THE UNIVERSITY OF MANITOBA

COMPUTER SIMULATION OF ENERGY RECOVERY THROUGH ANAEROBIC DIGESTION OF LIVESTOCK MANURE

by

Rakesh Kumar Singh

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ABSTRACT

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Energy shortages, escalating fuel prices and environmental pollution due to agricultural wastes focussed attention of scientists and engineers on economical recovery of energy from renewable resources such as livestock manure. One of the processes used for energy recovery from renewable resources is anaerobic digestion. It has been a common practice to operate anaerobic digesters at temperatures around $35^{\circ}C$, though it has been recognized for sometime that energy can be recovered at lower temperatures. Little effort has been made to study net energy production through anaerobic digestion of livestock manure at lower temperatures especially in cold climates such as that of Canada.

This study was designed to construct, test and utilize a model with which to develop relationships between energy input and output for design and operation of anaerobic digesters for farm-animal manure. The energy input constituted the sum of (a) energy required to raise the influent temperature, (b) energy required to maintain digester operating temperature and (c) energy required to mix the digester contents. Energy required to pump the influent and effluent and energy required to balance heat losses from influent carrying pipes were not included in this study. The efficiencies of the heating system and the mixing unit were taken as 100% and 60%, respectively. The energy output potential consisted of methane gas produced from the anaerobic digester at various operating conditions.

The simulation model in this study was comprised of an air temperature model, a soil temperature model, the "thermal bulb effect," an influent temperature model, a model for mixing the digester contents and a gas production model. The air temperature and soil temperature models were developed for a normal year for Winnipeg but provisions were made to accept data for any air temperature.

The simulation model developed in this study was used to predict net energy recovery from anaerobic digesters operating at: (a) total solids concentrations (TSC) of 3, 6, 9 and 12%; (b) solids retention times (SRT) of 10, 30 and 60 days; and (c) digester operating temperatures (DOT) of 20, 28 and 35^{o}C. The simulation model was also used to predict the effect of DOT on soil temperature and total energy required for digester operation. Net energy in this study was defined as the difference between gross energy production and energy required for digester operation.

Digesters operating at all the stated operating conditions were made of concrete and had wall, roof and floor thicknesses of 25.0 cm, 15.0 cm and 15.0 cm, respectively. Also, the digesters had insulation of 3.8 cm urethane and 0.64 cm of fir plywood around the walls and 7.5 cm urethane on the roof. No insulation was used under the floor but the digester itself was buried to a depth of 3 m below the soil surface. Heat losses from digester roof, walls and floor were calculated by applying steady-state unidirectional heat transfer theory.

The results of this study showed a net energy production at all the stated digester operating conditions throughout the year except at 3% TSC, 10-day SRT and 20^{o}C DOT during cold months of the year. Net energy from all digester operating conditions showed a minima on the

27th of January and a maxima on the 1st of August. The results indicated a maximum annual net energy production of 3.1040 TJ yr^{-1} from a digester operating at 12% TSC, 60-day SRT and 28^{o}C DOT. Similarly, a minimum annual net energy production of 0.1391 TJ yr^{-1} was observed from the digester operating at 3% TSC, 10-day SRT and 20^{o}C DOT. The results also indicated that the loading rate criteria for designing anaerobic digesters may be misleading in relation to net energy recovery unless TSC and SRT are known.

Annual net energy recovery showed a linear relationship to digester operating conditions. The effect of digester operating conditions on annual net energy production was in order of (relative importance): TSC > DOT > SRT.

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a	constant (day^{-1})
a_n	Fourier coefficient (^oC)
$a_o, a_1 \ldots a_6$	Fourier coefficients (^oC)
A_{o_a}	surface area of digester normal to heat flow between the levels H_L and H_T (m^2)
A_r	roof area (m^2)
A_s	outer area of digester under soil surface normal to the direction of heat flow (m^2)
A_{w_a}	surface area of digester normal to heat flow between the levels H_T and H_S (m^2)
A_{w_s}	surface area of digester normal to heat flow between the levels H_S and H_L (m^2)
A_o^1	surface area normal to direction of heat flow (m^2)
A_o, A_1	constants (^oC)
b	constant (K^{-1})
b_n	Fourier coefficient (^oC)
$b_1 \ldots . b_6$	Fourier coefficients (^oC)
BOD	biochemical oxygen demand
BOD_5	5 days biochemical oxygen demand
C	specific heat of influent (J kg^{-1} K^{-1})
C_p	specific heat of air at constant pressure (J kg^{-1} K^{-1})
C_s	specific heat of soil (J kg^{-1} K^{-1})
CNEP	cumulative net energy production (TJ yr^{-1})
$CNEP_{20}$	cumulative net energy production at 20^oC digester operating temperature (TJ yr^{-1})

$CNEP_{28}$	cumulative net energy production at $28^{\circ}C$ digester operating temperature (TJ yr^{-1})
$CNEP_{35}$	cumulative net energy production at $35^{\circ}C$ digester operating temperature (TJ yr^{-1})
D	inside diameter of digester (m)
DOT	digester operating temperature ($^{\circ}C$)
g	gas production (m^3 kg^{-1} v.s. added)
g_t	gas production at time t (m^3 kg^{-1} v.s. added)
G_m	maximum gas produced during digestion (m^3 kg^{-1} v.s. added)
h_i	unit surface conductance of gas inside the digester (W m^2 K^{-1})
h_o	unit surface conductance of air outside the digester (W m^2 K^{-1})
H	heat flux (J m^{-2} s^{-1})
H_L	liquid level in digester (m)
H_S	digester depth below soil surface (m)
H_T	total depth of digester (m)
k	thermal conductivity of digester wall or insulation materials (W m^{-1} K^{-1})
k_a	coefficient of conductance of gas (W m^{-2} K^{-1})
k_f	thermal conductivity of floor material (W m^{-1} K^{-1})
k_j	thermal conductivity of jth material (W m^{-1} K^{-1})
k_s	thermal conductivity of soil (W m^{-1} K^{-1})
k_{T_1}	reaction rate constant at temperature T_1 (day^{-1})
k_{T_2}	reaction rate constant at temperature T_2 (day^{-1})

ℓn	natural logarithm
M	dimensionless modulus
n	number of digester wall or roof materials
P	power requirement for mixing (W)
Q	heat loss (W)
Q_f	heat loss from floor (W)
Q_r	heat transfer from roof (W)
Q_{w_a}	heat loss from digester walls above liquid level where media surrounding the digester is air (W)
Q_{w_s}	heat loss from digester walls above liquid level where media surrounding the digester is soil (W)
Q_{w_1}	heat loss from digester walls below liquid level (W)
Q_{w_2}	heat loss from digester walls above liquid level (W)
Q_I	heat required to raise influent temperature (W)
Q_{L_s}	heat loss from walls below liquid level where surrounding media is soil (W)
Q_{L_A}	heat loss from walls below liquid level where surrounding media is air (W)
r	radial distance in soil mass from centre of digester where temperature T(r) is desired (m)
r^2	coefficient of determination
r_a	air resistance (s m^{-1})
r_i	inner radius of digester (m)
r_j	radius of jth wall material (m)
r_{n+1}	outer radius of digester (m)
r_o	outer radius of digester (m)

r_{os}	radial distance from the digester where digester temperature has no effect (m)
r_s	radius of thermally equivalent soil (m)
R_g	reaction rate constant (day^{-1})
S_f	thickness of thermally equivalent soil for floor (m)
SRT	solids retention time (day)
t	time (day)
t_o	wash-out time (day)
t_s	time for mixing (s)
t_{T_1}	wash-out time at temperature T_1 (day)
t_{T_2}	wash-out time at temperature T_2 (day)
t_∞	infinite time (day)
T	temperature (K)
T(r)	temperature at radial distance r in soil mass around digester (K)
T_a	outside air temperature (K)
T_i	inside temperature (K)
T_j	temperature of jth strip (K)
T'_j	elevated temperature of jth strip (K)
T_{j+1}	temperature of (j+1) th strip (K)
T_{j-1}	temperature of (j-1) th strip (K)
T_ℓ	mixed-liquor temperature (K)
T_o	outside temperature (K)

T_{os}	ambient soil temperature at a distance where digester temperature has no effect (K)
T_s	soil temperature surrounding digester (K)
T_{sa}	ambient soil temperature at a depth z_a from floor (K)
T_{ss}	soil surface temperature (K)
T'_s	soil temperature at a given soil depth (K)
T_z	temperature under floor at a depth z from floor (K)
T_I	influent temperature (K)
TSC	total solids concentration (%)
T_1	temperature (K)
T_2	temperature (K)
U	over-all coefficient of heat transfer (W m^{-2} K^{-1})
U_a	over-all heat transfer coefficient where heat transfer takes place from digester portion below liquid level to outside air (W m^{-2} K^{-1})
U_f	over-all heat transfer coefficient for floor (W m^{-2} K^{-1})
U_r	over-all heat transfer coefficient of roof (W m^{-2} K^{-1})
U_s	over-all coefficient of heat transfer from digester wall below soil surface (W m^{-2} K^{-1})
U_{w_a}	over-all heat transfer coefficient above the liquid level where media surrounding the digester is air (W m^{-2} K^{-1})
U_{w_s}	over-all heat transfer coefficient above liquid level where the media surrounding the digester is soil (W m^{-2} K^{-1})
v.s.	volatile solids
V_a	volume of liquid in the digester (m^3)
W_I	mass of influent added (kg day^{-1})

x_f	thickness of floor material (m)
x_j	thickness of jth roof material (m)
yr	year
z	a variable depth from floor where temperature T_z is desired (m)
z_a	depth under floor where digester temperature has no effect on ambient soil temperature (m)
Z	depth from soil surface (m)
Z_f	thickness of floor material (m)
α	thermal diffusivity (m^2 s^{-1})
θ	temperature coefficient
λ, λ_n	constants (m^{-1})
ρ_a	air density (kg m^{-3})
ρ_w	specific weight of slurry column (kg m^{-3})
ρ_s	density of soil (kg m^{-3})
τ	time (day)
τ_s	time (s)
ϕ	phase difference (rad)
ω_n	angular velocity (rad day^{-1})
Δt	time increment (s)
Δz	depth increment (m)

I. INTRODUCTION

Modern civilization and its economy have become dependent upon a prodigious consumption of energy derived mostly from the burning of fossil fuels. Energy has been the ultimate resource for society's commitment to economic growth. Energy is also involved in man's impact on the environment. No means of supplying energy is without liabilities, and no form of its consumption is without consequence to the ecosystems that support society.

Modern agricultural practices are also energy intensive and have detrimental effects on the environment. For example, confinement housing systems for livestock and poultry result in rapid accumulation of large quantities of manure. One beef animal produces wastes equivalent to that of 18 to 20 people, and large animal populations produce wastes equivalent to that of large cities (Loehr 1967). Disposal of these "wastes" or by-products has caused problems of environmental pollution which need not be elaborated at this time.

Dependence of modern agriculture on fossil fuels, escalating fuel prices and environmental pollution problems have focussed the attention of scientists and engineers on the feasibility of economical recovery of energy from renewable resources such as manure while continuing efforts at reducing the pollution potential of the agricultural industry. A process which recovers energy while simultaneously reducing environmental problems and retaining or improving the fertilizer value of the end-product could be of significant value to the agricultural industry and to society as a whole (Lapp 1974). Animal manure contains large quantities of organic matter which, if broken down by bacteria in the absence of oxygen and in a controlled environment, that is anaerobic digestion, will produce significant quantities of methane gas. The United States alone produces over 1.8 Gt of cattle manure. If this manure, urban and other agricultural wastes could be converted to pipe line gas, it would be equivalent to roughly 40% of the current annual natural gas production in the United States (Crentz 1973). If all the swine and poultry manure, 25% of the beef manure and available crop residues of Canada are converted to biogas, the net energy potential is about equal to the farm energy that is directly applied to cropland production (Downing 1975).

The anaerobic digestion process, discovered by Robert Boyle in 1680, has been used for sludge stabilization in municipal and domestic sewage treatment systems for many years. The process is used to produce methane gas from manure in India where small-scale plants have been put into operation to produce 3 to 250 m^3 day^{-1} of biogas from cow manure of which there is an ample supply (Hellman 1973). However, the technical and economical feasibility of producing methane gas through anaerobic digestion process has not yet been established in cold-climate regions (Lapp et al.1975a).

Anaerobic digestion involves a complexity of biochemical reactions, most of which are interrelated and many of which are currently inadequately understood (Kroeker et al. 1976a). The most common parameters involved in the operation of the anaerobic digestion process are digester operating temperature, solids retention time, volatile solids concentration, volatile acids concentration, pH, alkalinity and presence of toxic materials. The complexity of biochemical reactions and environmental conditions affecting these reactions make it difficult for laboratory and field-scale research to cover more than only a few possible circumstances. In cases like this, computer simulation models are often used when experimentation on the actual system is impossible, time-demanding, economically infeasible or simply inconvenient. In a broad sense, 'to simulate' means 'to duplicate' the essence of a system or activity without actually attaining reality itself. Simulation is essentially a two-phase operation involving modeling and experimentation (Dent and Anderson 1971).

Computer simulation could possibly be applied to the study of anaerobic digestion systems for animal manures to investigate a variety of operating conditions that in laboratory or field-scale operations would be economically infeasible and extraordinarily time-consuming. Conceivably, computer simulation could provide an effective tool for predicting net energy recovery from anaerobic digestion systems operating under various conditions on farm-animal manures. Keeping this possibility in mind this thesis was designed to fulfill the following objective:

To construct, test and utilize a model with which to develop relationships between energy input and output for design and operation of anaerobic digesters for farm-animal manure.

