	0.18	8	99.43
9	19.11	9	0.13	9	99.32
10	29.41	10	0.15	10	99.49
11	9.57	11	0.09	11	99.06
12	148.38	12	0.46	12	99.69
13	309.34	13	3.31	13	98.93
14	22.96	14	0.31	14	98.65
15	23.09	15	0.85	15	96.32

LATRINE	PHOSPHATE LOADED (KG)	LATRINE	PHOSPHATE ACCM. (KG)	LATRINE	PHOSPHATE REDUCTION(%)
1	60.00	1	2.10	1	96.50
2	12.12	2	0.40	2	96.70
3	25.00	3	0.10	3	99.60
4	0.45	4	0.40	4	12.40
5	60.00	5	3.30	5	94.50
6	23.52	6	1.60	6	93.20
7	41.41	7	4.10	7	90.10
8	24.00	8	3.60	8	85.00
9	15.38	9	1.60	9	89.60
10	18.75	10	0.30	10	98.40
11	8.33	11	0.10	11	98.80
12	100.00	12	0.10	12	99.90
13	200.00	13	0.60	13	99.70
14	50.00	14	0.10	14	99.80
15	17.85	15	0.50	15	97.20

Solids Reduction Data - Singur

LATRINE	TOTAL SOLIDS LOADED (KG)	LATRINE	TOTAL SOLIDS ACCM (KG)	LATRINE	TOTAL SOLIDS REDUCTION(%)
1	576.00	1	102.30	1	82.20
2	576.00	2	234.20	2	59.30
3	561.00	3	52.50	3	90.60
4	897.00	4	58.80	4	93.40
5	2556.00	5	44.10	5	98.20
6	1356.00	6	29.60	6	97.80
7	1419.00	7	130.30	7	90.80
8	708.00	8	88.30	8	87.50
9	1044.00	9	301.70	9	71.00
10	663.00	10	152.10	10	77.00
11	1074.00	11	306.40	11	71.40
12	702.00	12	969.70	12	-38.10
13	2577.00	13	631.70	13	75.40
14	1992.00	14	76.00	14	96.10
15	792.00	15	30.80	15	96.10

LATRINE	VOLATILE SOLID LOADED (KG)	LATRINE	VOLATILE SOLID ACCM (KG)	LATRINE	VOLATILE SOLID REDUCTION(%)
1	403.20	1	71.90	1	82.10
2	403.20	2	153.20	2	61.90
3	392.70	3	21.60	3	94.40
4	627.90	4	33.90	4	94.50
5	1789.20	5	14.60	5	99.10
6	949.20	6	8.10	6	99.10
7	993.30	7	92.70	7	90.60
8	495.60	8	31.80	8	93.50
9	730.80	9	263.90	9	63.80
10	464.10	10	120.00	10	74.10
11	751.80	11	143.90	11	80.80
12	491.40	12	564.30	12	-14.80
13	1803.90	13	412.10	13	77.10
14	1394.40	14	26.70	14	98.00
15	554.40	15	22.30	15	95.90

LATRINE	FIXED SOLIDS LOADED (KG)	LATRINE	FIXED SOLIDS ACCM (KG)	LATRINE	FIXED SOLIDS REDUCTION(%)
1	172.80	1	30.40	1	82.30
2	172.80	2	80.90	2	53.10
3	168.30	3	30.90	3	81.60
4	269.10	4	24.80	4	90.70
5	766.80	5	29.40	5	96.10
6	406.80	6	21.40	6	94.70
7	425.70	7	37.60	7	91.10
8	212.40	8	56.40	8	73.40
9	313.20	9	37.60	9	87.90
10	198.90	10	32.10	10	83.80
11	312.20	11	162.50	11	49.50
12	210.60	12	405.40	12	-92.50
13	773.10	13	219.50	13	71.60
14	597.60	14	49.30	14	91.70
15	237.60	15	8.40	15	96.40

Solids Reduction Data - Singur

LATRINE	COD LOADED (KG)	LATRINE	COD LOADED (KG)	LATRINE	COD REDUCTION(%)
1	288.00	1	270.80	1	87.30
2	288.00	2	4.50	2	91.10
3	280.50	3	24.10	3	79.20
4	448.50	4	80.90	4	93.00
5	1278.00	5	356.90	5	93.30
6	673.00	6	80.70	6	88.40
7	709.50	7	130.50	7	96.60
8	354.00	8	192.10	8	86.80
9	522.00	9	66.50	9	95.90
10	331.50	10	93.20	10	95.10
11	537.00	11	75.60	11	74.70
12	351.00	12	156.70	12	45.90
13	1288.50	13	214.70	13	85.30
14	996.00	14	215.90	14	97.90
15	396.00	15	80.50	15	86.70

LATRINE	NITROGEN LOADED (KG)	LATRINE	NITROGEN LOADED (KG)	LATRINE	NITROGEN REDUCTION(%)
1	40.25	1	0.29	1	92.30
2	38.75	2	0.01	2	92.00
3	38.55	3	0.03	3	91.70
4	62.06	4	0.11	4	97.10
5	172.41	5	0.27	5	97.10
6	92.30	6	0.12	6	94.30
7	96.77	7	0.19	7	96.90
8	48.93	8	0.18	8	90.60
9	68.75	9	0.13	9	96.80
10	44.18	10	0.15	10	95.70
11	74.10	11	0.09	11	88.80
12	48.69	12	0.46	12	73.10
13	179.93	13	3.31	13	93.60
14	130.76	14	0.31	14	98.70
15	54.54	15	0.85	15	93.40

LATRINE	PHOSPHATE LOADED (KG)	LATRINE	PHOSPHATE LOADED (KG)	LATRINE	PHOSPHATE REDUCTION(%)
1	30.88	1	2.10	1	93.20
2	30.37	2	0.40	2	92.10
3	29.30	3	0.10	3	94.70
4	46.66	4	0.40	4	97.00
5	128.57	5	3.30	5	97.90
6	69.76	6	1.60	6	95.70
7	72.41	7	4.10	7	97.10
8	37.36	8	3.60	8	90.30
9	53.57	9	1.60	9	97.20
10	32.00	10	0.30	10	97.50
11	57.44	11	0.10	11	90.60
12	37.60	12	0.10	12	75.30
13	138.00	13	0.60	13	95.00
14	100.00	14	0.10	14	99.00
15	40.74	15	0.50	15	94.60

Patna - Solids Accumulation Rates

LATRINE	TS ACCM RATE(KG/CAP/YR)	LATRINE	COD ACCM RATE(KG/CAP/YR)
1	3.15	1	8.44
2	0.48	2	0.59
3	0.53	3	0.86
4	204.40	4	323.60
5	4.20	5	11.15
6	3.68	6	6.20
7	3.62	7	6.02
8	4.91	8	15.16
9	5.83	9	8.06
10	10.84	10	7.76
11	2.95	11	18.14
12	0.69	12	2.56
13	2.61	13	1.74
14	7.07	14	23.13
15	8.38	15	8.78

LATRINE	VS ACCM RATE(KG/CAP/YR)	LATRINE	N ACCM RATE(KG/CAP/YR)
1	1.63	1	0.00
2	0.34	2	0.00
3	0.44	3	0.00
4	117.60	4	0.44
5	3.50	5	0.00
6	2.78	6	0.00
7	1.68	7	0.00
8	2.58	8	0.01
9	5.55	9	0.01
10	9.84	10	0.01
11	1.60	11	0.02
12	0.60	12	0.00
13	1.95	13	0.02
14	4.58	14	0.03
15	6.80	15	0.09

LATRINE	FS ACCM RATE(KG/CAP/YR)	LATRINE	P ACCM RATE(KG/CAP/YR)
1	1.52	1	0.06
2	0.14	2	0.05
3	0.08	3	0.00
4	86.80	4	1.60
5	0.70	5	0.10
6	0.90	6	0.12
7	1.93	7	0.18
8	2.32	8	0.28
9	0.27	9	0.19
10	1.00	10	0.02
11	1.34	11	0.02
12	0.08	12	0.00
13	0.65	13	0.00
14	2.48	14	0.01
15	1.57	15	0.05

Singur- Solids Accumulation
Rates

LATRINE	TS ACCM RATE(KG/CAP/YR)	LATRINE	COD ACCM RATE(KG/CAP/YR)
1	6.39	1	2.28
2	14.63	2	1.58
3	3.36	3	3.72
4	2.35	4	1.25
5	0.62	5	1.19
6	0.78	6	2.07
7	3.30	7	0.60
8	4.48	8	2.36
9	10.40	9	0.73
10	8.25	10	0.86
11	10.27	11	4.53
12	49.72	12	9.72
13	8.82	13	2.54
14	1.37	14	0.36
15	1.40	15	2.37

LATRINE	VS ACCM RATE(KG/CAP/YR)	LATRINE	N ACCM RATE(KG/CAP/YR)
1	4.49	1	0.193
2	9.57	2	0.193
3	1.38	3	0.205
4	1.36	4	0.072
5	0.20	5	0.070
6	0.21	6	0.127
7	2.35	7	0.076
8	1.61	8	0.233
9	9.10	9	0.075
10	6.51	10	0.103
11	4.82	11	0.278
12	28.93	12	0.671
13	5.75	13	0.155
14	0.48	14	0.030
15	1.01	15	0.163

LATRINE	FS ACCM RATE(KG/CAP/YR)	LATRINE	P ACCM RATE(KG/CAP/YR)
1	1.90	1	0.131
2	5.06	2	0.150
3	1.98	3	0.096
4	0.99	4	0.056
5	0.41	5	0.038
6	0.57	6	0.079
7	0.95	7	0.053
8	2.87	8	0.172
9	1.30	9	0.051
10	1.74	10	0.043
11	5.44	11	0.181
12	20.79	12	0.466
13	3.06	13	0.096
14	0.89	14	0.018
15	0.38	15	0.100