The net energy production from an anaerobic digester is a function of energy input and output from the system. In this study, simulated energy input variables were: (a) the energy required to heat the influent to bring its temperature to the digester operating temperature; (b) the energy required to maintain the digester operating temperature; (c) the energy required to mix the digester contents. The energy output variable was equivalent to methane production under a variety of operating conditions.

The computer simulation model was written in FORTRAN for use on an IBM 370/168 computer. The model was written in such a way that it could be used with any type of animal manure or sewage sludge at any location where air and soil temperatures are available.

To accomplish the stated objectives, the following set of circumstances were employed:

(i) management of manure produced from 2 000 growing and finishing hogs;

(ii) continuous loading of digester;

(iii) digester operating temperatures of 20, 28 and 35^{o}C;

(iv) solid retention times of 10, 30 and 60 days;

(v) influent solid concentrations of 3, 6, 9 and 12%;

(vi) influent temperatures similar to those recorded during the operation of pilot plant anaerobic digesters at the University of Manitoba's Glenlea Research Station;

(vii) assuming steady-state operating conditions throughout the digestion period;

(viii) constant production of volatile solids based on the number of animals;

(ix) complete mixing by gas recirculation;

(x) insulated cylindrical concrete digesters with varying heights and diameters to satisfy loading rate criteria. Base of digesters to be 3 m below soil surface.

(xi) air temperatures for a normal year from Environment Canada--

Winnipeg Weather Bureau Records.

(xii) soil temperatures for a normal year at various depths (maximum of 3 m depth) from the University of Manitoba Glenlea Research Station Records.

II. ANAEROBIC DIGESTION

The conversion of organic wastes to a substitute natural gas through anaerobic digestion is a complex biological process. In order to develop a simulation model of energy recovery from animal manure and evaluate results of this study, it was necessary to understand both the basic biochemical principles of anaerobic digestion and the characteristics of animal manure. This background material, further developed in Chapter IV, is especially for swine manure, the bulk of the discussion on characteristics of animal manure deals with swine manure.

2.1 General Characteristics of Animal Manure

The term manure may mean: (1) liquid manure including both the urine and feces and water from washing, spillage etc.; (2) urine and feces plus varying amounts of bedding; (3) solid material remaining after the liquid has evaporated or drained away; (4) the liquid portion of the total excrement; or (5) fresh excrement including only the urine and feces (Schulte and Tokarz 1976). The daily manure production from an animal is a function of the type and size of animal, the feed, the temperature and humidity within the building and the amount of water added through washing and leakage (Loehr 1974). For hogs, wet manure production rates range from 6 to 8% of the body weight per day. The total solids in swine manure may contain 83% volatile solids (Loehr 1974). Recommended estimates of wet and dry manure production rates from swine are 70 kg and 7.5 kg per day 1 000 kg of live-weight, respectively (Schulte and Tokarz 1976). Ngoddy et al. (1971)* determined that swine manure contained an average of 3.4 parts urine to 1 part feces and that the average elimination rate of hogs was 50.0 kg feces plus urine per day per 1 000 kg live-weight. Variation in the previous data exists mainly because of the varying management practices inside the barn.

Anaerobically-stored manures have a smell which can be a nuisance when air is exhausted from the building in which the manure is kept or when the manure slurry is spread on land (Loehr 1974). About 45 compounds have been identified in air associated with animal manure storage systems. The amines, mercaptans, organic acids and heterocyclic nitrogen compounds are generally regarded as greatest contributors to the smell of anaerobically-stored animal manures (Miner 1974). Most of the odorous compounds are produced by anaerobic bacteria when the manure is accumulated in pits or enclosures (Schulte and Kroeker 1976). When manure undergoing decomposition is exposed to the atmosphere, volatile products and intermediates tend to escape and cause an odor problem (Miner 1974). Anaerobic digestion, which is a controlled degradation process, substantially and significantly reduces odors from swine manure but there is still an identifiable odor in the manure (Welsh et al. 1976).

Animal feces commonly contain compounds which are added to feed to increase the weight gain of animals. Some of these additives are inhibitory to microorganisms and may affect the performance of anaerobic digestion systems for animal manures. These inhibitory substances are salts of sodium, potassium, calcium and magnesium; soluble

*taken from Loehr (1974).

sulfides; heavy metals such as copper, zinc, nickel and hexavalent chromium; high concentration of alcohols and long chain fatty acids (McCarty 1964). Sometimes swine manure slurries contain lye (Schulte)* and antibiotics such as tylosin and lynconrycin (Fischer et al. 1975) which are found toxic to anaerobic digestion process. The success of anaerobic digestion will depend on the presence of these toxic substances and the degree to which they are neutralized in the anaerobic digester.

Normally, mechanical handling equipment is needed for livestock manure removal from a livestock area, transfer to a storage pit or movement to an anaerobic digester. Swine manure usually averages 15 to 20% dry matter (solids) while slurries normally can be pumped only in concentrations up to 12% dry matter (Loehr 1974). Thus, swine manure may require dilution to enable pumping. In some cases where enough dilution occurs due to leaky waterers or cleaning of barn, no extra dilution is needed.

The biochemical oxygen demand (BOD), chemical oxygen demand (COD), solids and nutrient contents of animal manure are important parameters to individuals who are concerned with pollution control activities and to those who must design and evaluate anaerobic digesters. Often these characteristics are reported in terms of concentration in a liquid slurry. Since the water content of slurries varies widely, values based on concentration can also be expected to vary widely (Table 2.1). Schulte and Tokarz (1976) provided a comprehensive list of elements in swine manure with the respective rates of production by hogs (Table 2.2).

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*Schulte, D. D. 1976 11 ?. Personal communication. Department of Agricultural Engineering, University of Manitoba, Winnipeg, Manitoba.

TABLE 2.1 POLLUTION CHARACTERISTICS OF HOG MANURE[+]

Total solids	Volatile solids	Suspended solids	BOD_5	COD	Ammonia nitrogen	Total nitrogen	References
			kg day^{-1} kg^{-1} animal				
0.80	0.62		0.20	0.75	0.024		Hart and Turner 1965
0.97	0.80		0.43	0.96			Taiganides et al. 1964
0.50	0.35			0.47			Clark 1965
0.59	0.47	0.47	0.20[a]	0.52			Schmid and Lipper 1969
		0.05-0.28	0.13-0.35				Pontin and Baxter 1968
0.23			0.33	0.55			Townshend et al. 1969
0.47-0.86			0.19-0.34				Weller 1970
						1.86-2.17%	Fisher 1974
			kg m^{-3} of slurry				
6-8			27-33	70-90	5.5-7.5		Scheltinga 1966
0.7-6.2			2-52	5-143	2-7		Irgens and Day 1966
			1.3-13	30			Poelma 1966
		7-16	20-34[a]	62-74			Schmid and Lipper 1969
			18-20				Pontin and Baxter 1968
			16-22	47-75			O'Callaghan et al. 1971
	80-84%		29-47	61-90	1.9-4.6	5.6-9.2	Ngoddy et al. 1971

[+]most of the references are taken from Loehr (1974).

[a]ultimate BOD.

TABLE 2.2 DATA REPORTED FOR WET AND DRY MATTER AND FOR NUTRIENTS EXCRETED BY SWINE
AFTER SCHULTE AND TOKARZ (1976)

	Wet matter	Dry matter	N	P	K	Ca	Na	Mg	S
	kg per day per 1 000 kg liveweight								
Range	60-80	5-10	0.3-0.7	0.09-0.26	0.05-0.51	0.08-0.44	0.05-0.21	0.03-1.10	0.015-0.092
Recommended value	70	7.5	0.5	0.17	0.25	0.22	0.05	0.05	0.05

	Fe	Zn	Cu	Mn	Al	B
	kg per day per Gg liveweight					
Range	5.7-35.3	0.96-18.0	0.17-8.6	0.86-4.2	2.1-6.7	2.0
Recommended Value	9.4	3.8	1.1	2.3	4.1	2.0

	Mo	Co	Cd	Pd
	kg per day per Gg live weight			
Range	0.0015-0.0038	0.017-0.11	0.0023-0.018	0.03-0.32
Recommended value	0.0025	0.046	0.0075	0.09

2.2 General Background of the Anaerobic Digestion Process

Anaerobic digestion is a biological process which occurs in the absence of free oxygen. Compounds containing oxygen are broken down, and the oxygen obtained from these compounds is used for respiration by the anaerobic bacteria and the net chemical reaction of the process is often expressed as

$$CHX + H_2O \longrightarrow CO_2 + CH_4 + X \qquad (2.1)$$

The biochemical processes involved in the conversion of complex wastes to methane can be divided into three steps (O'Rourke, 1968): (1) hydrolysis, which is the enzymatic breakdown of large complex organic molecules into smaller molecules which can be taken into the cell and utilized; (2) acid fermentation, or the intracellular conversion of simple organic molecules into a variety of organic acid end-products by common facultative and anaerobic, saprophytic micro-organisms; and (3) methane fermentation, or the conversion of long and short chain organic acids to methane and carbon dioxide by a group of substrate-specific, strictly anaerobic, methane-producing organisms.

2.2.1 Hydrolysis

Animal manure is a complex mixture of carboyhdrates, fats, proteins and their breakdown products (Miner 1974). Since bacteria can utilize only low molecular-weight carbonaceous and nitrogenous materials, bacteria need to develop some system to hydrolyze such large molecules into smaller ones for their normal metabolic activities (Rogers 1961). Generally, extracellular enzymes are elaborated by bacteria and are diffused into the surrounding media to breakdown substances of high molecular weight into simpler compounds which can diffuse into the cell. The primary purpose of hydrolysis in a biological system is to render large complex molecules available for biological utilization, whether by the excretion of extracellular enzymes or by the direct contact of the organisms with the complex substrate. In contrast, the ultimate source of energy for the bacteria is provided not by hydrolysis, but by the subsequent chemical oxidation-reduction reaction performed on the hydrolysis products (O'Rourke 1968).

2.2.2 Acid Fermentation

The resultant products from the hydrolysis of proteins, carbohydrates and fats serve as substrates for the normal metabolic functions of many commonly occurring acid-forming organisms. Some of the more prominent end-products of importance to anaerobic digestion systems are acetic, propionic, butyric and higher volatile fatty acids, alcohols, hydrogen and carbon dioxide.

2.2.3 Methane Fermentation

The complex organic molecules, which have been previously hydrolyzed and further degraded to alcohols and volatile fatty acids are finally converted through methane fermentation to gaseous forms. This step is carried out by a group of strict anaerobes, the methane formers, which belong to the genera *Methanobacterium*, *Methanosarcina*, and *Methanococus* (McCarty 1964). These organisms require carbon dioxide for the reduction of volatile acids to methane. The carbon dioxide acts as the hydrogen acceptor and is reduced to methane gas.

Acetic and propionic acids have been shown to be the principal intermediates in the anaerobic digestion process. The importance of these two acids as precursors to methane was illustrated (Figure 2.1)

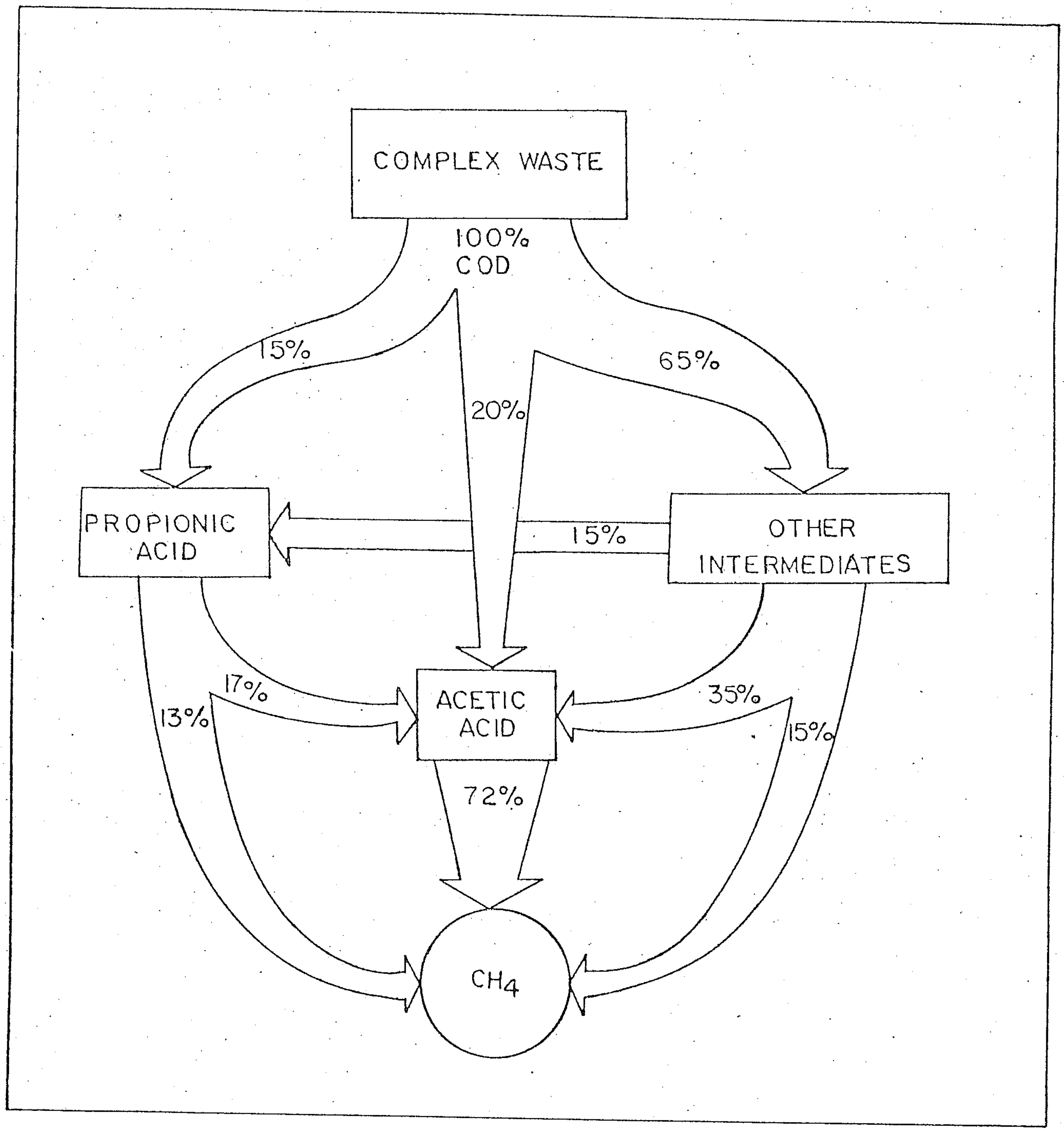

FIG. 2.1 PATHWAYS IN METHANE FERMENTATION OF COMPLEX WASTES. AFTER Mc CARTY (1964)

by McCarty (1964). Degradation of the complex waste into variable percentages of intermediate compounds is dependent on the composition of the waste and the environmental conditions in the digester. The production of the final product is also dependent on the work of intermediate groups of organisms which prepare the material for subsequent groups. The values shown in Figure 2.1 are merely an indication of these proportions (O'Rourke 1968).

2.3 Environmental Factors Affecting Anaerobic Digestion

Saprophytic bacteria are a mixed culture and exist in large numbers in animal manures. These bacteria multiply rapidly and generally are insensitive to environmental changes. The methane-producing bacteria, however, are few in number in the raw manure and are slow to reproduce. Methane bacteria are very sensitive to environmental changes and are obligate anaerobes. Consequently, a controlled environment must be maintained to stimulate their growth. The following discussion outlines some of the important practices and conditions necessary for an optimum environment.

2.3.1 Seeding

Seeding is recommended as a start-up practice for anaerobic digestion of swine manure (Hobson and Shaw 1973). Seeding consists of the addition of actively digesting material to a new digester to ensure that a culture of methane-producing bacteria is present for start-up. The time required for active digestion to begin is reduced by seeding.

2.3.2 Nutrient Balance

All biological systems require an adequate supply of nutrients, particularly, carbon, nitrogen and phosphorus. Many others are also needed in trace amounts. Animal manures normally contain an adequate, well-balanced nutrient supply. The lack of any specific element required for bacterial growth in anaerobic digesters will limit gas production.

2.3.3 Solids

The concentration of solids required for anaerobic digestion is a fundamental factor in this type of animal manure management system. Since the optimum total solids concentration in an anaerobic digester is normally 7 to 9% solids, considerable dilution may be required. However, as mentioned in section 2.1, liquid manure systems often are found in barns where adequate dilution occurs due to washing and leaking waterers. Therefore, not much, if any, further dilution may be required. Ideally, the total solids content of an anaerobic digester should be maintained uniformly with only gradual changes at times such as start-up (Lapp et al. 1975b).

Volatile solids (v.s.) commonly are used to estimate the organic portion of the total solids. The biological organisms utilize a portion of this material as substrate, making volatile solids an important parameter in estimating potential gas production. Approximately 20% of the volatile solids in swine manure are non-biodegradable and a biological process always converts a portion of its substrates to new cell mass. Because of this, generally less than 50% of the volatile solids are destroyed in practice (Lapp et al. 1975b).

2.3.4 Loading Rate

The loading for anaerobic digesters usually is expressed in terms of the weight of volatile solids per unit digester volume per unit time. Loading rates for swine manure reported in the literature vary from 0.32 to 4.01 kg m^{-3} day^{-1} (Table 2.3). Sometimes, loading rates up to 5.6 kg m^{-3} day^{-1} are possible if optimum environmental conditions are maintained in the anaerobic digester (Taiganides et al. 1963). Optimum conditions include adequate mixing, continuous feeding, adequate solids retention time and high temperatures. Higher loading rates make better use of digester capacity but are sometimes restricted by factors such as the water content of slurries. To maintain uniform gas production, and to minimize the possibility of upsetting the balance between acid fermentation and methane fermentation in the digester, the loading rate should be maintained as uniformly as possible. However, where adequate bicarbonate buffering capacity exists, temporary upsets in solids loading rates may be tolerated by the microflora in the system (Kroeker et al. 1976a).

2.3.5 Solids Retention Time (SRT)

The length of time that volatile solids remain in an anaerobic digester is a fundamental factor in the digestion process. The SRT represents the average time microorganisms spend in the system and can be determined by dividing the mass of volatile solids in the digester by the amount leaving the digester per day. Minimum SRT's for anaerobic digestion systems operating in the thermophilic temperature range are in the range of 2 to 6 days (Loehr 1974). In continuous flow thermophilic digesters, 80 to 90% of the gases are produced within the first 10 to 20 days of digestion and sludge becomes inoffensive (Garber 1954) while 20 to 30 days are required for similar quantities of gas production from mesophilic digesters (Rowe 1971).

TABLE 2.3 GAS COMPOSITION AND PRODUCTION RATES FROM ANIMAL WASTES*

AFTER SCHULTE et al. (1976)

	Gas Production ($m^3 kg^{-1}$ v.s. added)	V.S. reduction (%)	CH_4 (%)	Temperature (^oC)	Loading rate (kg v.s. m^{-3} day^{-1})	Detention time (days)	Reference
SWINE	0.49-0.64	41-54	59	35	0.32-3.2	10-50	Taiganides et al. 1963
	0.37-0.54	53-62	68	35	2.41-3.05	20	Jeffry et al. 1964
	0.48-1.05	26-76	57-60	32-52	2.41-4.01	10-15	Fong 1973
	0.26-0.45	44-61	58-61	33	1.92-3.85	10-15	Gramms et al. 1971
	0.62-0.82	36-44	66	35	1.05-2.10	15-30	Kroeker et al. 1975
DAIRY	0.12-0.19	42-53	65	35	2.56-3.53	17-20	Jeffry et al. 1964
	0.26-0.9	16-29	57-68	32-52	2.41-4.01	10-15	Fong 1973
	0.07-0.16	11-16	52-64	23-35	2.08-3.53	25-26	Hart 1963
	0.06-0.10	18-27	61-66	33	1.92-3.85	10-15	Gramms et al. 1971
	0.04-0.06	38-53	74-79	35	1.60-2.89	12-20	Dalrymple and Proctor 1967
POULTRY	0.10-0.27	20-45	11-49	35	2.72-4.97	23-26	Hart 1963
	0.28-0.36	57-68	58	33	1.92-3.85	10-15	Gramms et al. 1971
	0.56	?	69	50	?	9	Savery and Cruzan 1972

*v.s., volatile solids; some data taken from Smith 1)

1) Smith, R. J. 1973. The anaerobic digestion of livestock wastes and the prospects for methane production. Unpublished Report, Agric. Eng. Dept., Iowa State University, Ames, Iowa.

In completely-mixed anaerobic digesters, where no recycling occurs, the SRT is equal to hydraulic retention time (HRT). The HRT is the digester volume divided by the volume of daily feed. Both solids and hydraulic retention times for adequate destruction of organic solids and optimum gas production are temperature dependent. Hydraulic retention times usually vary from 10 to 30 days (Lapp et al. 1975b).

2.3.6 Temperature

Temperature affects the time required for digestion and the quantity of gas produced. Anaerobic systems normally function better at warm temperatures than at cold temperatures. There are three distinct ranges of temperature in which anaerobic decomposition can take place: Cryophilic or psychrophilic, mesophilic and thermophilic.

(a) Cryophilic or psychrophilic: Psychrophiles are properly defined as the organisms which grow well at $0^{o}C$ within 2 weeks (Farrel and Rose 1965). The temperature limits to the existence of psychrophilic bacteria is poorly defined however. For example, Metcalf and Eddy (1972) state that it is limited to the range -2 to $30^{o}C$ yet it has been known for some time that the temperature zone exists as low as $-24^{o}C$ in the case of <u>Oaspora lactis</u> (Berry 1934)*. Psychrophilic bacterial action is very slow and a long time is required to stabilize solids. Solids retention times in excess of one year may be required, thus making the psychrophilic range of digestion impractical in most situations.

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*taken from Farrell and Rose (1965).

(b) Mesophilic: Mesophilic bacteria are predominant in the 20 to 45^{o}C temperature range. In this range, the bacteria are quite active and methane gas production is significant. Solid retention times are in the range of 20 to 30 days in a properly operating mesophilic digester (Rowe 1971).

(c) Thermophilic: The thermophilic temperature range is from 45^{o}C to 73^{o}C but the rate of bacterial action is maximum around 55^{o}C. Thermophilic digesters can have SRTs as short as 14 days at 55^{o}C, as compared to a minimum of 24 days for mesophilic digestion at 35^{o}C (Malina 1964). However, high-rate anaerobic digesters often run at shorter SRTs in both the thermophilic and mesophilic ranges of temperature. A high-rate digester is characterized by continuous heating and continuous mixing of the entire digester contents. Consequently, a minimum of 2 to 6 days SRT may be sufficient for digestion in the thermophilic range (Loehr 1974).

The rates of most chemical and biochemical reactions depend strongly on temperature. Biochemical reactions catalyzed by enzymes are no exception to this rule. Furthermore, low temperatures characteristic of Canada impose a possible restriction on the feasibility of anaerobic digestion in this country. It therefore is appropriate to further review the general affects of temperature on biological processes.

Most investigations have concluded that, within specific temperature ranges, an equation of the form

$$R_g = a.e^{bT} \tag{2.2}$$

can be used to express the relationship of a reaction rate R_g and temperature T. The values of a and b are functions of the specific process and reaction within that process. Reaction rates which are determined or known at a specific temperature can be estimated at other temperatures by

$$k_{T_2} = k_{T_1} \cdot \theta^{(T_2 - T_1)} \qquad (2.3)$$

where: k_{T_2} = desired reaction rate at temperature T_2 (day^{-1})

k_{T_1} = known reaction rate at temperature T_1 (day^{-1})

θ = temperature coefficient

The frequently used approximation of van't Hoff states that reaction rates double for each $10^{\circ}C$ rise in temperature. If $\theta = 1.072$ in Equation 2.3, the reaction rate is doubled for an increase of $10^{\circ}C$. This equation generally is useful for a given temperature range, around $20^{\circ}C$. Its use is less applicable at extreme temperature conditions (Loehr 1974).

Fair and Moore (1934) presented a summary of previous work pertaining to the time of digestion in relation to temperature. They concluded from their review, and then verified it in a subsequent study (Fair and Moore 1937), that there were two distinct temperature ranges for anaerobic digestion of sewage solids: the mesophilic range 20 to $35^{\circ}C$; and the thermophilic range, 42 to $55^{\circ}C$. They indicated a range of discontinuity or a transition zone between these two temperature ranges. They also indicated that the optimum temperatures for digestion were 30 to $35^{\circ}C$ for the mesophilic range and $55^{\circ}C$ for the thermophilic range. Since that time there have been a number of investigations on the effect of temperature on anaerobic digestion. Many of the investigations (Malina 1961; Heukelekian and Kaplovsky 1948; Garber 1954; Golueke 1958 and Pohland and Bloodgood 1963) were conducted at 30°C and above to investigate and compare thermophilic operation with mesophilic operation. Pfeffer (1967) studied population dynamics in anaerobic treatment at 25°C and 35°C and concluded that effective treatment could be accomplished at the lower temperature if the sludge age was increased above that normally employed at 35°C. O'Rourke (1968) conducted experiments at temperatures of 15°, 20°, 25° and 35°C on sewage sludge and concluded that effective and efficient anaerobic digestion can be accomplished at reduced temperatures. However, the effect of low temperatures on anaerobic digestion of animal manures are not yet reported.

The methane-producing bacteria are thought to be very sensitive to sudden temperature changes. For example, a 2.8°C drop in temperature may stop digestion entirely (Garber 1954; Golueke 1958). However, Kroeker et al. (1976a)demonstrated that rapid temperature fluctuations of 3 to 6°C had little or no significant effects on gas production rates while a temperature fluctuation as large as 8°C simply altered gas production in direct proportion to the temperature change. In the study by Kroeker et al., digestion stability was not impaired despite rapid temperature changes because of a high alkalinity and an acclimation procedure which had been applied to the system.

Temperature affects the microorganism wash-out time, the minimum SRT at which gas production can be maintained in anaerobic digestion systems. The lower the digester operating temperature, the greater will be wash-out time and the relationship can be expressed as

$$t_{T_2} = t_{T_1} \cdot \theta^{-(T_2-T_1)} \tag{2.4}$$

where: t_{T_2} = wash-out time at temperature T_2 (days)

t_{T_1} = wash-out time at temperature T_1 (days)

The equation 2.4 is an attempt to estimate the wash-out time at various temperatures because not much is known about the mathematical dependency of wash-out time on temperature.

2.3.7 Alkalinity and pH

Alkalinity is a measure of the capacity to neutralize acids chemically. Common forms of alkalinity are OH^-, HCO_3^- and $CO_3^=$ which generally are expressed as the equivalent concentration of $CaCO_3$. The pH is a measure of the H^+ ions present in solution and is calculated from the formula

$$pH = -\log_{10}(H^+) \tag{2.5}$$

The alkalinity and pH relationship is very important in anaerobic digestion. Municipal digesters normally operate in a pH range of 6.6 to 7.6 with an alkalinity of 1.0 to 5.0 kg m^{-3} as $CaCO_3$. However, pilot-scale digestion at the University of Manitoba, using swine manure as a substrate, have operated successfully at pH levels up to 8.5 and an alkalinity of 14 kg m^{-3} as $CaCO_3$ (Lapp et al. 1975a). Other investigators, who have studied anaerobic digestion of animal manures have also reported high pH and high alkalinity levels. For example, Taiganides et al. (1963) reported satisfactory performances at alkalinity levels of 6.8 kg m^{-3} as $CaCO_3$ and pH 7.4 for anaerobic digestion of swine manure. Hart (1963) found that dairy manure digested actively in a pH range of 7.3 to 8.0 and alkalinity of 7.0 to

9.0 kg m^{-3} as $CaCO_3$.