TABLE GP-1 Gas Production Rates: Patna and Singur (litres gas/hr/kg volatile solids added)

Pit Sample	Patna	Singur
1	0.472	0.20
2	3.014	0.011
3	0.178	0.136
4	0.022	0.030
5	0.228	2.800
6	1.100	0.857
7	0.675	0.031
8	0.126	0.098
9	0.034	0.007
10	0.013	0.007
11	0.446	0.053
12	0.024	0.058
13	0.002	0.026
14	0.024	0.046
15	0.056	0.058
MEAN ± SD	0.428 ± 0.781	0.283 ± 0.728
MEDIUM	0.056	0.048

Soil Particle Size Analysis: Patna Site A

	SAMPLE DEPTH	CLAY (%)	SILT (%)	SAND (%)	SOIL TYPE
USDA	0 - 76 cm	23	72	28	silt loam
	76 - 99 cm	23	51	26	silt loam
	99 - 168 cm	16	46	38	loam
	168 - 240 cm	37	48	15	silty clay loam
ASTM	0 - 76 cm	33	45	22	
	76 - 99 cm	35	45	20	
	99 - 168 cm	25	47	28	
	168 - 240 cm	45	45	10	

Soil Particle Size Analysis: Patna Site B

	SAMPLE DEPTH	CLAY (%)	SILT (%)	SAND (%)	SOIL TYPE
USDA	0 - 37 cm	28	32	40	clay loam
	37 - 130 cm	23	34	43	loam
	130 - 240 cm	20	25	55	sandy loam
	240 - 350 cm	30	35	35	clay loam
ASTM	0 - 37 cm	37	31	32	
	37 - 130 cm	31	31	38	
	130 - 240 cm	25	27	48	
	240 - 350 cm	38	31	31	

Soil Particle Size Analysis: Patna Site C

	SAMPLE DEPTH	CLAY (%)	SILT (%)	SAND (%)	SOIL TYPE
USDA	0 - 165 cm	30	40	30	clay loam
	165 - 205 cm	8	17	75	loamy sand
	205 - 270 cm	34	36	30	clay loam
ASTM	0 - 165 cm	42	33	25	
	165 - 205 cm	13	16	71	
	205 - 270 cm	44	32	24	

Soil Particle Size Analysis: Patna Site D

	SAMPLE DEPTH	CLAY (%)	SILT (%)	SAND (%)	SOIL TYPE
USDA	0 - 40 cm	25	33	42	clay loam
	40 - 200 cm	30	30	30	clay loam
	200 - 270 cm	33	37	30	clay loam
ASTM	0 - 40 cm	34	33	34	
	40 - 200 cm	36	33	31	
	200 - 270 cm	45	31	25	

Soil Particle Size Analysis: Singur Site A

	SAMPLE DEPTH	CLAY (%)	SILT (%)	SAND (%)	SOIL TYPE
USDA	A-50	16	44	40	loam
	100	23	61	16	silt loam
	150	9	55	36	silt loam
	200	23	64	13	silt loam
	250	11	59	30	silt loam
	300	3	47	50	sandy loam
	350	19	61	20	silt loam
	400	20	72	8	silt loam
ASTM	A-50	20	70	10	
	100	29	65	6	
	150	11	67	22	
	200	32	64	4	
	250	14	74	12	
	300	6	88	6	
	350	14	82	4	
	400	30	68	2	

	Classification Particle Diameter (mm)	Classification Particle Diameter (mm)
Clay	smaller than 0.002	smaller than
0.005Silt		0.002 to
0.05	0.005 to 0.0074	
Sand	0.005 to 2.00	0.074 to 2.00

Soil Particle Size Analysis: Singur Site B

	SAMPLE DEPTH (cm)	CLAY (%)	SILT (%)	SAND (%)	SOIL TYPE
USDA	B-50	13	41	46	loam
	100	17	61	22	silt loam
	150	20	66	14	silt loam
	200	14	34	52	loam
	250	18	68	14	silt loam
	300	18	68	14	silt loam
	350	12	70	18	silt loam
	400	11	47	42	loam
ASTM	B-50	18	77	5	
	100	24	67	9	
	150	25	71	4	
	200	22	72	6	
	250	25	69	6	
	300	22	73	5	
	350	18	76	6	
	400	16	78	6	

Soil Particle Size Analysis: Singur Site C

	SAMPLE DEPTH	CLAY (%)	SILT (%)	SAND (%)	SOIL TYPE
USDA	C-50	22	62	16	silt loam
	100	20	62	18	silt loam
	150	28	57	15	silt loam
	200	20	52	28	silt loam
	250	4	54	42	silt loam
	300	1	11	88	sand
	350	2	16	82	loamy sand
ASTM	C-50	28	68	4	
	100	25	71	4	
	150	36	56	8	
	200	24	60	16	
	250	6	79	15	
	300	1	39	60	
	350	3	47	50	

Soil Hydraulic Conductivity (Patna)

TEST DEPTH	TYPE OF SOIL	NO. OF TESTS	K (average)
		Site A	
a) 123 cm	loam	1	0.0038 cm/sec (3.28 m/day)
b) 186 cm	silty clay loam	2	0.0006 cm/sec (0.519 m/day)
		Site B	
a) 100 cm	loam	1	0.0003 cm/sec (0.274 m/day)
		Site C	
a) 145 cm	loamy sand	2	0.0145 cm/sec (12.53 m/day)
		Site D	
a) 103 cm	clay loam	1	0.0005 cm/sec (0.394 m/day)
b) 156 cm	clay loam	1	0.0003 cm/sec (0.254 m/day)

Soil Hydraulic Conductivity (Singur)

TEST DEPTH	TYPE OF SOIL	NO. OF TESTS	K (average)
		Site A	
a) 100 cm	loam	5	0.0011 cm/sec (0.958 m/day)
b) 350 cm	silt loam	7	0.0025 cm/sec (2.136 m/day)
c) 400 cm	silt loam	2	0.00012 cm/sec (0.102 m/day)
		Site B	
a) 100 cm	silt loam	3	0.0011 cm/sec (0.936 m/day)
b) 250 cm	silt loam	7	0.0010 cm/sec (0.831 m/day)
c) 400 cm	loam	2	0.0009 cm/sec (0.741 m/day)

Soil Hydraulic Conductivity (Patna)

TEST DEPTH	TYPE OF SOIL	NO. OF TESTS	K (average)
		Site A	
a) 123 cm	loam	1	0.0038 cm/sec (3.28 m/day)
b) 186 cm	silty clay loam	2	0.0006 cm/sec (0.519 m/day)
		Site B	
a) 100 cm	loam	1	0.0003 cm/sec (0.274 m/day)
		Site C	
a) 145 cm	loamy sand	2	0.0145 cm/sec (12.53 m/day)
		Site D	
a) 103 cm	clay loam	1	0.0005 cm/sec (0.394 m/day)
b) 156 cm	clay loam	1	0.0003 cm/sec (0.254 m/day)

Soil Hydraulic Conductivity (Singur)

TEST DEPTH	TYPE OF SOIL	NO. OF TESTS	K (average)
		Site A	
a) 100 cm	loam	5	0.0011 cm/sec (0.958 m/day)
b) 350 cm	silt loam	7	0.0025 cm/sec (2.136 m/day)
c) 400 cm	silt loam	2	0.00012 cm/sec (0.102 m/day)
		Site B	
a) 100 cm	silt loam	3	0.0011 cm/sec (0.936 m/day)
b) 250 cm	silt loam	7	0.0010 cm/sec (0.831 m/day)
c) 400 cm	loam	2	0.0009 cm/sec (0.741 m/day)

Patna
Effective and Equivalent
Hydraulic Conductivities

Latrine Number	k-equivalent (m/day)	k-effective (m/day)
1	0.63	0.102
2	0.85	0.009
3	0.63	0.013
4	0.55	0.257
5	0.85	0.042
6	0.62	0.308
7	0.81	0.019
8	1.00	0.035
9	0.50	0.467
10	0.51	0.211
11	0.32	0.102
12	0.53	——
13	0.37	——
14	0.32	0.011
15	0.32	0.002

Singur
Equivalent and Effective
Hydraulic Conductivities

Latrine Number	k-equivalent (m/day)	k-effective (m/day)
1	1.50	0.001
2	1.23	0.001
3	1.04	0.002
4	0.79	0.003
5	1.04	0.032
6	1.00	0.008
7	1.09	0.003
8	1.31	0.016
9	0.94	0.004
10	1.30	0.015
11	1.32	0.026
12	1.37	0.005
13	0.55	0.029
14	0.63	0.001
15	0.84	0.005

Appendix B

Derivations

APPENDIX B

Effective Hydraulic Conductivity Calculations

1. SINGUR LATRINES

Assuming a hydraulic gradient of 1, Darcy's Law predicts that the rate of drainage from a pit will be (Eqn. 1):

$$Q(t_i) = K_{eff} \times A(t_i)$$

where

$Q(t_i)$ = flow rate at time t_i (m^3/day)

K_{eff} = hydraulic conductivity of soil surrounding pit (m/day)

$A(t_i)$ = drainage area (m^2)