Concentrations of un-ionized volatile acids exceeding 0.06 kg m^{-3} are known to be toxic to methane-producing bacteria (Kroeker et al. 1976b). Therefore, according to Equation 2.6, a high alkalinity should favour active digestion by neutralizing the formation of un-ionized volatilized acids. In this way high alkalinities enable the methane-producing bacteria to tolerate temporary over-loading and temperature shocks as indicated in Sections 2.3.4 and 2.3.6.

$$CH_3COOH \rightleftharpoons CH_3COO^- + H^+ \tag{2.6}$$

2.3.8 Mixing

Mixing of digester contents provides an intimate contact between the microorganisms and their substrate, a mechanical re-lease for the gas produced and a partial assist in preventing scum formation. Mixing can be accomplished by mechanical means, by liquid recirculation, or by recycling the produced gas through diffusers in the bottom of the digester. Mixing devices should also be designed to prevent the deposition of heavier materials such as grit and undigested feed from accumulating in the digester.

Scum is a collection of lightweight, inert material which collects on the surface of the liquid in the digester. This accumul-ation, unless broken and removed, can reduce effective volume of a digester and impede the release of gas from the liquid media (Lapp et al. 1975b). Indirect mixing obtained from gasification plus sludge recirculation can keep highly loaded anaerobic units adequately mixed (Loehr 1974). According to Metcalf and Eddy (1972) the daily amount of gas required for gas recirculation mixing is 1.8 m^3 per m^3 of digester volume at atmospheric pressure.

2.3.9 Inhibitory Substances

High volatile acids concentrations were once believed to be the cause of most digester failures. Buswell (1947) and Schlenz (1947) concluded that volatile acids were toxic to methane bacteria at concentrations above 2 kg m^{-3}. Then McCarty and McKinney (1961) proposed that digester failures were not due to volatile acid toxicity, but due to salt toxicity. They found that volatile acids concentrations as high as 10 kg m^{-3} could be neutralized by magnesium hyroxide and lime without affecting methane fermentation. Hart (1963) found that manure-fed digesters worked even at volatile acids concentration of 7 kg m^{-3} without addition of a neutralizing agent. Results of work conducted by Andrews (1969) and supported by Brune (1975)* suggested that digester toxicities were caused by the un-ionized portion of the volatile acids and as a result volatile-acids toxicities were directly related to mixed liquor pH as well as to the concentration of un-ionized volatile acids which in turn inhibit the activity of methane bacteria (Kroeker et al. 1976a).

The principal inhibitors of anaerobic digestion other than the volatile acids, carbon dioxide and pH, are the cationic portions of sodium, potassium, calcium and magnesium salts, ammonia, copper, zinc, chromium and nickel, as well as soluble sulfides. Oxygen and oxidized forms of nitrogen serve as hydrogen acceptors, replacing CO_2 and oxidized organic matter and, in this role, inhibit methane production (Lapp et al. 1975b).

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*taken from Kroeker et al. (1976a).

Animal manure is high in alkaline earth metal salts, ammonia and sometimes in copper, zinc and sulfur content. Soluble copper and zinc concentrations as low as 0.01 kg m^{-3} have resulted in complete inhibition of gas production (Loehr 1974). Copper concentrations alone in pig slurry have been reported to range from 0.004 to 0.365 kg m^{-3} (Loehr 1974).

It has been reported that methane formation will be inhibited when ammonia-nitrogen concentrations are of the range 1.5 to 3.0 kg m^{-3} at higher pH values and that when the concentration exceeds 3 kg m^{-3} the ammonia ion itself becomes quite toxic regardless of pH (McCarty 1964). McCarty and McKinney (1961) reported that pH played a significant role in ammonia toxicity and they deduced that when the free ammonia concentration exceeds 0.15 kg m^{-3} severe toxicity will result. Hart (1963) and Gramms et al. (1971) reported inhibited digestion of poultry manure. Schmid and Lipper (1969) reported unsuccessful digestion of swine manure due to ammonia toxicity. However, studies at the University of Manitoba have shown that it is possible to tolerate ammonia levels of 3.5 kg m^{-3} at a pH of 8.4 with no apparent reduction in methane production (Lapp et al. 1975a). Kugelman and Chin (1971) provided an explanation for these variations by conducting experiments to show that in a multiple-cation system, tolerance to potentially toxic cations is produced by acclimation of the microorganisms to the toxic agent or by antagonism to the toxic cation or by both. Following this, Kroeker et al. (1976a) concluded that with proper attention to acclimation procedures, the anaerobic digestion of organic residues containing high nitrogen concentrations is likely to be more stable than digestion within the limits of "normal anaerobic treatment."

2.4 Gas Production Variables

Most researchers claim that gas can be produced from swine manure in the range of 0.26 to 1.05 m^3kg^{-1} of volatile solids added to the digester (Loehr 1968; Taiganides et al. 1963; Fong 1973, Gramms et al. 1971). A comprehensive list of gas production rates from swine, dairy and poultry manures is given in Table 2.3. Patel (1967) claims that from operating systems in India 0.43 to 0.64 m^3 of gas was collected per kg of volatile solids added from cow manure while 0.72 to 1.0 m^3 of gas was collected per kg of volatile solids added from poultry manure. This data also agrees with the data presented in Table 2.3.

The composition of gas produced by an anaerobic digester normally should be about 60 to 70% methane and 30 to 40% carbon dioxide with a small amount of hydrogen, hydrogen sulfide, nitrogen, ammonia and other gases. The fraction of gases in gas produced through anaerobic digestion depends on the composition of organic matter decomposed (Taiganides and Hazen 1966). The amount of gas produced in laboratory studies (Table 2.3) varies widely depending on temperature, loading rate, detention time and type of manure. It is these variables that are most often used to predict gas production from the anaerobic digestion process.

As already discussed, temperature affects gas production severely because it controls the biochemical reaction rate which is responsible for gas production. At 15°C over a year may be required to digest organic material while at 35°C one month will stabilize most wastes (Patel 1967). Temperatures above 70°C, i.e. the upper range of thermophilic bacterial activity, may sterilize the waste, killing all the bacteria thus stopping gas production. Consequently, proper temperatures are always necessary to enable good gas production rates.

Since organic loading rate is a design parameter which combines both the SRT and influent solids concentration into one term, the change in gas production may reflect the effect of one or both. The results of Hobson and Shaw (1972) show that at a constant SRT total gas production increased from 0.0035 to 0.011 m^3 day^{-1} when the loading rate was increased from 0.96 to 3.2 kg v.s. m^{-3} day^{-1} due to a solids concentration increase from 2 to 5.2% respectively. However, when the total gas production data were converted into gas production rates (m^3 day^{-1} kg^{-1} v.s. added) no apparent change occurred at a constant SRT. Taiganides et al. (1963) showed a relationship among SRT, loading rate and total solids concentration which clearly indicates that at a constant SRT, any effect of loading rate is rather an indirect effect of total solids concentration on gas production. In another study, Schulze (1958) demonstrated an increase in gas production with an increase in loading rate from 0.40 to 3.4 kg dry solids m^{-3} day^{-1}. This study did not maintain a constant SRT, so it is hard to conclude that the change in gas production was due to SRT or due to solids concentration. Lapp (1976) also found that there was a change in gas production rate up to a loading rate of 4 kg v.s. m^{-3} day^{-1} but where SRT was kept constant no change occurred in gas production rates with changes in solids concentration from 2.7 to 7.6%. Schulze (1958) found a normal rate of gas production up to a concentration of 39%

total solids, starting with a low concentration and increasing gradually.

The studies by Hobson and Shaw (1972), Schulze (1958) and Lapp (1976) as discussed in the previous paragraph show that solids concentration does not appear to affect gas production rates but that SRT has a significant effect on the gas production rate. The optimum SRT is dependent on the digester temperature and the volatile solids concentration in the slurry. Beyond the optimum limit of SRT, there is no significant increase in gas production.

III. HEAT TRANSFER CHARACTERISTICS OF ANAEROBIC DIGESTION SYSTEMS

In the anaerobic digestion process the operating temperature of the digester is one of the important environmental factors affecting process operation. Normally, heat is required to maintain the digester operating temperature. When operating the digester during cold weather the digester heating requirements will be significant, especially at elevated process temperatures. The total energy involved in maintaining a desired operating temperature includes: (1) heat losses through the digester walls, roof and floor; (2) heat required to raise the temperature of the digester influent to the desired operating temperature; (3) heat losses in biogas from the digester; and (4) heat generated by microorganisms, (Figure 3.1).

To estimate digester heating requirements, the energy necessary to replace wall, roof and floor heat losses and to raise the temperature of the raw manure influent, basic heat transfer theory was applied to each component as discussed in this chapter. However, calculations for typical gas production volumes from mesophilic digesters showed that the loss of heat through biogas transfer from a 3.2 m^3 digester was on the order of 0.1 W. Total heat losses from a similar digester excluding heat loss through biogas transfer (Lapp 1976) were approximately 500 W. Therefore the effect of heat loss through biogas production was not incorporated in this thesis.

The microorganisms may produce some heat during degradation of organic matter in anaerobic digester. However, in practice, the heat generated by microorganisms is not encountered in calculations

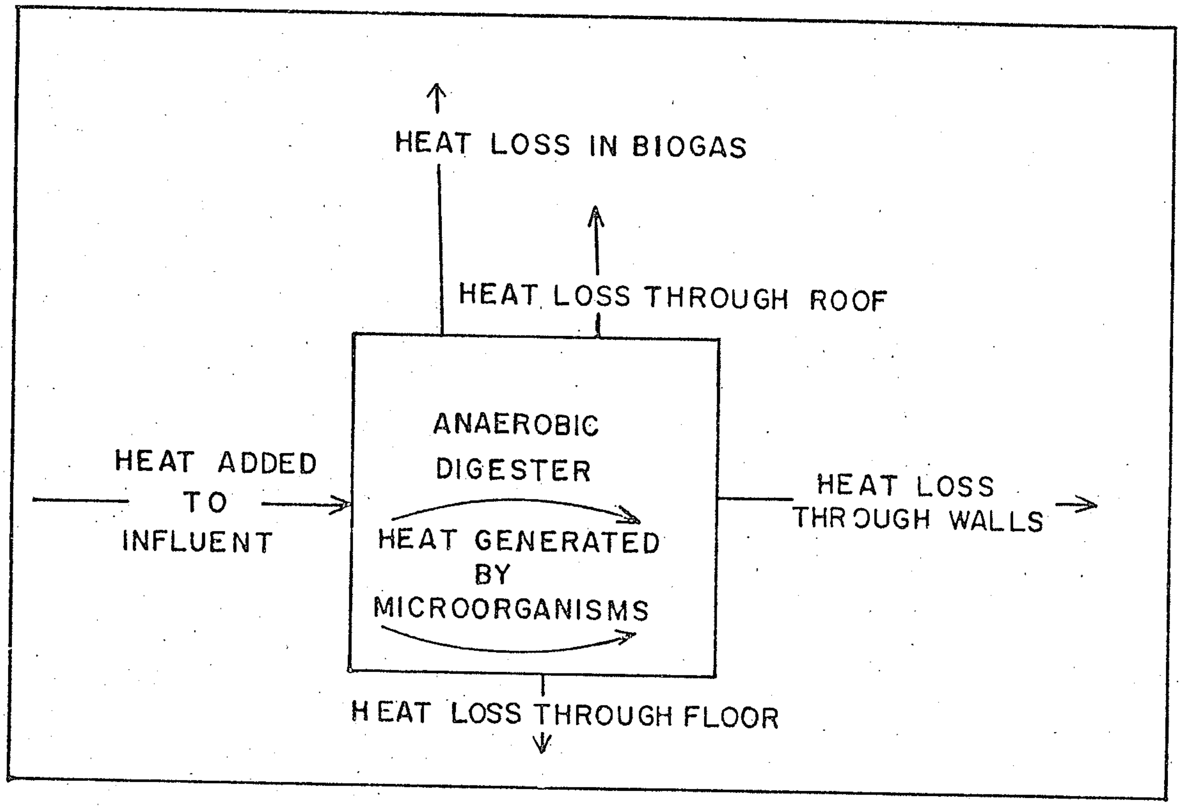


FIG. 3·1 SCHEMATIC DIAGRAM OF HEAT TRANSFER IN AN ANAEROBIC DIGESTION SYSTEM of total heat losses (WPCF 1959). Therefore the heat generated by microorganisms was not included in this thesis.

3.1 Modes of Heat Transfer

There are three distinct modes of heat transfer: conduction, convection and radiation.

Heat flows by conduction from a region of higher temperature to a region of lower temperature within a medium (solid, liquid or gas) or between different mediums through direct physical contact. Conductive heat transfer occurs by collision of fast moving molecules with slower-moving molecules without appreciable displacement of the molecules. The mechanism of convection involves the transfer of energy within a liquid or gas by physical movement from one location to another in which energy is stored. Radiation is heat flow by electromagnetic waves between two bodies separated by space.

Kroeker et al. (1975) found that conductive heat transfer theory accurately predicted energy requirements for digester heating. Therefore, in this study the effects of convective and radiative heat transfer were indirectly included in an overall coefficient of heat transfer (U). This practice is usually followed to determine heat transfer in heat exchangers and from composite wall structures (Kreith 1967).

Conductive heat transfer takes place from all the external surfaces of a digester except the surface above ground level where a combination of conductive, convective and radiative heat transfer occurs. The overall heat transfer coefficients used in this study took into consideration the film coefficients for heat transfer from each component of the digester depending on the mode of heat transfer.

3.2 Heat Transfer from Digester Walls

The shape of the digester affects heat losses because the surface area for a given volume is greater for some shapes than others. This study assumed a cylindrically shaped digester at a fixed depth below the soil surface. The most economical cylindrical shape, insofar as heat losses are concerned, is one in which the diameter is equal to the total depth (WPCF 1959).

The general equation of steady-state, uni-directional heat transfer is:

$$Q = U.\ A_o^1.(T_i - T_o) \tag{3.1}$$

where: Q = heat loss (W)

U = overall heat transfer coefficient (W $m^{-2}K^{-1}$)

A_o^1 = surface area normal to direction of heat flow (m^2)

T_o = outside temperature (K)

T_i = inside temperature (K)

This is the general equation from which much of the theory in the subsequent sections was derived.

3.2.1 Heat Transfer from Walls Below Liquid Level

The liquid level in the digester is a function of the digester diameter and amount of slurry stored in the digester. Two possibilities may occur while considering heat transfer from digester walls below the liquid level: (a) the liquid level (H_L) may be equal to or less than that of the digester depth below soil surface (H_S); (b) the liquid level may be higher than that of the digester depth below the soil surface (Figure 3.2). Each situation involves separate equations to determine heat losses from a hollow cylindrical surface.

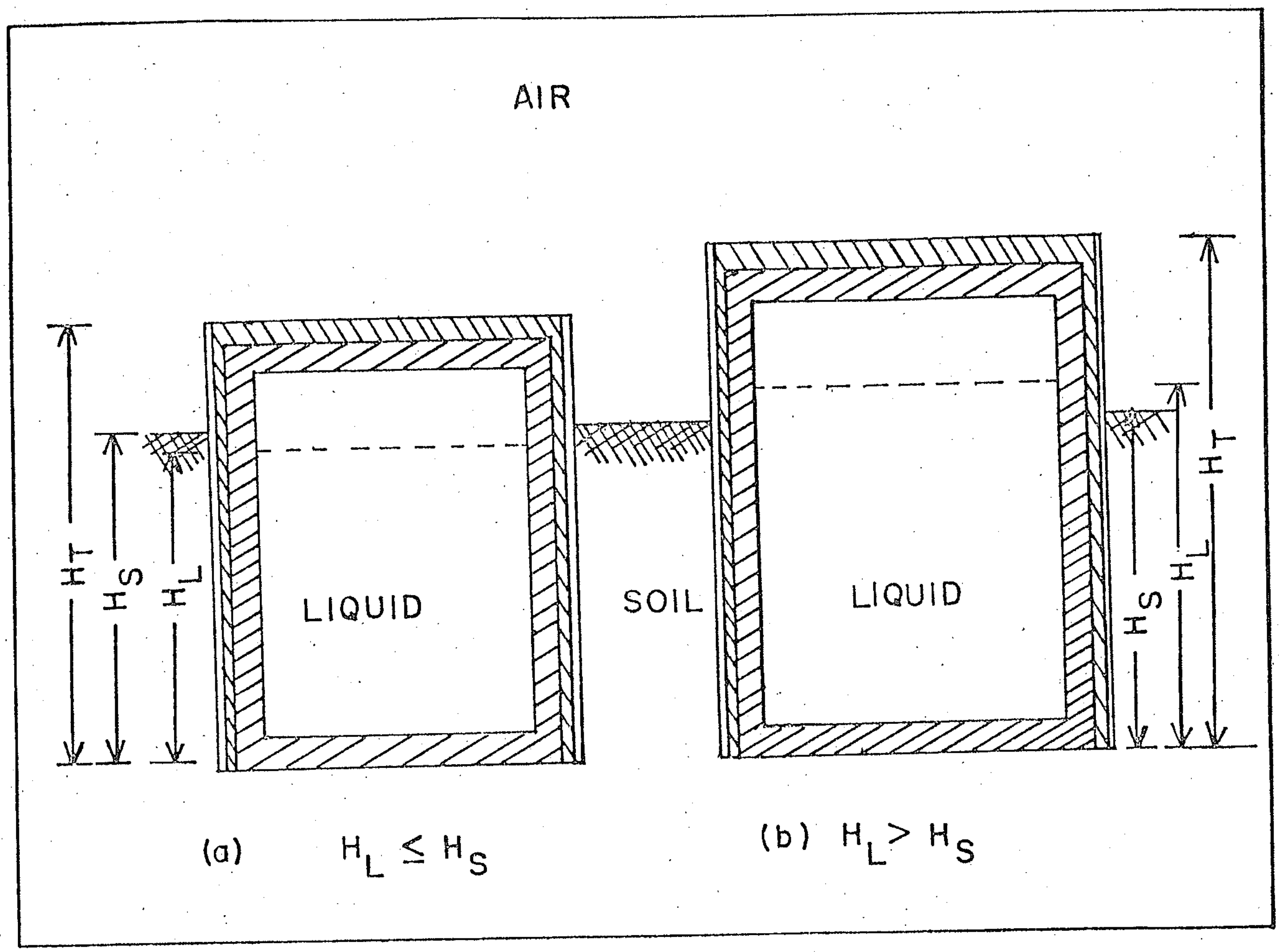


FIG. 3.2 POSSIBLE SITUATIONS OF LIQUID LEVEL IN THE DIGESTER

(a) If $H_L \leq H_S$

$$Q_{w_1} = U_s \cdot A_o^1 \cdot (T_\ell - T_s) \tag{3.2}$$

and

$$U_s = \frac{1}{r_{n+1} \cdot \sum_{j=1}^{n} \frac{\ell n\left(\frac{r_{j+1}}{r_j}\right)}{k_j}} \tag{3.3}$$

$$A_o^1 = 2\pi \cdot r_{n+1} \cdot H_L \tag{3.4}$$

where: Q_{w_1} = heat loss from walls below liquid level (W)

T_ℓ = mixed-liquor temperature (K)

T_s = temperature of soil surrounding digester walls (K)

n = number of digester wall materials

r_{n+1} = outer-most radius of digester (m)

r_j = radius of j th wall material (m)

k_j = thermal conductivity of j th wall material (W $m^{-1}K^{-1}$)

ℓn = natural logarithm

(b) If $H_L > H_S$

$$Q_{w_1} = Q_{L_s} + Q_{L_A} \tag{3.5}$$

where: Q_{L_s} = heat loss from walls below liquid level where surrounding media is soil (W)

Q_{L_A} = heat loss from walls below liquid level where surrounding media is air (W)

Now: $$Q_{L_s} = U_s \cdot A_s \cdot (T_\ell - T_s) \tag{3.6}$$

The value of U_s was made equal to the value of U_s from Equation 3.3 because both correspond to the same situation.

$$A_s = 2\pi . r_{n+1} \cdot H_S \tag{3.7}$$

where: A_s = outer area of digester under soil surface normal to the direction of heat flow (m^2)

H_S = depth of digester below soil surface (m)

and

$$Q_{L_a} = U_a \cdot A_a \cdot (T_\ell - T_a) \tag{3.8}$$

$$U_a = \frac{1}{r_{n+1} \cdot \sum_{j=1}^{n} \frac{\ell n(\frac{r_{j+1}}{r_j})}{k_j} + \frac{1}{h_o}} \tag{3.9}$$

$$A_a = 2\pi . r_{n+1} \cdot (H_L - H_S) \tag{3.10}$$

where: U_a = over-all heat transfer coefficient where heat transfer takes place from digester portion below liquid level to outside air ($W\ m^{-2}K^{-1}$)

A_a = surface air of digester portion below liquid level and above soil surface, normal to heat flow (m^2)

T_a = outside air temperature (K)

h_o = unit surface conductance of air outside the digester ($W\ m^{-2}K^{-1}$)

3.2.2 Heat Transfer From Walls Above Liquid Level

Heat transfer from walls above the liquid level also must consider two possibilities which occur depending on the depth of liquid level in the digester (Figure 3.1). These possibilities are: (a) the media surrounding the digester above the liquid level is air and soil; (b) the media surrounding the digester above the liquid level is air only. In other words, situation (a) arises when $H_L < H_S$ and (b) arises when $H_L \geq H_S$.

(a) If $H_L < H_S$

$$Q_{w_2} = Q_{w_s} + Q_{w_a} \tag{3.11}$$

where: Q_{w_2} = heat loss from digester walls above liquid level (W)

Q_{w_s} = heat loss from digester walls above liquid level where media surrounding the digester is soil (W)

Q_{w_a} = heat loss from digester walls above liquid level where media surrounding the digester is air (W)

Now: $$Q_{w_s} = U_{w_s} \cdot A_{w_s} \cdot (T_\ell - T_s) \tag{3.12}$$

$$U_{w_s} = \frac{1}{\dfrac{r_{n+1}}{r_i \cdot h_i} + r_{n+1} \cdot \sum_{j=1}^{n} \dfrac{\ln\left(\dfrac{r_{j+1}}{r_j}\right)}{k_j}} \tag{3.13}$$

$$A_{w_s} = 2\pi \cdot r_{n+1} \cdot (H_S - H_L) \tag{3.14}$$

$$Q_{w_a} = U_{w_a} \cdot A_{w_a} \cdot (T_\ell - T_a) \tag{3.15}$$

$$U_{w_a} = \frac{1}{\dfrac{r_{n+1}}{r_i \cdot h_i} + r_{n+1} \cdot \sum_{j=1}^{n} \dfrac{\ln\left(\dfrac{r_{j+1}}{r_j}\right)}{k_j} + \dfrac{1}{h_o}} \tag{3.16}$$

$$A_{w_a} = 2\pi . r_{n+1} \cdot (H_T - H_S) \tag{3.17}$$

where: U_{w_s} = over-all heat transfer coefficient above liquid level where the media surrounding the digester is soil ($W\ m^{-2}K^{-1}$)

A_{w_s} = surface area of digester normal to heat flow between the levels H_S and H_L (m^2)

r_i = inner radius of digester (m)

h_i = unit surface conductance of gas inside the digester ($W\ m^{-2}K^{-1}$)

U_{w_a} = over-all heat transfer coefficient above liquid where media surrounding the digester is air ($W\ m^{-2}K^{-1}$)

A_{w_a} = surface area of digester normal to heat flow between the levels H_T and H_S (m^2)

H_T = total depth of digester (m)

(b) If $H_L \geq H_S$

$$Q_{w_2} = U_{w_a} \cdot A_{o_a} \cdot (T_\ell - T_a) \tag{3.18}$$

$$A_{o_a} = 2\pi . r_{n+1} \cdot (H_T - H_L) \tag{3.19}$$

where: A_{o_a} = surface area of digester normal to heat flow between the levels H_L and H_T (m^2)

The value of U_{w_a} was taken from Equation 3.16.

3.3 Heat Transfer From Roof

The roof of digester was considered to be a flat composite surface. While considering heat transfer from the roof, it was assumed to be losing heat according to steady-state, one-dimensional heat transfer phenomena.

$$Q_r = U_r \cdot A_r \cdot (T_\ell - T_a) \tag{3.20}$$

$$U_r = \frac{1}{\frac{1}{h_i} + \frac{1}{k_a} + \sum_{j=1}^{n} \frac{x_j}{k_j} + \frac{1}{h_o}} \tag{3.21}$$

$$A_r = \frac{\pi \cdot D^2}{4} \tag{3.22}$$

where: Q_r = heat transfer from roof (W)

U_r = over-all heat transfer coeffieient of roof ($W\ m^{-2}K^{-1}$)

A_r = roof area (m^2)

k_a = coefficient of conductance of gas ($W\ m^{-2}K^{-1}$)

x_j = thickness of j th roof material (m)

k_j = thermal conductivity of j th roof material ($W\ m^{-1}K^{-1}$)

n = number of roof materials

D = inside diameter of digester (m)

3.4 Heat Transfer From Floor

The floor of digester was assumed to be flat made of only one material and in contact with soil at a given depth from the soil surface. Heat loss from the floor is given as:

$$Q_f = U_f \cdot A_f \cdot (T_\ell - T_s) \tag{3.23}$$

$$U_f = \frac{k_f}{x_f} \tag{3.24}$$

where: Q_f = heat loss from floor (W)

U_f = overall heat transfer coefficient for floor ($W\ m^{-2} K^{-1}$)

T_s = elevated soil temperature under floor (K)

x_f = thickness of floor material (K)

k_f = thermal conductivity of floor material ($W\ m^{-1} K^{-1}$)

The area of floor A_f was taken equal to the area of roof, A_r from Equation 3.22.

3.5 Heat Required to Raise Influent Temperature

Usually the influent temperature is lower than the digester operating temperature. Therefore, in addition to heat losses from the digester, heat is also required to raise the influent temperature to digestion temperature. The formula for obtaining this heat requirement is:

$$Q_I = \frac{W_I . C. \ (T_\ell - T_I)}{76\ 400} \tag{3.25}$$

where: Q_I = heat required to raise influent temperature (W)

W_I = mass of influent added ($kg\ day^{-1}$)

C = specific heat of influent ($J\ kg^{-1} K^{-1}$)

T_ℓ = mixed liquor temperature (K)

T_I = influent temperature (K)

The factor 76 400 in Equation 3.25 converts the time-scale day to s.