Assuming drainage occurs through both the pit base and side walls, for circular pits (Eqn. 2):

$$A(t_i) = 2\pi r h(t_i) + \pi r^2$$

Substituting Eqn. 1 into Eqn. 2 (Eqn. 3):

$$Q(t_i) = 2\pi K_{eff} r(h(t_i) + r/2)$$

If during time t_i, the water level in the pit falls a distance of dh, the drainage rate that occurs is (Eqn. 4):

$$Q(t_i) = -\pi r^2 (dh/dt)$$

Substituting Eqn. 4 into Eqn. 3 (Eqn. 5):

$$2K_{eff}\pi r(h(t_i) + r/2) = -\pi r^2 (dh/dt)$$

Integration of Eqn. 5 between the limits:

$$t_i = t_1,\ h(t_i) = h(t_1)$$

$$t_i = t_n,\ h(t_i) = h(t_n)$$

yields (Eqn. 6):

$$(2K_{eff}/r)(t_n - t_1) = \ln(h(t_1) + r/2) - \ln(h(t_n) + r/2)$$

Rearranging Eqn. 6 and converting to common logarithms

$$K_{eff} = \frac{1.15r \; \log(h(t_i) + r/2) - \log(h(t_n)+r/2)}{t_n - t_1}$$

2. PATNA PITS

A singular analysis using,

$$A(t_i) = 2(L+W)h(t_i) + LW$$

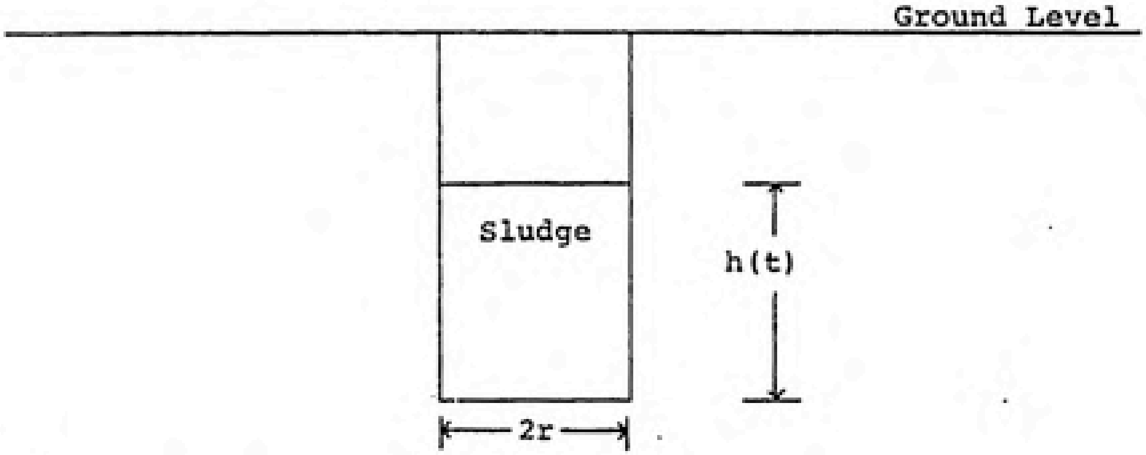
and

$$Q(t_i) = -LW(dh/dt)$$

yields the following equation for K_{eff} in rectangular pits:

$$K_{eff} = \frac{1.15(LW/L+W) \; \log[h(t_1) + LW/2(L+W)] - \log \; (h(t_n) + LW/2(L+W)}{t_n - t_o}$$

MODEL DERIVATION FOR CIRCULAR PITS



EQN 1 $$Vol_{t+\Delta t} = Vol_t + (NX)\Delta t - Y_t \Delta t$$

where Vol = volume of sludge accumulated in a pit at any time (t) (volume)

N = number of people using a latrine (a constant)

X = per capita liquid loading rate (a constant, volume/time)

t = time

Y_t = rate of liquid loss at any time, t (volume/time)

Assuming drainage to occur only in the horizontal direction and the hydraulic gradient to equal unity the rate of liquid loss can be described using the equation

EQN 2 $$Y_t = K_{eff}\, A(t)$$

where K_{eff} = effective hydraulic conductivity of soil near a pit (length/time)

A(t) = drainage area ($length^2$)

Assuming that drainage occurs through that portion of the sidewall area which is unlined,

EQN 3 $$Y_t = K_{eff}(\gamma)(2\pi r)(h(t))$$

where γ = ratio of unlined sidewall area to total sidewall area (unitless)

$(2\pi r)(h(t))$ = total sidewall area (length^2)

r = pit radius (length)

$h(t)$ = height of sludge in pit at any time, t.

Substituting EQN 3 into EQN 1 and dividing through by t

EQN 4

$$\frac{Vol_{t+\Delta t} - Vol_t}{\Delta t} = NX - (2\pi\gamma)(K_{eff})(r)(h(t))$$

Taking the limit of EQN 4 as $\Delta t \longrightarrow$

$$\frac{dVol}{dt} = NX - (2\pi\gamma)(K_{eff})(r)(h(t))$$

Since the volume of sludge accumulated in a pit at any time, t equals

$$Vol = h(t)(\pi r^2)$$

EQN 4 becomes

EQN 5 $$\pi r^2 \frac{dh(t)}{dt} = NX - (2\pi\gamma)(K_{eff})(r)(h(t))$$

Dividing both sides of EQN 5 by r^2 yields

EQN 6 $$\frac{dh(t)}{dt} = \frac{NX}{\pi r^2} - \frac{2\gamma K_{eff}\, h(t)}{r}$$

or

EQN 7 $$\frac{dh(t)}{dt} = C_1 + C_2\, h(t)$$

where $C_1 = \frac{NX}{\pi r^2}$ $\qquad C_2 = -\frac{2\gamma K_{eff}}{r}$

SOLUTION OF DIFFERENTIAL EQUATION

EQN 7 can by separation of variables,

$$\frac{dh(t)}{dt} = C_1 + C_2\ h(t)$$

$$dh(t) = [C_1 + C_2\ h(t)]\ dt$$

EQN 8 $$\frac{dh(t)}{C_1 + C_2\ h(t)} = dt$$

Integrating both sides of EQN 8

EQN 9 $$\frac{1}{C_2} \ln\ (C_1 + C_2\ h(t)) = t + \text{Constant}$$

Solving for the constant value at h(0) = 0

$$\text{Constant} = \frac{1}{C_2} \ln C_1$$

EQN 9 becomes

EQN 10 $$\frac{1}{C_2} \ln\ (C_1 + C_2\ h(t)) = t + \frac{1}{C_2} \ln C_1$$

Multiplying both sides of EQN 10 by C_2 and then raising each side to the value e

EQN 11 $$C_1 + C_2\ h(t) = e^{C_2(t + 1/C_2 \ln C_1)}$$

or

$$C_2\ h(t) = C_1\ e^{C_2 t} - C_1$$

$$h(t) = \frac{C_1}{C_2}\ e^{C_2 t} - \frac{C_1}{C_2}$$

EQN 12 $$h(t) = \frac{C_1}{C_2} (e^{C_2 t} - 1)$$

where again

$$C_1 = \frac{NX}{\pi r^2} \qquad C_2 = -\frac{2 (\gamma K_{eff})}{r}$$

Conversion of EQN 12 to predict total accumulation rate (tar)

EQN 13

$$\underset{(m^3/cap/yr)}{TAR} = \frac{h(t) \ (\pi r^2)}{(N) \ (\text{pit age})} \ \text{Volume of material accumulated}$$

$$= \frac{C_1/C_2 \ (e^{C_2 t} - 1) \ (\pi r^2)}{(N) \ (t)}$$

with $C_1/C_2 = (\frac{NX}{\pi r^2}) \ / \ (-\frac{2 \gamma K_{eff}}{r})$

$$= \frac{NX}{(-2 \pi \gamma) \ (K_{eff}) \ (r)}$$

and

$$C_2 = -\frac{2 \gamma K_{eff}}{r}$$

Substituting the values of C_1/C_2 and C_2 into EQN 13

$$TAR = \frac{[\frac{NX}{(-2 \pi \gamma) \ (K_{eff}) \ (r)}] \ (e^{((-2\gamma K_{eff})/r)(t)} - 1) \ (\pi r^2)}{(N) \ (t)}$$

$$TAR = (-\frac{(x) \ (r)}{2 \ (\gamma) \ (K_{eff}) \ (t)}) \ (e^{\frac{-2 \gamma K_{eff} t}{r}} - 1)$$

where again

x = per capita liquid loading rate

r = pit radius

γ = ratio of unlined sidewall area to total sidewall area

K_{eff} = effective hydraulic conductivity

t = pit age

Appendix C

Theoretical Supplement:

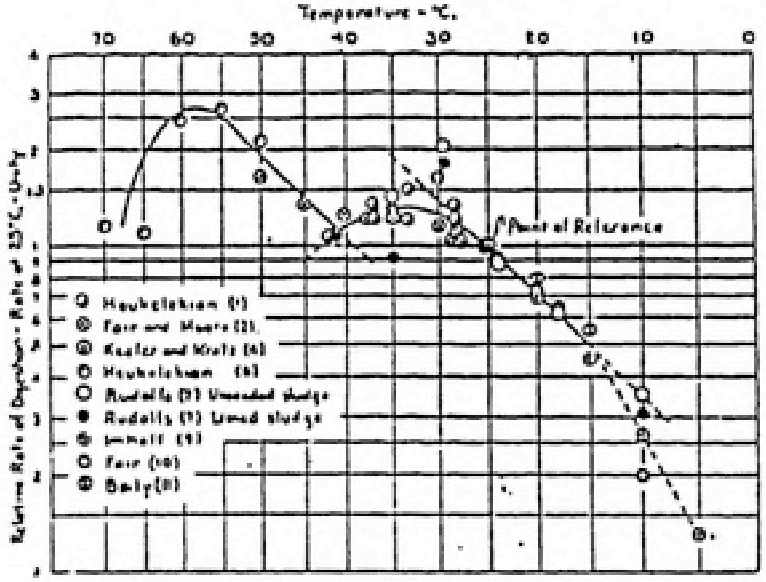
C1. Temperature
C2. Hydrogen Ion Concentration
C3. Salt Toxicity
C4. Composition
C5. Soil Type

APPENDIX C1: TEMPERATURE

The relationship between digestion rate and temperature was the subject of some of the earliest research conducted on the anaerobic digestion process. A series of articles written by Fair and Moore in the early 1930's described this relationship (Fair and Moore, 1932). In their experiments they measured the rate of digestion (in terms of gas produced) at different temperatures. As substrate, they used raw sludge. The microbial population in the sludge served as the seed. As a result of their research, a formula was derived by which the amount of gas expected in a certain time period could be predicted.