The influent to most anaerobic digesters is quite dilute, with total solids content varying from 3 to 12%. In sewage treatment plant design the mean specific heat (C) of sewage sludge is taken to be the same as that of water for total solids concentrations of 5 to 10% (WPCF 1959). Since data were not available on the thermal properties of swine manure slurries, the specific heat of swine manure slurry for the total solids concentrations of 3 to 12% was taken equal to that of water (4187 J kg^{-1} K^{-1}). It should be noted that Houkom et al. (1974) found that the specific heat of beef manure at 15% total solids concentration was 3860.41 J kg^{-1} K^{-1} and that at total solids concentrations above 15% the specific heat of beef manure slurry was quite different from that of water.

3.6 Thermal Properties of Soil

Since soil is a granular medium consisting of solid, liquid and gaseous phases, its thermal properties depend upon the porosity, moisture content and mineral and organic matter content of the soil.

The thermal conductivities (k) of different soils follow the order of sand > loam > clay > peat (Baver et al. 1972). The thermal conductivity of different types of soil under different physical conditions ranges from 0.576 to 2.016 W m^{-1} K^{-1} (WPCF 1959). However, according to information collected by Merva (1975), the thermal conductivity may range from 0.15 to 4.52 W m^{-1} K^{-1} depending upon changes in soil density and moisture content (Table 3.1).

The thermal diffusivity (α) is the quotient of the thermal conductivity and the heat capacity (Equation 3.26) and has units of m^{2}s^{-1}. The thermal diffusivity determines the temperature wave penetration into the soil, whereas k determines the rate of heat transport (Rosenberg 1974).

$$\alpha = \frac{k}{C_s \cdot \rho_s} \qquad (3.26)$$

where: C_s = specific heat of soil (J kg^{-1}K^{-1})

ρ_s = density of soil (kg m^{-3})

TABLE 3.1 SELECTED VALUES FOR THERMAL PROPERTIES OF SOILS

Soil type	Bulk density kg m^{-3}	Moisture content (%)	Conductivity W m^{-1} K^{-1}	Diffusivity $10^{-7} \times m^2 s^{-1}$	Specific heat (J kg^{-1} K^{-1})	Reference
Clay	1180	0	0.59	6.2	801.7	Johnston 1937*
	1470	29.0	3.47	11.6	801.7	Johnston 1937*
	1800	--	1.205	2.0	3347	Rosenberg 1974
Light soil with roots	300	--	0.11	3.0	1255	Rosenberg 1974
Wet sandy soil	1600	--	2.7	10.0	1674	Rosenberg 1974
Granitic sand	1900	13.1	4.52	17.0	853.5	Johnston 1937*

*taken from Merva (1975).

The thermal diffusivity of different types of soil varies greatly depending upon bulk density, type of soil and moisture content. Typical values of the thermal diffusivity of soil are also shown in Table 3.1.

In this study, values for the thermal conductivity and the thermal diffusivity of soil were needed to determine heat transfer and temperature wave penetration through the soil mass. The values for a clay soil (1.205 W m^{-1} K^{-1} and 2.0X10^{-7} m^2 s^{-1}) were used.

IV. METHODS AND PROCEDURES

The simulation model of the anaerobic digestion system developed for this study included six components. This chapter is devoted to an explanation of the models for these components: (1) air temperature; (2) soil temperature; (3) the thermal bulb effect; (4) gas production; (5) mixing; and (6) influent temperature. Also included in this chapter is a flow diagram of the simulation model and the experimental design.

4.1 Air Temperature Model

Daily mean temperature is defined by Environment Canada (1974) as the average of the maximum and minimum temperatures for the day and has been used in this study to indicate air temperature. The data for development of the air temperature model were obtained from Environment Canada weather records for a normal year in Winnipeg. The normal year, as constructed by Environment Canada, was based on daily normal temperature for a 99-yr period, from 1872 to 1970.

The air temperature model was developed from the Environment Canada normal year to predict average daily air temperature for a 1-yr period starting January 1, and ending December 31. The presence of periodicity in the data suggested that some type of periodic function would fit the observed data. The Fourier Series furnished such a function and air temperature (T_a) was expressed as:

$$T_a = a_o + \sum_{n=1}^{m} \{a_n . \cos(\omega_n \tau) + b_n . \sin(\omega_n \tau)\} \qquad (4.1)$$

where: a_{o}, a_n and b_n are scalar coefficients and ω_n is angular velocity (rad day^{-1}).

To determine the arguments $\omega_n \tau$ it was necessary only that as

τ varied from zero to t, where t was the interval of time over which the model was desired, the argument vary from zero to some integer multiple of 2π. In this study the model was desired for a period of 365 days and the necessary conditions were fulfilled by making $\omega_n = 2n\pi/365$ in Equation 4.1 which took the form:

$$T_a(\tau) = a_o + \sum_{n=1}^{m} \{a_n . \cos\left(\frac{2n\pi}{365} . \tau\right) + b_n . \sin\left(\frac{2n\pi}{365} . \tau\right)\} \quad (4.2)$$

Fourier analysis of the average daily temperature data of the normal year was used to calculate the values of the coefficients a_o, a_n and b_n in Equation 4.2. A WATFIV subroutine named HARMAN, available in the Computer Library of the University of Manitoba, was used to calculate the Fourier coefficients a_o, a_n and b_n up to the desired number of terms (n = 1, 2, ..., 6 in this study). The values of the Fourier coefficients used in the air temperature model of this study are given in Table 4.1.

The air temperature model, using the values of Fourier coefficients in Table 4.1, predicted the daily air temperatures shown in Figure 4.1.

TABLE 4.1 CALCULATED VALUES OF FOURIER COEFFICIENTS FOR AIR TEMPERATURE MODEL

Parameters	Values (^oC)	Parameters	Values (^oC)
a_o	1.877		
a_1	-18.277	b_1	-6.027
a_2	-1.410	b_2	-1.259
a_3	0.724	b_3	-0.241
a_4	0.114	b_4	-0.494
a_5	0.043	b_5	0.100
a_6	0.272	b_6	-0.426

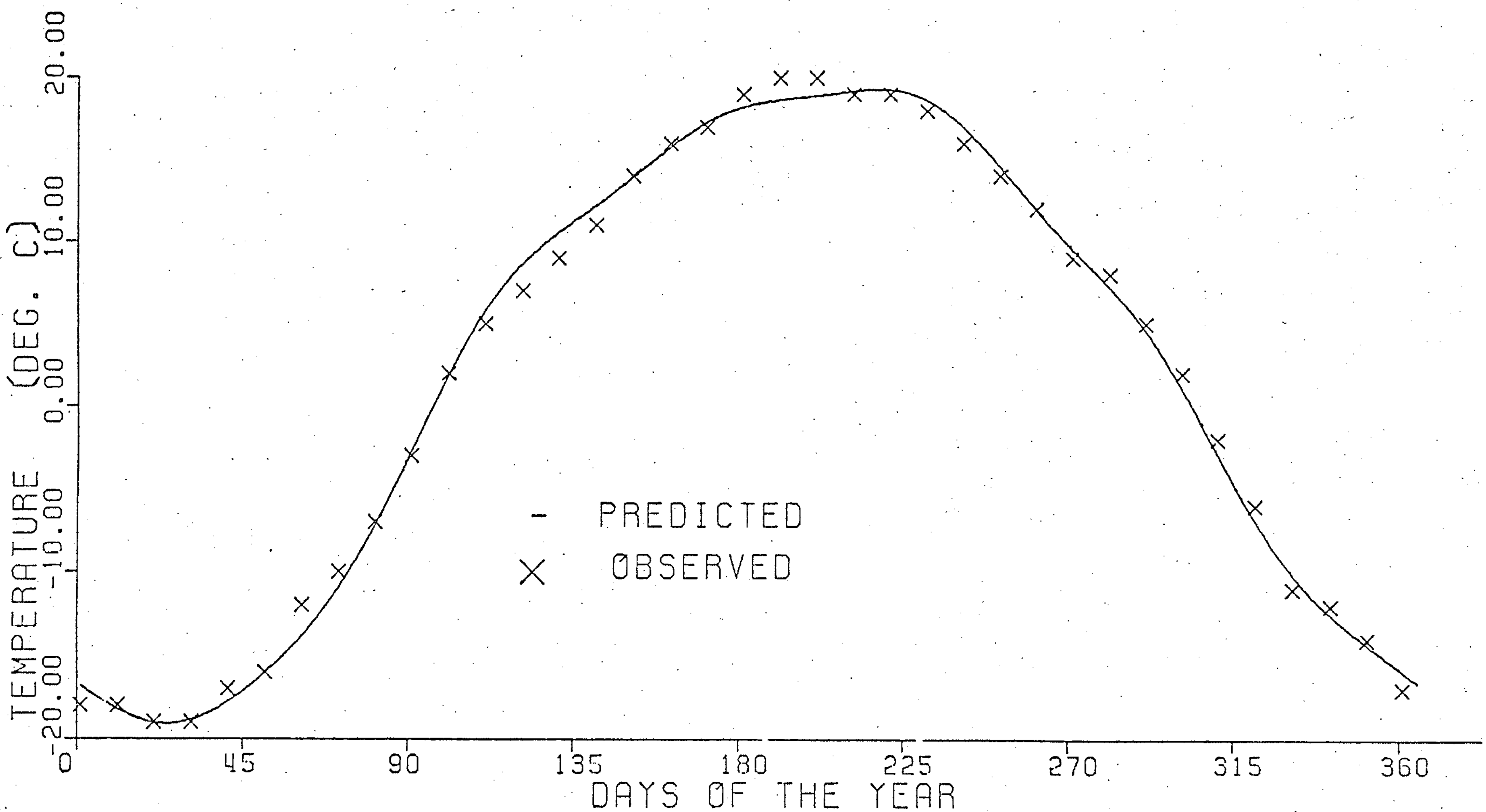


FIG. 4.1 PREDICTED AND ØBSERVED DAILY AIR TEMPERATURES FØR WINNIPEG

4.2 Soil Temperature Model

Soils are composed of different horizons. Each horizon may have different thermal properties but for purposes of simplicity, it was assumed that the soil thermal properties were uniform throughout the soil mass. The thermally homogeneous soil mass was then divided into planes parallel to the soil surface at equal increments of depth Z, positive downward in soil mass.

A simplification was also made regarding lateral heat flow. If the sole source of energy was radiation, and if a uniform radiation flux unimpaired by clouds or other obstructions was assumed, then the temperature at the soil surface would be everywhere equal for a given surface condition (Merva 1975). Under these assumptions, a temperature gradient would exist only in the Z direction. Thus, heat transfer through a soil mass can be written (Merva 1975) as:

$$\frac{d^2T}{dZ^2} = \frac{1}{\alpha} \cdot \frac{dT}{\delta\tau_s} \qquad (4.3)$$

where: T = temperature in the soil mass (K)

α = thermal diffusivity of soil mass ($m^2\ s^{-1}$)

Z = depth from soil surface (m)

τ_s = time (s)

To obtain a solution to Equation 4.3, the mathematical technique of separation of variables was used. The final solution is of the form (Merva 1975).

$$T(Z,\tau) = e^{-\lambda . Z/\sqrt{2}} \cdot \{A.\cos(\lambda^2\alpha\tau - \frac{\lambda . Z}{\sqrt{2}}) + B.\sin(\lambda^2\alpha\tau - \frac{\lambda . Z}{\sqrt{2}})\} \qquad (4.4)$$

However, this is not the most general form for the solution. To obtain the general solution, the n terms of the Fourier Series were introduced with coefficients A, B and λ. Thus the most general form of solution is:

$$T(Z,\tau) = \sum_{n=o}^{\infty} e^{-(\lambda_n . Z/\sqrt{2})} \{A_n . \cos(\lambda_n^2 \alpha\tau - \frac{\lambda_n Z}{\sqrt{2}}) + B_n . \sin(\lambda_n^2 \alpha\tau - \frac{\lambda_n Z}{\sqrt{2}})\} \qquad (4.5)$$

The solution shown in Equation 4.5 will be complete if the values of A_n, B_n and λ_n are available to satisfy the boundary condition $T(o,\tau)$. To determine the values A_n, B_n and λ_n, it was necessary to know the soil surface temperature. Unfortunately, the soil surface temperature data were not available from the University of Manitoba Glenlea Research Station records, therefore the following section is devoted to developing a technique to predict soil surface temperature using air temperature and soil temperature at the 0.05-m depth (the minimum depth at which soil temperature normally is measured).

4.2.1 Predicting Soil Surface Temperature Using Air Temperature and Soil Temperature at the 0.05-m Depth

Heat transfer within a soil mass is due to conduction but the heat transfer to or from the soil surface is due to sensible heat flux transfer (Rosenberg 1974). Monteith (1963)* used a "resistance" approach to simplify the computation of sensible heat flux from natural surfaces.

$$\text{Heat flux (H)} = \frac{\text{temperature gradient (the driving force)}}{\text{resistance to flow exerted by air}} \qquad (4.6)$$

The physical equation of this process is (Rosenberg 1974):

$$H = -\frac{\rho_a \cdot C_p \cdot (T_{ss} - T_a)}{r_a} \qquad (4.7)$$

where: ρ_a = air density (1.13 kg m^{-3} at STP)

C_p = specific heat of air at constant pressure (1004.836 J $kg^{-1}K^{-1}$)

*taken from Rosenberg (1974).