To confirm their findings Fair and Moore decided to compare their work to that of other researchers. In order to do this, they had to define a relative rate of digestion. This relative rate was based on two ideas. A standard rate of digestion was chosen to be that which occurred at $25^{\circ}C$. The time of digestion was taken to be the time it took to produce 90% of the lowest total gas yield.

The results of Fair and Moore's review can be seen in Figure T-1. In this figure a plot of relative rate versus the inverse of temperature (absolute) is provided. There are two straight-line portions on the graph. From 10° to $28^{\circ}C$ and from $42^{\circ}C$ to $55^{\circ}C$ the relationship between relative rate and temperature is constant. In these regions the reaction rate-temperature relationship followed Arrhenius'



-Relative Digestion Rate of Plain-Sedimentation in Sludge Digested at Temperatures of 5° to 70° C. Over-all Rate Is Referred to Over-all Rate at 25° C. Vertical Scale Is Logarithmic. Horizontal Scale Is Based on the Reciprocal of the Absolute Temperature (°C. + 273.1).

Figure T-1
(Fair and Moore, 1934)

law for the effect of temperature on the rate of reaction, namely,

$$\log K_T - \log K_o = \frac{u}{2.3026R} \left(\frac{1}{T} - \frac{1}{T_o}\right)$$

where

K_T = velocity of the reaction at absolute temperature (T)

K_o = velocity of the reaction at absolute reference temperature (T_o)

R = the gas constant, 1.9885 calories

u = the temperature constant, or characteristic of the reaction.

In the regions between 28°-42°C the rate of digestion did not appear to follow the Arrhenius equation. Fair and Moore suggested that in this region a transition in the predominate bacteria was taking place. They labeled the bacteria in the 10-28°C as non-thermophilic and those functioning between 42-55°C as thermophilic. In the region of 28-42°C the data suggested that neither thermophilic nor non-thermophilic bacteria were strongly established.

Fair and Moore concluded that within the temperature range they looked at there were two zones in which the rate of reaction-temperature could be predicted. They were the thermophilic zone (42-55°C) and the intermediate zone (10-28°C). In these zones the digestion rate followed ordinary chemical laws with regard to temperature. In the zone from 28-42°C, Fair and Moore identified an optimum operating temperature of 33°C but noted that within the range 28-42°C the effect of changing temperature was only slight on the digestion rate. For this temperature region they were not able to develop a predictive equation for the relationship between the digestion rate and temperature.

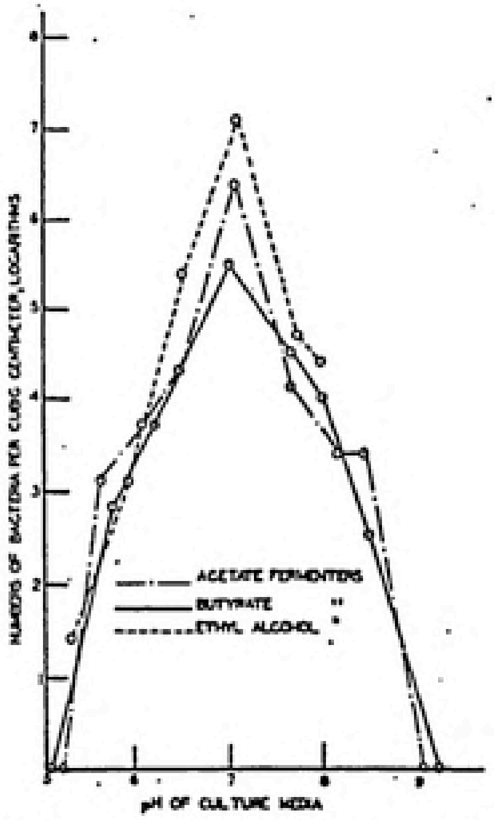
APPENDIX C2: HYDROGEN ION CONCENTRATION

($pH = -\log[H^+]$)

In 1939, Heukelekian and Heinemann conducted one of the first studies on the relationship between hydrogen ion concentration and the anaerobic digestion process (Heukelekian, 1939). In research on enumeration techniques, Heukelekian and Heinemann attempted to define optimum environmental conditions for the growth of enriched cultures of methanogenic bacteria. One of the conditions considered was pH ($-\log[H^+]$).

Heukelekian and Heinemann's findings are shown graphically in Figure H-1. The highest growth density of methanogenic bacteria was observed on a media which was at pH 7.0. A sharp decline in the number of bacteria occurred at both lower and greater pH values.

As techniques of isolating strains of anaerobic bacteria were refined, it became possible to study pure cultures of methanogenic bacteria. In Mylroie and Hungate's research on Methanobacterium formicicum it was found growth would occur in the pH range 6.6 to 8.0 (Mylroie, 1954). In a similar study by Smith and Hungate on Methanobacterium ruminantium, growth was observed in the pH range 6.5 to 7.5 (Smith, 1958). In neither study was an optimum pH identified as in the study enriched cultures by Heukelekian and Heinemann.



-Effect of pH of the culture on the growth of methane-producing bacteria incubated at 35° C.

Figure H-1 (Heukelekian and Heinemann, 1939)

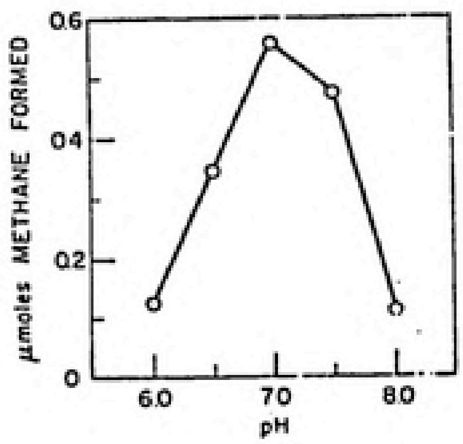


Figure H-2 Gas production versus pH
(Wolin, et al, 1963)

Wolin and his co-workers studied the effect of pH on methane production instead of growth (Wolin, 1963). They experimented with cell extracts of Methanobacillus omelianskii. A graph of methane formed versus pH is shown in Figure H-2. As in the study done by Heukelekian and Heinemann, an optimum pH was identified as pH 7.0. On either side of pH 7.0, the amount of methane formed was significantly reduced as pH changed.

All of the early studies indicated a growth range for methanogenic bacteria from about pH 6.6 to 7.6 with an optimum at pH 7.0. The next question to be raised was what effect would pH have over time on an established population of methanogenic bacteria. An attempt to answer this question was presented in a paper by Clark and Speece in 1970.

In their research, Clark and Speece monitored the response of an established population of methanogenic bacteria to changes in pH. The results of their work showed a greater tolerance of the bacteria to hydrogen ions than had been previously demonstrated. A plot of pH inhibition factor (R)** versus pH is provided in Figure H-3. Inhibition of the bacteria did not occur between pH 6.0 and 8.0, and then was virtually non-existent below pH 5 and above pH 9.

Before the work of Speece and Clark was reported, guidelines for anaerobic digestor operation recommended the maintenance of pH in the range 6.6 to 7.6, with an optimum in the region 7.0 to 7.2 (McCarty, 1964). Current standards no longer include the recommendation of an optimum pH but do maintain that pH should be maintained in the pH 6.6-7.6 region (EPA, 1979).

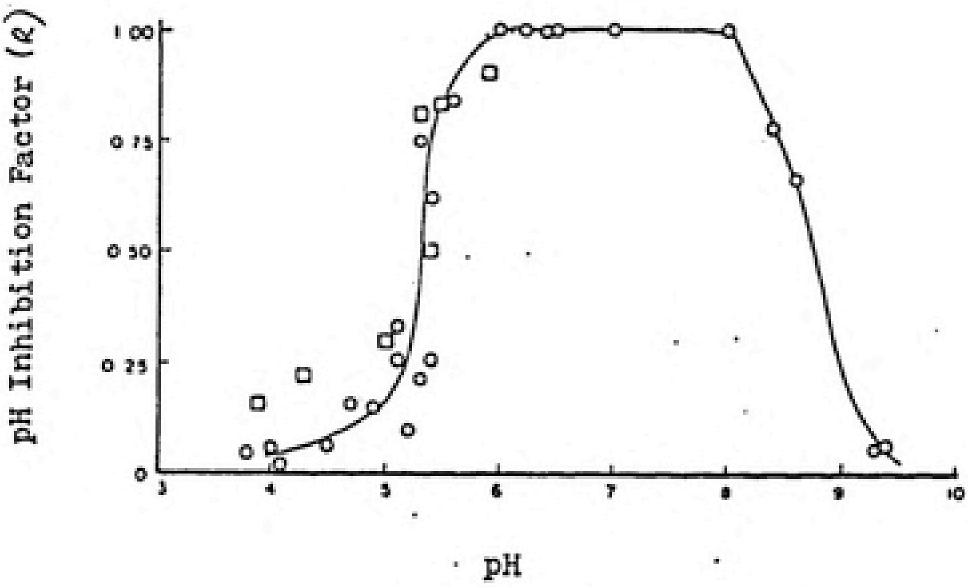


Figure H-3 pH inhibition factor versus pH (Clark and Speece, 1971)

APPENDIX C3: SALT TOXICITY

Interest in the relationship between the anaerobic digestion process and salt concentration in sludge first began when it was noticed that the addition of different metallic bases (Na_2CO_3 vs. $CaCO_3$ for example) for pH control could have opposite effects on the digestion rate. Early investigators tried to understand the reason for this phenomena but it was not until the late 1950's that definitive work on salt toxicity began with a series of papers by Perry McCarty and his colleagues.