T_{ss} = soil surface temperature (K)

T_a = air temperature (K)

r_a = air resistance (s m^{-1})

Heat flux due to conduction to the soil surface from a soil mass for steady-state conditions is given as:

$$H = - \frac{k_s}{Z} (T'_s - T_{ss}) \tag{4.8}$$

where: k_s = thermal conductivity of soil (W m^{-1} K^{-1})

Z = depth at which soil temperature is known (m)

T'_s = soil temperature at depth Z (K)

Equating equations (4.7) and (4.8)

$$- \frac{\rho_a . C_p . (T_{ss} - T_a)}{r_a} = - \frac{k_s}{Z} . (T'_s - T_{ss}) \tag{4.9}$$

or

$$T_{ss} = \frac{\frac{k_s}{Z} \cdot T'_s + \frac{\rho_a C_p}{r_a} \cdot T_a}{\frac{\rho_a C_p}{r_a} + \frac{k_s}{Z}} \tag{4.10}$$

The value of r_a is needed to compute the soil surface temperature from Equation 4.10. The value of r_a is a function of the surface roughness and wind speed (Monteith and Szeicz 1962). The surface roughness parameter is near zero over very smooth surfaces. In this study the soil surface was assumed to be smooth and bare. Therefore the surface roughness parameter was given a value of 0.0002 m. The monthly average wind speed in Winnipeg, based on a 30-yr period from 1941 to 1970, varies from 4.60 to 6.35 m s^{-1} (Environment Canada 1974). For purposes of simplicity and to keep the value of r_a constant, an average wind speed for the 12-month period was taken to be 5.55 m s^{-1}.

Therefore, for a wind speed of 5.55 m s^{-1} and an extrapolated surface roughness parameter of 0.0002 m, the value of r_a^{-1} was found to be 0.002 m s^{-1} (Figure 4.2).

As discussed previously, the value of Z for Equation 4.10 was fixed at 0.05 m to determine soil surface temperature. With Equation 4.10 it was possible to compute the value of the soil surface temperature (T_{ss}) for a normal year by substituting values of r_a, k_s, ρ_a, C_p, Z, T_s' and T_a.

4.2.2 Use of Predicted Soil Surface Temperature to Develop A Soil Temperature Model For Any Soil Depth

At the soil surface, the boundary condition for Equation 4.5 is governed by radiant energy input and sensible heat flux output. Since solar radiation and air temperature patterns through the year are periodic in nature, a condition whereby the temperature at the soil surface fluctuates periodically can be expressed mathematically as a Fourier Series.

$$T(0,\tau) = a_o + \sum_{n=1}^{\infty} \{a_n \cdot \cos (\frac{2n\pi}{t} \cdot \tau) + b_n \cdot \sin (\frac{2n\pi}{t} \cdot \tau)\} \quad (4.11)$$

where t is the maximum length of time from which the series was derived. In this study t has been taken as 365 days.

By setting Z in Equation (4.5) equal to zero and equating Equations (4.5) and (4.11), the following equation is determined:

$$A_o \cdot \cos (\lambda_o^2 \alpha\tau) + B_o \cdot \sin(\lambda_o^2 \alpha\tau) + \sum_{n=1}^{\infty}\{A_n \cdot \cos (\lambda_n^2 \alpha\tau) + B_n \cdot \sin(\lambda_n^2 \alpha\tau)\} =$$

$$a_o + \sum_{n=1}^{\infty}\{a_n \cdot \cos (\frac{2n\pi}{365} \tau) + b_n \cdot \sin (\frac{2n\pi}{365} \tau)\} \quad (4.12)$$

The two infinite series are equal if and only if the coefficients

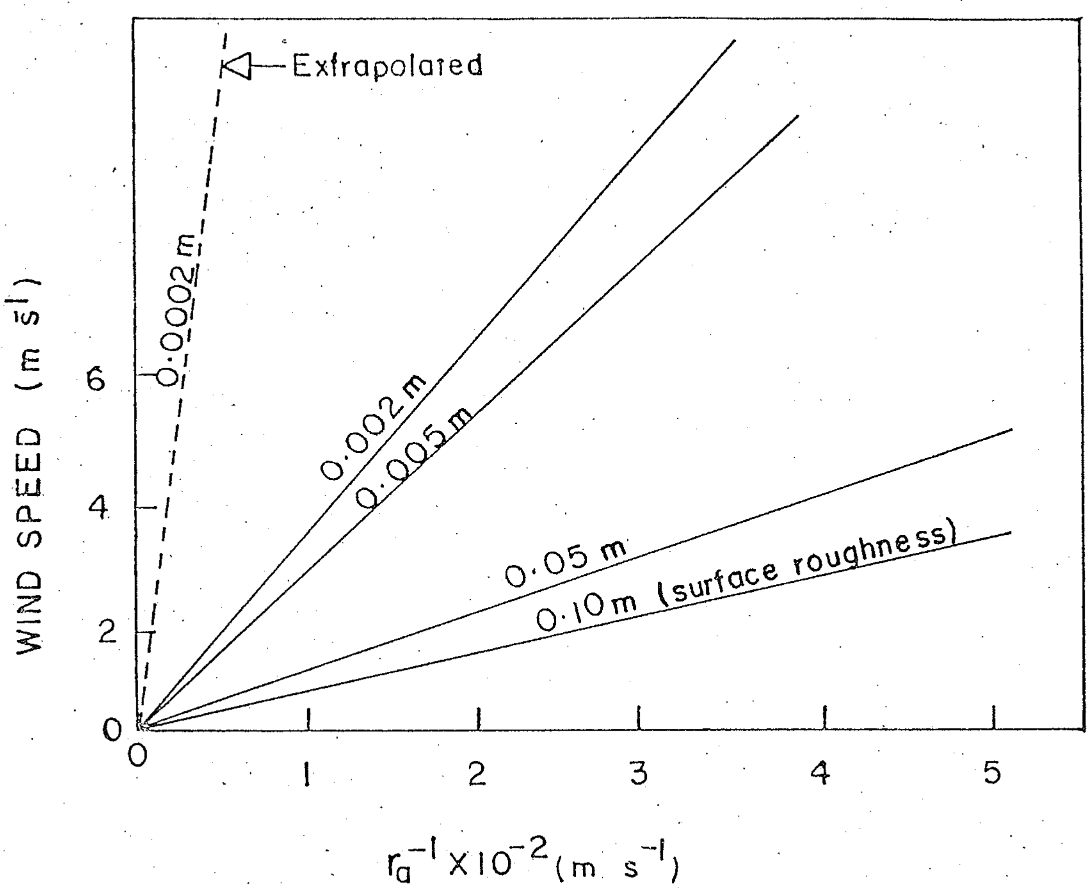


FIG. 4·2 VARIATION OF r_a^{-1} WITH WIND SPEED AND SURFACE ROUGHNESS. AFTER MONTEITH AND SZEICZ (1962).

of like terms are equal. If the arguments of the sine and cosine terms are made equal (Merva 1975),

$$\lambda_n^2 \alpha \tau = \frac{2n\pi}{365} \tau \tag{4.13}$$

for which $\lambda_n = + \sqrt{\frac{2n\pi}{365\alpha}}$, $n = 0, 1, 2 \ldots$ (4.14)

Substituting the value of λ_n from Equation 4.14 into Equation 4.12

$$A_o = a_o \tag{4.15a}$$

$$A_n = a_n \tag{4.15b}$$

$$B_n = b_n \tag{4.15c}$$

Using the information in Equations 4.14 and 4.15, the solution of Equation 4.3 for the case where the energy input to the soil surface is expressed as Fourier Series can be written (Merva 1975):

$$T(Z,\tau) = a_o + \sum_{n=1}^{\infty} e^{-(\sqrt{n\pi/365\alpha}.Z)} . \{a_n . \cos\left(\frac{2n\pi}{365}\tau - \sqrt{\frac{n\pi}{365\alpha}} . Z\right)$$

$$+ b_n . \sin\left(\frac{2n\pi}{365}\tau - \sqrt{\frac{n\pi}{365\alpha}} . Z\right)\} \tag{4.16}$$

Although Equation 4.16 contains an infinite number of terms it is shown later that six terms gave sufficient accuracy for engineering purposes. Therefore, in this study only six terms were considered.

The values of constants a_o, a_n, and b_n ($n = 1, 2, \ldots, 6$) were determined from the soil surface temperatures calculated through Equation 4.10. A WATFIV subroutine named HARMAN, available in the Computer Library of the University of Manitoba, was used to calculate a_o, a_n and

b_n. HARMAN took the soil surface temperatures predicted by Equation 4.10 and returned the values of a_o, a_n and b_n for Equation 4.11. The values of a_o, a_n, and b_n calculated by this method are given in Table 4.2.

TABLE 4.2 VALUES OF FOURIER COEFFICIENTS FOR SOIL TEMPERATURE MODEL

Parameters	Values (^oC)	Parameters	Values (^oC)
a_o	4.894		
a_1	-10.919	b_1	-5.129
a_2	1.157	b_2	0.574
a_3	-0.091	b_3	0.119
a_4	0.031	b_4	-0.365
a_5	0.519	b_5	0.332
a_6	0.027	b_6	0.068

For comparison of predicted and observed results the daily mean soil temperature from the Glenlea Research Station at the University of Manitoba was taken as the average of maximum and minimum soil temperatures at a particular depth. However, data were available for only a 4-yr period. From these data it was observed that the daily mean soil temperature did not vary much in different years at a given soil depth. A normal year was constructed by averaging the daily soil temperature for the 4-yr period at seven soil depths (0.05, 0.10, 0.20, 0.50, 1.00, 1.50 and 3.00 m from the soil surface).

A graph of predicted and observed soil temperatures at different depths is shown in Figure 4.3. All temperature values at each depth are close to a 45° line from the origin which shows that the model predicts soil temperature values at each depth with sufficient accuracy.

4.3 The "Thermal Bulb Effect"

In section 4.2.2 a soil temperature model was developed to determine ambient soil temperatures at any depth for any day of the year. An anaerobic digester operates at a different temperature than the ambient soil temperature. The temperature difference between the digester and the soil causes an energy gradient for heat transfer to or from the digester through the surrounding soil mass. The direction of heat flow depends on the magnitude of the digester operating temperature and the ambient soil temperature. Heat flow to or from the digester changes the stored energy of the soil mass and thus causes a change in temperature of the medium. This change in temperature of the medium is defined as the "thermal bulb effect" in this study. The altered temperature of the surrounding soil mass must be used in computation of heat transfer to or from the digester if estimates of net energy production from anaerobic digesters are to be realistic.

4.3.1 Assuming Thermally Homogeneous Medium Around the Digester

To determine the change of temperature in the soil mass due to the "thermal bulb effect" a thermally homogeneous soil was assumed to exist around the buried portion of the digester. The assumption of

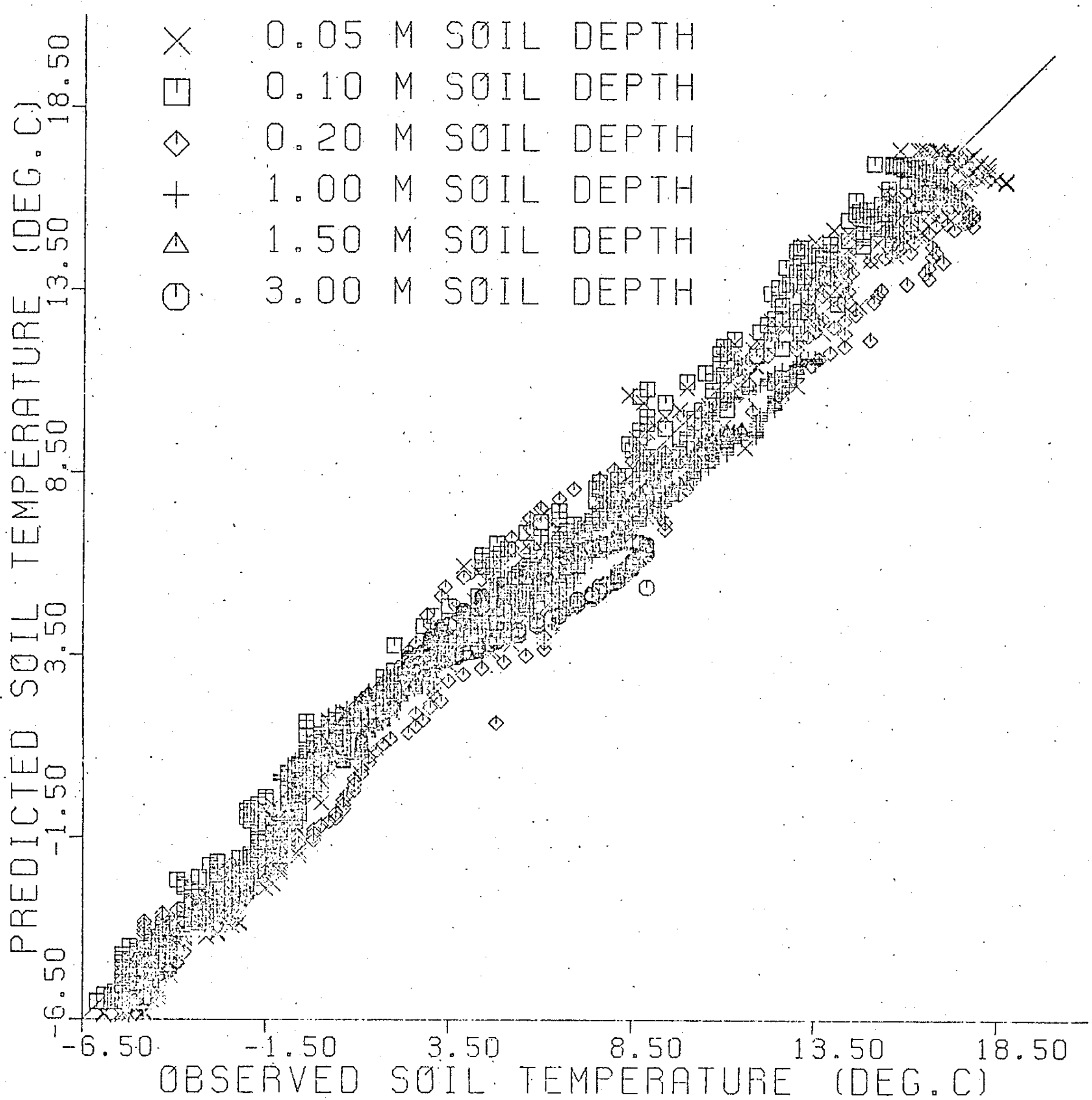


FIG. 4.3 CØMPARISØN BETWEEN PREDICTED AND OBSERVED SØIL TEMPERATURES AT VARIOUS SØIL DEPTHS

a thermally homogeneous medium was also applied to the digester wall and insulation materials. This assumption allowed application of a finite-difference method to locate the region beyond which digester operating temperature did not affect the ambient soil temperature.