McCarty based his research on the work of microbiologists who had investigated the relationship between salt toxicity and the growth of cells. Previous research had shown the effect of salts on growth had more to do with cations (positively charged ions) than anions (negatively charged ions) (McCarty, 1961). At relatively low concentrations cations could be stimulatory, as they were required for cell growth. After the nutritional requirements were satisfied, however, the effect of raising the cation concentration could become inhibitory. Microorganisms could adjust to high levels of cations yet their rate of growth would be slowed. At very high levels the cations had a toxic effect. A typical plot of the relationship between salt concentration and rate of biological reaction is shown in Figure S-1.

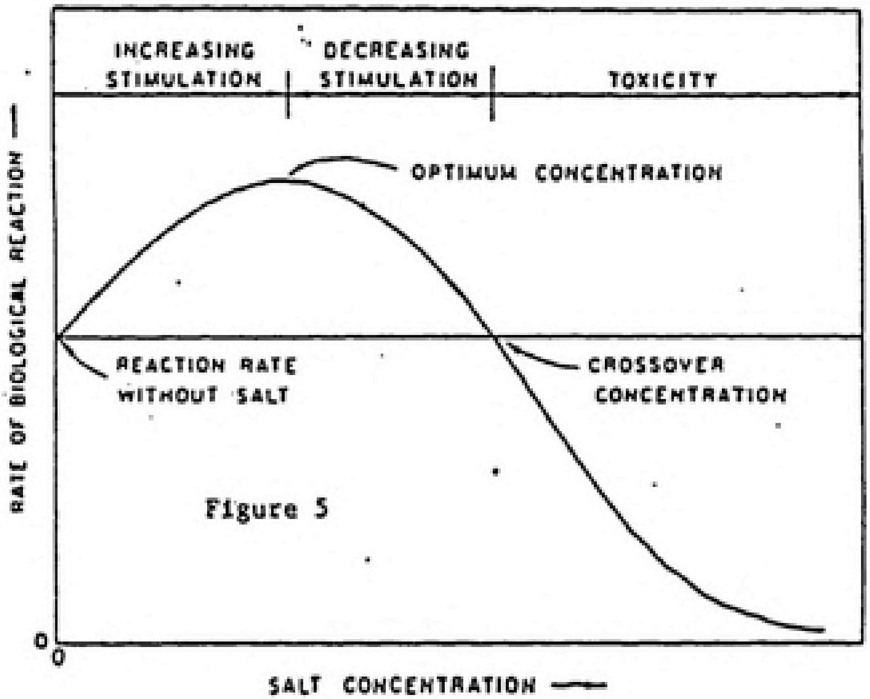


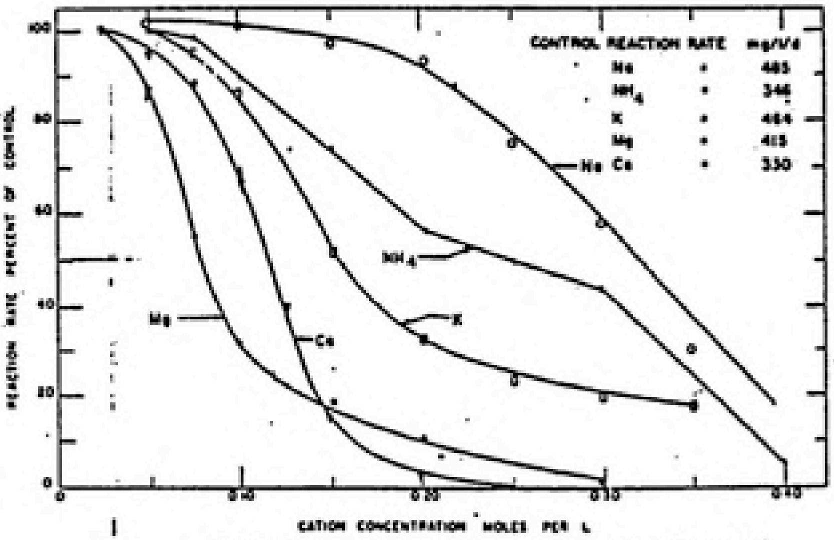
Figure S-1 Relationship between rate biological reaction and salt concentration (McCarty, 1964)

McCarty and McKinney first studied the affect of salt toxicity when investigating the relationship between sludge digestion and volatile acid concentration (McCarty, 1961). They found that the importance of volative acid concentration was due to the formation of sodium acetate. At high levels of this acetate, methagenic bacteria would cease to function. The data suggested that this was the result of the presence of the sodium (Na^{+}) ion rather than the acetate group.

In the next paper by McCarty and McKinney, they looked solely at the relationship between salt toxicity and anaerobic digestion (McCarty, 1961). They examined the rate of digestion at several concentrations of five cations. The cations were calcium ($Ca^{+}2$), magnesium (Mg^{+2}), sodium (Na^{+}), potassium K^{+}), and ammonium (NH_4^{+}). In this work the relative toxicity of the cations on equivalent concentration basis were (in order of increasing toxicity): (a) calcium; (b) magnesium; (c) sodium; (d) potassium; and (e) ammonium. This paper was to serve as a basis for more exhaustive studies on salt toxicity which were carried out by McCarty and Kugelman.

In two papers entitled "Cation Toxicity and Stimulation in Anaerobic Waste Treatment" (McCarty and Kugelman, 1963, 1965), McCarty and Kugelman attempted to define the range of cation concentrations in which anaerobic digestion could occur. They hoped to find the optimum and toxic levels of cation concentration. In their first paper, the tolerance of methanogenic bacteria to slug feeding was measured. They ran both single and multiple cation systems. Figure S-2 shows the results of the work done on single cation systems. In it the relative toxicity of the five cations can be seen. On the ordinant is the rate of reaction based on the amount of gas produced compared to a control reaction. On the abscissa the cation ion concentration is given. The use of a relative rate of reaction prevents the development of a strict rate of reaction - concentration graph. The data which Figure S-2 is based are not provided in the paper. However the plot does allow a comparison of the relative effects of the various ions. Sodium had the least toxic effect. The bacteria could tolerate relative high concentrations of sodium without much alteration in the reaction rate. For the other cations, a change in concentration produced a much more drastic effect on the rate of digestion.

From experimentation with the multiple cation systems, McCarty and Kugelman concluded that the optimum levels for sludge digestion were 0.01M for monovalent ions and 0.005M for divalent ions. They based their conclusion on a number of different experiments where they tried different combinations of cations and concentrations. Stated values for optimum levels of cations in single cation ion systems were not given. Upper limit of cation concentration for



·Effect of individual cation concentration on the rate of acetate utilization.

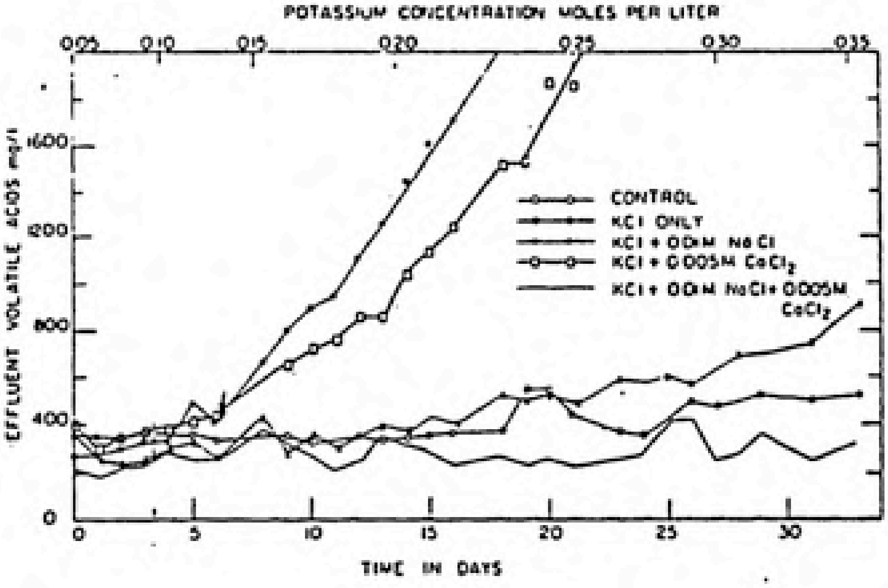
Figure S-2
(McCarty and Kugelman, 1963)

slug addition of salts is shown in Table S-1. The values represent "the upper limit of cation concentration which a waste can contain and still be treatable anaerobically" (McCarty and Kugelman, 1965). A more precise definition of the upper limit was not stated.

TABLE S-1: UPPER LIMIT OF CATION CONCENTRATION FOR SLUG ADDITION OF SALTS

Cation	Molar Concentration Single Cation Systems	Antagonists Present
Na	0.2	0.3 - 0.35
NH_4	0.1	0.25
K	0.09	0.15-0.2
Ca	0.07	0.125-0.15
Mg	0.05	0.125

In their second paper McCarty and Kugelman repeated the work they had done in their first work except on a continuous feed basis. This allowed for the examination of the microorganisms ability to acclimatize to the toxic effect of the cations. The cations of sodium, potassium, magnesium, and calcium were studied. In Figures S-3 through S-6 the results of the experimentation are plotted. The effect of change in concentration on rate of reaction can be seen in the differences in volatile acid destruction at different concentrations. In all cases the feed into the experimental digestor contained 7,500 mg/l of volatile acids. The higher the level of volatile acids in the effluent, the lower the rate of reaction. As before both



Potassium toxicity daily feed.

Figure S-5 (McCarty and Kugelman, 1965)

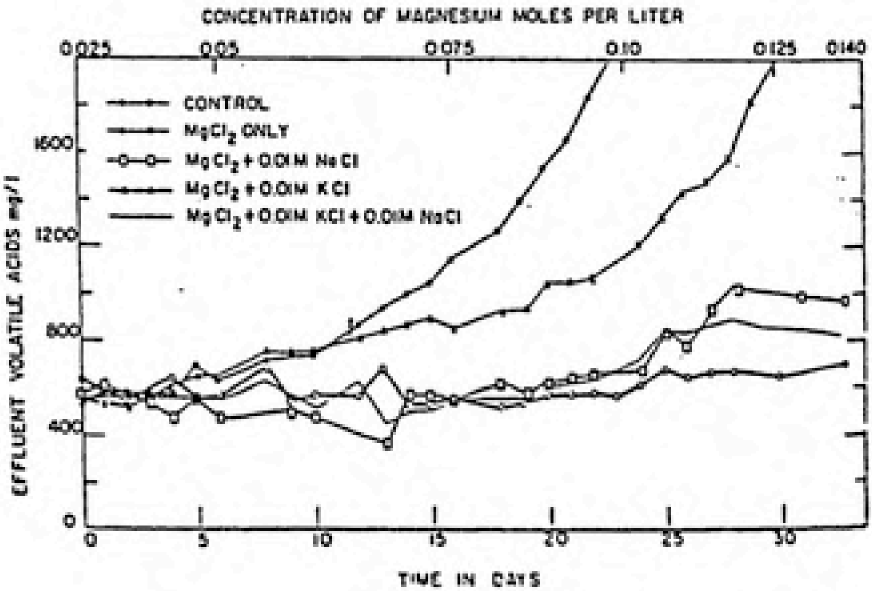
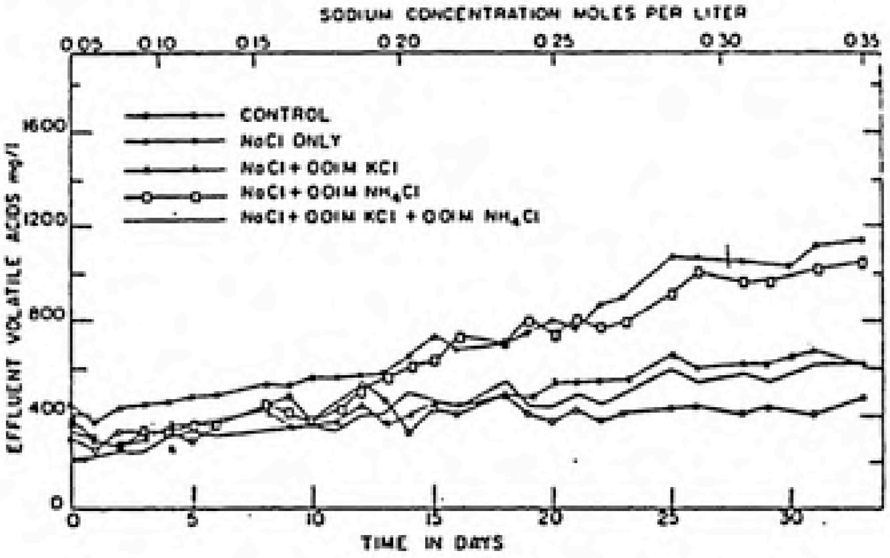
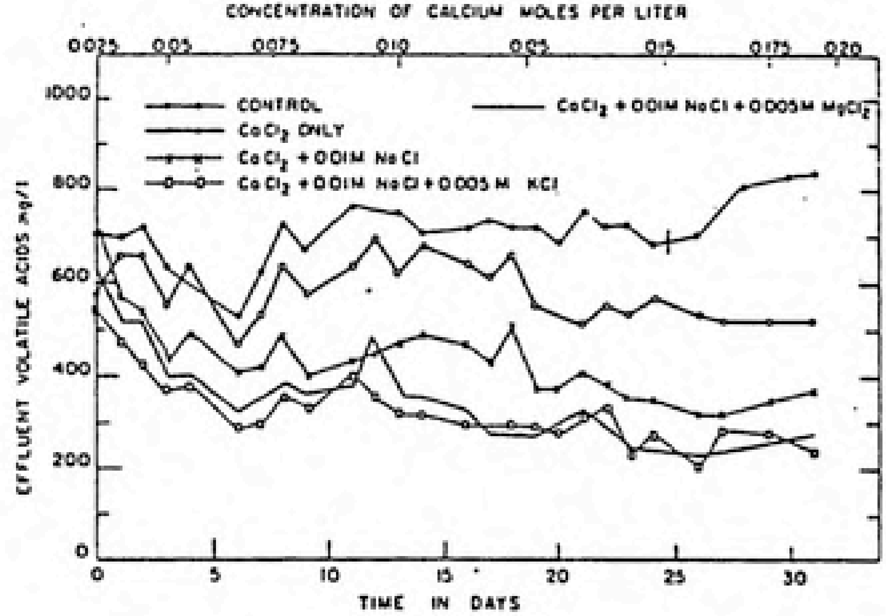


Figure S-6 (McCarty and Kugelman, 1965)



- Sodium toxicity daily feed.

Figure S-3 (McCarty and Kugelman, 1965)



Calcium toxicity daily feed.

Figure S-4 (McCarty and Kugelman, 1965)

single and multiple cation systems were studied. In the single cation studies, the rate of reaction for sodium and calcium did not show large changes over the ranges of concentration. The rates of reaction for potassium, magnesium, did show large changes with change in concentration. Care must be taken however in interpreting the results as the concentration scale for sodium and potassium is not the same as that for magnesium and calcium. The multiple cation systems are shown on the same graphs as the single cation systems. In this experiment the cation concentrations of the antagonist were maintained at the 0.01M and 0.005M levels recommended from the slug-feed study. In every case the toxicity of the cation in question was lowered by the addition of secondary cations.

From this study of daily feeding of cations McCarty and Kugelman concluded that methanogenic bacteria would acclimatize themselves to high concentrations of cations if the level of the cations was increased gradually rather than abruptly as had been the case in the first series of experiments. As in the case of slug feeding upper limits of cation concentration were proposed. These can be seen in Table S-2. They are higher than those based on slug-feed. The implications for digestion operation are that higher levels or concentrations of cations can be tolerated in a digestor if they are fed gradually to the digestor rather than at one time.

TABLE S-2 UPPER LIMIT OF CATION CONCENTRATION FOR DAILY FEED ADDITION OF SALTS

	Molar Concentration	
Cation	Single Cation Systems	Antagonists Present
Na	0.3	0.35
K	0.13	0.35
Ca	0.15	0.2
Mg	0.065	0.14

APPENDIX C4: COMPOSITION

One of the earliest studies on the relationship between composition and the anaerobic digestion process was done by Buswell in 1932 (Buswell, 1932). He looked at the quality (CH_4:CO_2 ratio) and quantity of gas produced in the digestion of the three major groups of organic compounds - fats, proteins and carbohydrates.

As a basis for his study Buswell suggested the decomposition of organic compounds could be predicted according to simple hydrolysis equations. In Table C-1 examples of the anaerobic digestion and three organic compounds are given as described in terms of hydrolysis.

TABLE C-1: ANAEROBIC DIGESTION REPRESENTED BY HYDROLYSIS EQUATIONS

n-Butyric acid (Fat)

$2C_4H_8O_2 + 2H_2O = 3CO_2 + 5CH_4$

Peptone (Protein)

$4C_{148}H_{233}O_{48}N_{37}S + 524H_2O = 136CO_2 + 308CH_4 + 148NH_4HCO + 4H_2S$

Cellulose (Carbohydrate)

$(C_6H_{10}O_5) + H_2O = 3CO_2 + 3CH_4$

Conducting his own experiments and reviewing the works of others, Buswell found good agreeement between theoretical prediction based on the hydrolysis concept and actual production of gas. The results of anaerobic fermentation of a number of pure substances is provided in Table C-2. The ratio of CO_2:CH_4 measured was very close to the CO_2:CH_4 ratio predicted according to hydrolysis equations.

In conclusion, Buswell stated that a difference in the quality and quantity of gas can be expected in the digestion of substances of different C:H:O:N ratios. Typical values for the constituents of sewage sludge were given (See Table C-3). When fats were digested, relatively large amounts (Wt. Gas/Wt. Substance Decomposed) of high quality gas were produced. The digestion of carbohydrates yielded gases of low quality in medium amounts. The quality of gas produced in the digestion of proteins was higher than that of carbohydrates yet its quantity was less. No reference was made by Buswell on differences in the rate of anaerobic digestion according to composition either in terms of the C:H:O:N ratio or classification as fat, protein or carbohydrate.

After initial investigations in the 1930's on composition such as that done by Buswell, research in this area did not continue at a steady rate. This occurred for a number of reasons. One was that it was found very difficult to continuously digest pure or even relatively simple organic substances in the lab (Speece and McCarty, 1964). On the other hand there was no difficulty experienced in the digestion of domestic sewage sludge in the typical digestor of the time. The main interest of researchers was in the development of the

Table C-2 Anaerobic fermentation of pure substances (Buswell and Boruff, 1932)

Substance Fed	Grams Fed	CH_4 as Drawn %[a]	Gas Recovered, S. T. P.[a] Vol., Liters	Weight,[a] Gms.	Ratio $CO_2:CH_4$	Theoretical Ratio[a] $CO_2:CH_4$	Per Cent of Material Fed Recovered as $CO_2 + CH_4$ Found	Theoretical
Cellulose[a]	180.0	48–55	152.30	197.00	1:1.03	1:1.00	111	111
Starch[a]	68.5	48–55	56.71	74.86	1:1.0	1:1.00	109	111
Glycerol[b]	10.0	50–60	7.11	8.81	5:7.07	5:7.00	88	90
Acetic acid[c]	114.18	48–55	80.80	107.41	1:0.97	1:1.00	94	100
Propionic acid[c]	130.08	56–60	110.70	145.15	5:6.93	5:7.00	112	112
Butyric acid[d]	150.0	60–65	158.40	184.82	1:1.70	1:1.67	123	120
Benzoic acid[d]	91.38	55–60	103.27	144.0	1:1.20	1:1.16	158	108
Casein[e]	47.5	65–72	44.50	57.8	1:1.08	1:1.07	...	171
					1:2.30	1:2.20	70	82
Peptone[e]	27.5	62–72	25.56	26.21	1:0.6	1:0.8	...	160
					1:2.0	1:3.2	48	46
Carbon (theoretical)	1.0		1.87	2.5		1:1		250

Table C-3 Gas production from various sewage constituents (Buswell and Boruff, 1932)

Material	CH_4 %	Volume per Gram Decomposed, Cc.	Weight per Gram Decomposed, Gm.	Volume per Lb. Decomposed, Cu. Ft.
Fats	62-72	1112-1403	1.33-1.54	18-23
Scum*	70-75	900-1000***	...	14-16
Grease*	68	1030	1.13	17
Crude fibre	45-50	802	1.11	13
Protein**	73	720	0.76	12

anaerobic digestion process for handling sewage sludge. Hence although the issue of composition was of concern, it was not pursued very vigorously.

Some studies did occur in the 1940's and 50's on the anaerobic digestion of organic substances other than sewage sludge. One of the most relevant studies of this period to the pit latrine study was done by Snell (Snell, 1943).

Snell examined the anaerobic digestion of human excreta. He began with the contention that undiluted human excreta would not anaerobically decompose. The purpose of his paper was to show why digestion would not occur normally and to investigate ways of creating conditions such that digestion would occur.

Snell's first experiments centered on demonstrating that the failure of excreta to decompose was related to the presence of urine. He showed this by conducting digestion tests with different combinations of urine and faeces. The results of these experiments are shown in Figure C-1.

On the graph the total amount gas produced (liters gas/kg vs. added) is plotted against time. A definite difference in the digestion rate (gas production/time) can be seen in the tests run at the different levels of urine concentration. With a full concentration of urine (no. 38) almost no digestion occurred in the time frame considered. As the concentration of urine was decreased, the time lag before the commencement and the rate of digestion increased (no. 39 and no. 40). The

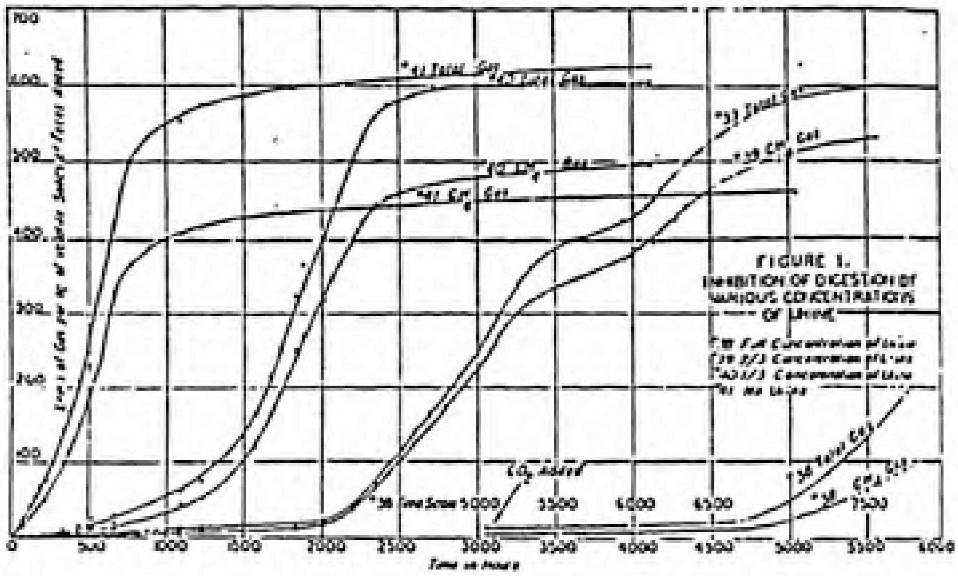


Figure C-1   Inhibition of digestion by various concentrations of urine   (Snell, 1943)

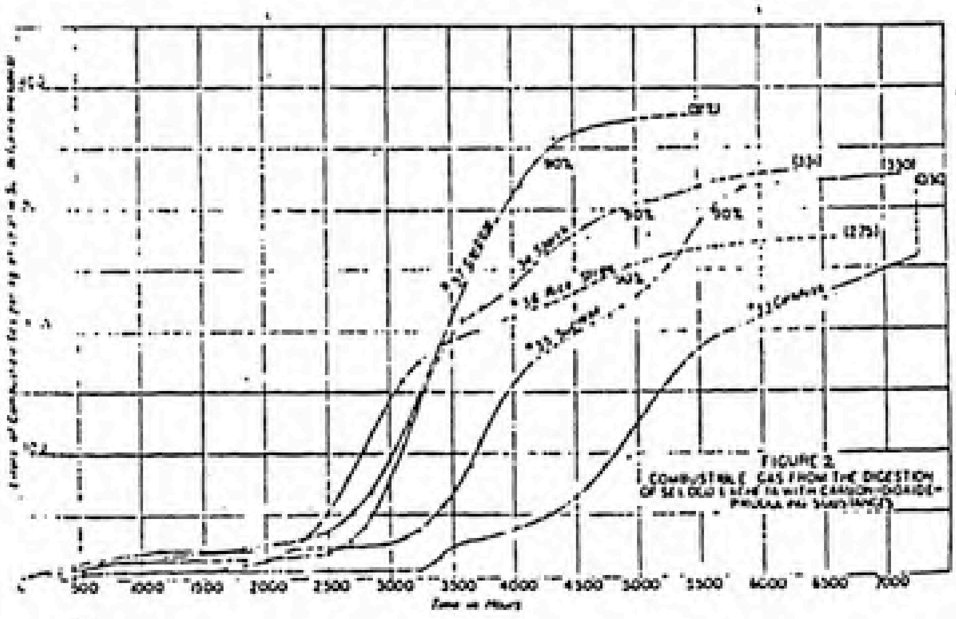


Figure C-2   Combustible gas from the digestion of seeded excreta with carbon-dioxide producing substances (Snell, 1943) highest rate of digestion was observed when no urine was added (no. 41). Digestion in this case began almost immediately.

Snell attributed the differences in digestion of faeces with and without urine to the introduction of ammonium carbonate in urine decomposition. According to Snell, urea (the main component of urine) would decompose as:

Eqn 1

$$\underset{\text{UREA}}{CO(NH_2)_2} + 2H_2O \rightarrow \underset{\text{AMMONIA}}{NH_3} + HNCO + 2H_2O \rightarrow \underset{\text{AMMONIUM CARBONATE}}{(NH_4)_2CO_3}$$

Eqn 2

$$(NH_4)_2CO_3 + CO_2 \rightarrow H_2O + 2NH_4HCO_3$$

The second step of the process (Eqn 2) was thought to be critical. If enough carbon dioxide was not present to convert ammonium carbonate to bicarbonate, digestion would stop. Failure was related to either ammonium carbonate toxicity or a shifting of pH outside (above) the range where digestion could occur (see Hydrogen Ion Concentration).

Snell thought if more carbon dioxide could be generated in the digestion process, the chance of failure would be lessened. To this end he conducted experiments in which human excreta was mixed with substances which would produce carbon dixoide in their decomposition. These substances were primarily carbohydrates which were thought at the time to decompose as shown in Eqn 3. A list of the substances added to excreta by Snell is provided in Table C-5.

Eqn 3

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4$$

carbohydrate

TABLE C-5 "CARBON DIOXIDE-PRODUCING" SUBSTANCES ADDED TO HUMAN EXCRETA"

1. Cellulose
2. Starch
3. Sucrose
4. Rice Straw
5. Garbage

The results of the second phase of experimentation by Snell can be seen in Figure C-2. The addition of carbohydrates to excreta for the most part did improve the digestibility of human excreta. Comparison can be made between no. 38 (CH_4 gas) in Figure C-1 and any of the carbohydrate-excreta mixtures, nos. 33-37, in Figure C-2, to see this. When compared to the digestion of faeces alone (no. 41 in Figure 1), however, the rates of digestion for the mixtures (nos. 33-37) were not as high.

Snell attempted to extend his findings in batch experiments to a continuously-fed digestion system. He desired to "discover the maximum rate at which a mixture of excreta and cellulose, starch, etc. can be added continuously and still produce good digestion." Unfortunately he was not able to achieve his goal.

Another study of interest is one done by Sanders and Bloodgood (Sanders and Bloodgood, 1965). Like Snell's work, this report is not considered as a major study in defining the effect of composition on anaerobic digestion. The study is considered here because it looks at the effect of the nitrogen-to-carbon ratio on anaerobic digestion. This is the inverse of similar to the C/N ratio commonly used to judge the suitability of a material for composting.

Sanders and Bloodgood's goal was to determine the growth-limiting N/C ratio for anaerobic digestion. They considered the same three classes of organic substances as Buswell - fats, proteins and carbohydrates.

TABLE C-6: COMPOUNDS USED IN EXPERIMENTATION BY SANDERS AND BLOODGOOD

1. Caproic Acid ($C_5H_{13}COOH$)
   A lipid (fatty acid)

2. Maltose ($C_{12}H_{22}O_{11}$)
   A carbohydrate

3. L-Leucine ($C_6H_{13}NO_2$)
   A protein (amino acid)

Sanders and Bloodgood's work was fairly limited in scope in that evaluation of the optimum N/C ratio was based mainly on whether or not their experimental digestors continued working or failed under the conditions that they were testing. A build-up of volatile acids in most cases was the cause of digestor failure. Gas production at a constant rate was taken as a sign of good digestion.

Data Showing Dependence of Success or Failure of Decomposition on N/C ratio

Digester No.	Organic Substrate	Volatile Solids (g)	Nitrogen as N (g)	Carbon as C (g)	N/C Ratio	Remarks about Operation
2	Pig food	3.6	0.100	1.652	6.05	Good
3	Pig food Caproic acid	4.35	0.127	2.117	6.00	Good
5	Pig food Caproic acid	4.92	0.150	2.471	0.07	Good
6	Pig food Maltose	4.35	0.120	1.952	0.15	Good
6	Pig food Caproic acid	5.06	0.150	2.475	6.06	Good
1	Pig food Caproic acid	4.35	0.100	2.117	4.72	Fail
4	Pig food Maltose	4.35	0.100	1.952	5.12	Fail
5	Pig food Caproic acid	4.922	0.123	2.471	4.98	Fail
Wojek* study	Pig food Glucose	6.00	0.125	2.665	4.7	Fail
Wojek* study	Pig food Glucose	5.25	0.125	2.365	5.3	Fail

* Interpretation of data from a study by Wojek (18).

Figure C-7
(Sanders and
Bloodgood, 1965)

From their work Sanders and Bloodgood identified a minimum N/C ratio of 0.0620 as necessary for successful anaerobic decomposition. A higher N/C ratio did not noticeably improve or harm digestion. A lower N/C ratio led to failure of digestion. The results of Sanders and Bloodgood's study in terms of digestion success or failure are provided in Table C-7.

Perhaps the most comprehensive work to date that has been conducted on the relationship of the process of anaerobic digestion and composition was done by Speece and McCarty in 1964 (Speece and McCarty, 1964).

The objective of their study was two-fold:

1. to determine the conditions necessary to continuously digest pure organic compounds; and
2. to determine the biological solids accumulation and associated nitrogen and phosphorus uptake (requirement) in the continuous digestion of fats, proteins and carbohydrates.

The general findings of the Speece and McCarty research are rather extensive and therefore difficult to summarize. The main conclusions drawn in their study were (a) that the general empirical formula for anaerobic biological solids is $C_5H_9O_3N$, and (2) based on this equation it is possible to predict the nutrient requirements for the utilization of a given substrate in the production of biomass and cell metabolism.

APPENDIX C5: SOIL TYPE

The matric potential will vary with the moisture content of a soil. In saturated soils the matric potential of water is zero. As the moisture content decreases, the matric potential increases. In Figure MP-1, a graph of the soil moisture content-matric potential relationship for several different soil types is provided. It will be noted that the matric potential in different soil types at the same moisture content is not the same. This difference is most easily explained by drawing an analogy between the movement of water in soils to that in a capillary tube (see Figure MP-2).

The same forces which pull water into dry soil pores will draw water up a thin glass tube if it is placed in a container of water. Water will move up the glass tube due to adhesive and cohesive forces. In the same situation as the glass tube, these forces are often grouped under the name of capillary forces.

The height to which water will rise in the tube is determined by the balance between gravitational and capillary forces acting on the water molecules. The water will stop rising at the point where the capillary force equals the force of gravity. At this point the water molecules can be viewed as being in tension. Hence the use

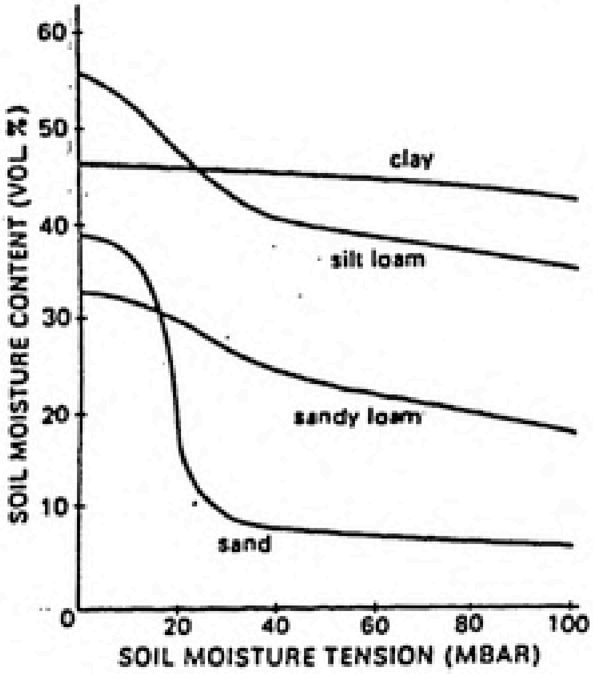


Figure MP-1 Relationship between soil moisture content and soil moisture tension (Bouma, et, al., 1972)

UPWARD MOVEMENT BY CAPILLARITY IN GLASS TUBES AS COMPARED WITH SOILS

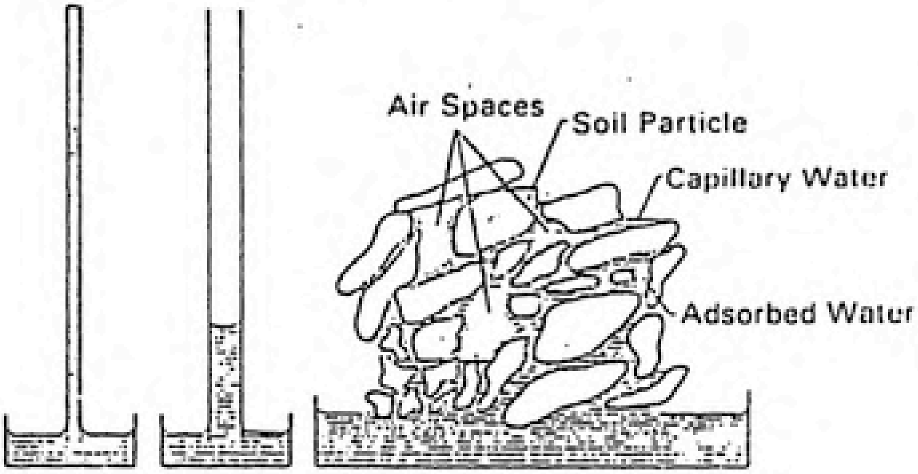
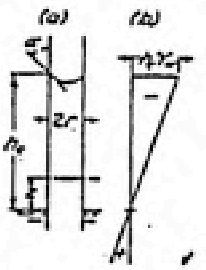


Figure MP-2
(Brady, 1974)



(a) Rise of water in capillary tube. (b) State of stress of water in capillary tube.

Figure MP-3
(Terzaghi and Peck, 1967)

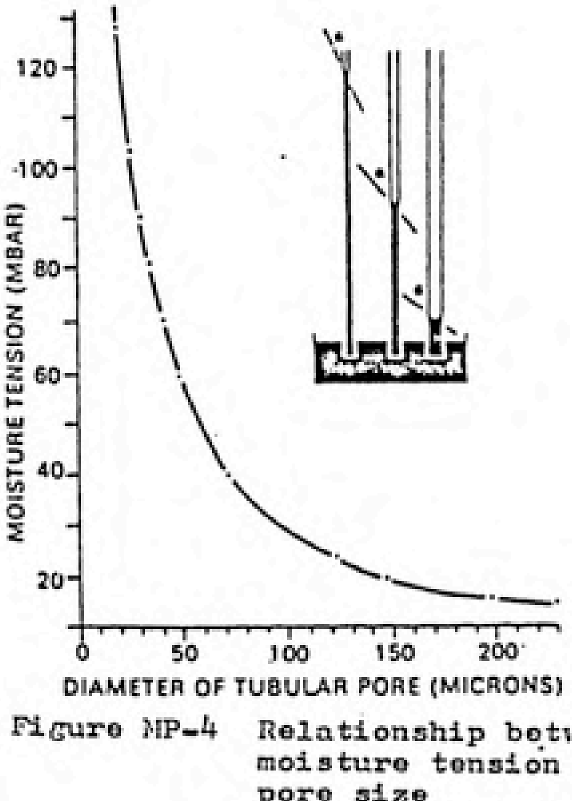


Figure MP-4 Relationship between moisture tension and pore size
(Bouma, et al, 1972)

of the expression of soil moisture tension in the measurement of matric potential.

The idea of the forces of gravity and capillarity being in balance has also led to the convention of using negative pressure to express the effect of capillary forces. Taking the downward direction (the direction in which gravity acts) as being positive, the capillary forces are seen as negative (acting upward).

A profile of the pressure gradient which exists in a capillary tube can be seen in Figure MP-3. Above the free water surface, the negative pressure due to capillarity increases with distance from the free water level.

Quantitatively, the pressure created by capillary forces can be measured using the equation (Terzaghi and Peck, 1967),

Equation MP-1

$$P = (2T \cos \quad)/r$$

where,

P = pressure (g/cm^2),

T = surface tension (for water ~0.075 g/cm),

= contact angle

r = radius of capillary tube (cm)

All of the parameters in Equation MP-1 are a function of the diameter of a tube. A graph of moisture tension versus tube diameter is provided in Figure MP-4. An exponential relationship is seen to exist between the tube diameter and moisture tension.

A soil in a sense can be considered to be a bundle of capillary tubes of different diameters. The tubes represent pores in a particular soil. The forces pulling water into a soil with small pores are much stronger than those of a soil with large pores. In the opposite sense (as in the description of capillary tubes) a soil with large pores does not hold water in its pores as well as a soil with small pores.

In the graph of soil moisture content versus moisture tension (Figure MP-1), four types of soil were considered -- sand (Type I), sandy loam (Type II), silt loam (Type III), and clay.

As soil moisture tension is increased, sands very readily give up their water. Large, continuous pores exist in sands. In contrast, clay, which is known for its small and non-continuous pores, yields relatively little of its water with increasing moisture tension.