To make the digester wall materials of uniform thermal conductivity (the thermal conductivity of soil) the thickness of digester wall and insulation materials was converted to a thermally equivalent soil thickness by the formula

$$r_s = r_i \left(\frac{r_o}{r_i}\right)^{\frac{k_s}{k}} \tag{4.17}$$

where: r_s = radius of thermally equivalent soil (m)

r_i = inner radius of digester (m)

r_o = outer radius of digester (m)

k_s = thermal conductivity of soil (W m^{-1} K^{-1})

k = thermal conductivity of digester wall or insulation materials (W $m^{-1}K^{-1}$)

The floor of the digester was converted to a thermally equivalent soil thickness by Equation 4.18.

$$S_f = \frac{Z_f}{k_f} \cdot k_s \tag{4.18}$$

where: S_f = thickness of thermally equivalent soil for floor (m)

Z_f = thickness of floor material (m)

k_f = thermal conductivity of floor material (W m^{-1} K^{-1})

For computational purposes, heat transfer from the buried portion of the digester was calculated at the thermally equivalent distances represented by the digester wall and insulation materials in a radial direction and by the floor in a downward direction from the floor.

4.3.2 Elevated Soil Temperatures Around Digester Walls

The previously discussed "thermal bulb effect" changes the soil temperature near the digester. The soil near the digester was considered as a series of radial strips and the situation was treated as a radial heat transfer problem from a hollow cylindrical body. The temperature distribution pattern was estimated according to Equation 4.19 (Kreith 1967).

$$T(r) = T_{\ell} - \frac{T_{\ell} - T_{os}}{\ell n(\frac{r_{os}}{r_i})} \cdot \ell n(\frac{r}{r_i}) \tag{4.19}$$

where: $T(r)$ = temperature at radial distance r in soil mass around digester (K)

T_{ℓ} = mixed liquor temperature (K)

T_{os} = ambient soil temperature at a distance where digester temperature has no effect (K)

r = radial distance in soil mass from centre of digester where temperature $T(r)$ is desired (m)

r_i = inner radius of digester (m)

r_{os} = radial distance from the digester where digester temperature has no effect (m)

In Equation 4.19, T_{ℓ}, T_{os} and r_i are known and r was made equal to the thermally equivalent radius for the digester wall and insulation materials. $T(r)$ can be calculated only when r_{os} is known. For temperate zones the value of r_{os} is usually taken as 6 m plus r_i, but for cold zones this value is unknown (WPCF 1959).

Certainly the soil temperature remains at the ambient level at an infinite distance from the digester walls. However, this assumption does not lead Equation 4.19 to a finite solution. Therefore, an approximation to the finite value of r_{os} was required. To accomplish this, an extreme operating situation was used to estimate the value of r_{os}. This condition was one which had a maximum effect on the soil temperature surrounding the digester. This situation used the maximum digester operating temperature, maximum digester size and minimum ambient soil temperature. Equation 4.20, which was derived from basic considerations of heat balance phenomena when heat flows in radial direction through a soil mass, was used to determine r_{os}.

$$T'_j = \frac{r_i + (j-1) \cdot \Delta r}{M(r_i + j.\Delta r - \frac{\Delta r}{2})} \cdot T_{j-1} + (1 - \frac{2}{M}) \cdot T_j + \frac{r_i + j.\Delta r}{M(r_i + j.\Delta r - \frac{\Delta r}{2})} \cdot T_{j+1} \tag{4.20}$$

where: T'_j = elevated temperature of j th strip (K)

r_i = inner radius of digester (m)

T_{j-1} = temperature of (j-1) th strip (K)

T_j = temperature of j th strip (K)

T_{j+1} = temperature of (j+1) th strip (K)

Δr = radial increment (m)

M = dimensionless modulus

The value of M is given by Equation 4.21 (Kreith 1967):

$$M = \frac{C_s \rho_s (\Delta r)^2}{k_s \cdot \Delta t} = \frac{(\Delta r)^2}{\alpha . \Delta t} \tag{4.21}$$

where: α = thermal diffusivity of soil ($m^2\ s^{-1}$)

Δt = time increment (s)

T_j' for each increment in radial distance from the digester wall was calculated from Equation 4.20. After a number of repetitions the value of T_j' at increasing distances from the digester approximated that of the ambient soil temperature. The distance where T_j' had approximately ($\pm 0.04^{\circ}C$) the same value as that of the ambient soil temperature was taken as the value of r_{os} for Equation 4.19.

4.3.3 Elevated Soil Temperature Under Floor

The "thermal bulb effect" also affects the soil temperature under the digester floor. Assuming that heat flow is uni-directional downward from the floor, the temperature distribution in the region under the floor was estimated by Equation 4.22.

$$T_z = \frac{(Z_a - Z) \cdot T_\ell + Z \cdot T_{sa}}{Z_a} \tag{4.22}$$

where: T_z = temperature under floor at a depth z from floor (K)

Z_a = depth under floor where digester temperature has no effect on ambient soil temperature (m)

T_{sa} = ambient soil temperature at a depth Z_a from floor (K)

Z = a variable depth from floor where temperature T_z is desired (m)

In Equation 4.22 all parameters were known except Z_a. To calculate the value of Z_a, the maximum digester operating temperature and minimum soil temperature at different depths were again applied, but through Equation 4.23 (Kreith 1967).

$$T'_j = \frac{1}{M} \{T_{j-1} + (M-2)\ T_j + T_{j+1}\} \qquad (4.23)$$

and $$M = \frac{(\Delta Z)^2}{\alpha.\Delta t} \qquad (4.24)$$

where: ΔZ = incremental depth (m)

4.4 Gas Production Model

A number of mathematical models of the anaerobic digestion process have been developed. Andrews and Graef (1970) established a mathematical model which considered un-ionized volatile acids as the growth-limiting substrate as well as the inhibiting agent. Lawrence (1970) developed a model based on continuous-culture theory which identified biological-solids retention time (SRT) as an independent design parameter and which measured carbonaeous organic material as chemical oxygen demand (COD). Cassell and Anthonisen (1966)* constructed a model for poultry-manure digestion based on continuous-culture theory which used volatile solids as a measure of substrate available for microbial degradation and which assumed that total daily gas production was directly proportional to the amount of substrate utilized. Unfortunately, the value of constants or coefficients used in these models could not be used to describe the anaerobic digestion of swine manure because of differing characteristics from those of sewage sludges or poultry-manure for which the models were available.

To develop a gas production model in this study, the variables were limited to SRT and temperature. It was felt that these would have a direct effect on gas production assuming that other operating parameters were in a normal range of digester operation as discussed in Chapter II.

*taken from Lapp (1976).

As previously discussed (Section 2.4) the effect of influent solids concentration on gas production rate is reflected in the loading rate of a digester at a given SRT. Therefore, the effect of influent solids concentration was not directly included in the gas production model. However, the influent solids concentration at a given SRT will affect digester size and therefore the heat balance.

Normally, total gas production plotted against SRT at any temperature follows a pattern which resembles a first-order reaction curve (Figure 4.4). Therefore, an attempt was made to apply a first-order equation to the data in Figure 4.4. The application was based on the consideration that the reaction rate constant (R_g) and the wash-out time (t_o) are functions of the digester operating temperature.

$$\frac{dg}{dt} = R_g \cdot (G_m - g) \qquad (4.25)$$

where: g = gas production ($m^3\ kg^{-1}$ v.s. added)

t = time (days)

R_g = reaction rate constant (day^{-1})

G_m = maximum gas produced during digestion ($m^3\ kg^{-1}$ v.s. added)

The boundary conditions for Equation 4.25 are gas production at time t_o and at time t_∞, where t_∞ denotes infinite time. In integrated form Equation 4.25 becomes

$$g_t = G_m \cdot \{1-e^{-R_g \cdot (t-t_o)}\} \qquad (4.26)$$

where: g_t = gas production at time t ($m^3\ kg^{-1}$ v.s. added)

The values of G_m, t_o and R_g for 35°C were calculated from Figure 4.4. As shown in Equation 4.4 the rate of gas production (g_t)

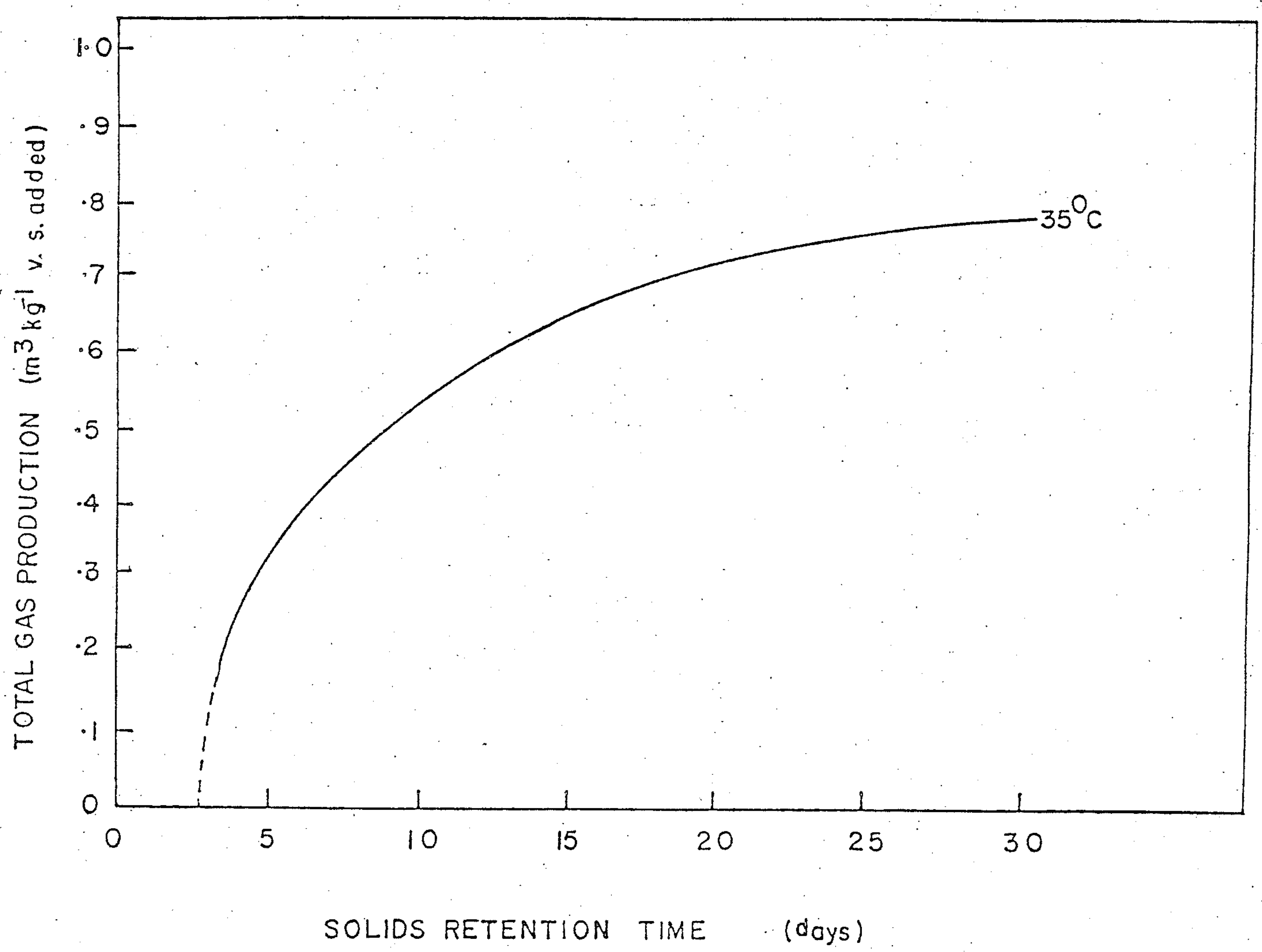


FIG.4-4 EFFECT OF SOLIDS RETENTION TIME ON GAS PRODUCTION
AFTER LAPP(1976)

changes with time (which corresponds to SRT) and is influenced by wash-out time and reaction rate constant. Since the reaction rate constant and wash-out time are functions of temperature as shown in Equation 2.3 and 2.4 respectively, the gas production also depends on digester operating temperature. As previously discussed (Section 2.3.6) a temperature coefficient is required to compute reaction rates and wash-out times at different temperatures. The value of the coefficient ($\theta = 1.072$) suggested by van't Hoff's postulate that the reaction rate doubles with every 10°C rise in temperature was not found to be accurate in the case of swine manure digestion when gas production (Lapp 1976) at 35°C and 25°C were compared. Calculations based on limited gas production data for 25 and 35°C temperatures from Lapp (1976) led to a θ value of 1.063 which was used in this study to predict gas production and wash-out times at various temperatures.

Predicted values of gas production, obtained at various temperatures and SRT's from Equation 4.26 are shown in Figure 4.5.

4.5 Model for Mixing the Digester Contents

As discussed in Section 2.3.8, mixing of digester contents is one of the important parameters in the design and operation of anaerobic digesters. This study assumed gas recirculation mixing because gas recirculation is simple and may aid the digestion process. It is more costly but needs less maintenance (Taiganides et al. 1963). The energy requirement in gas recirculation mixing was calculated from Equation 4.27 (Fair et al. 1968).

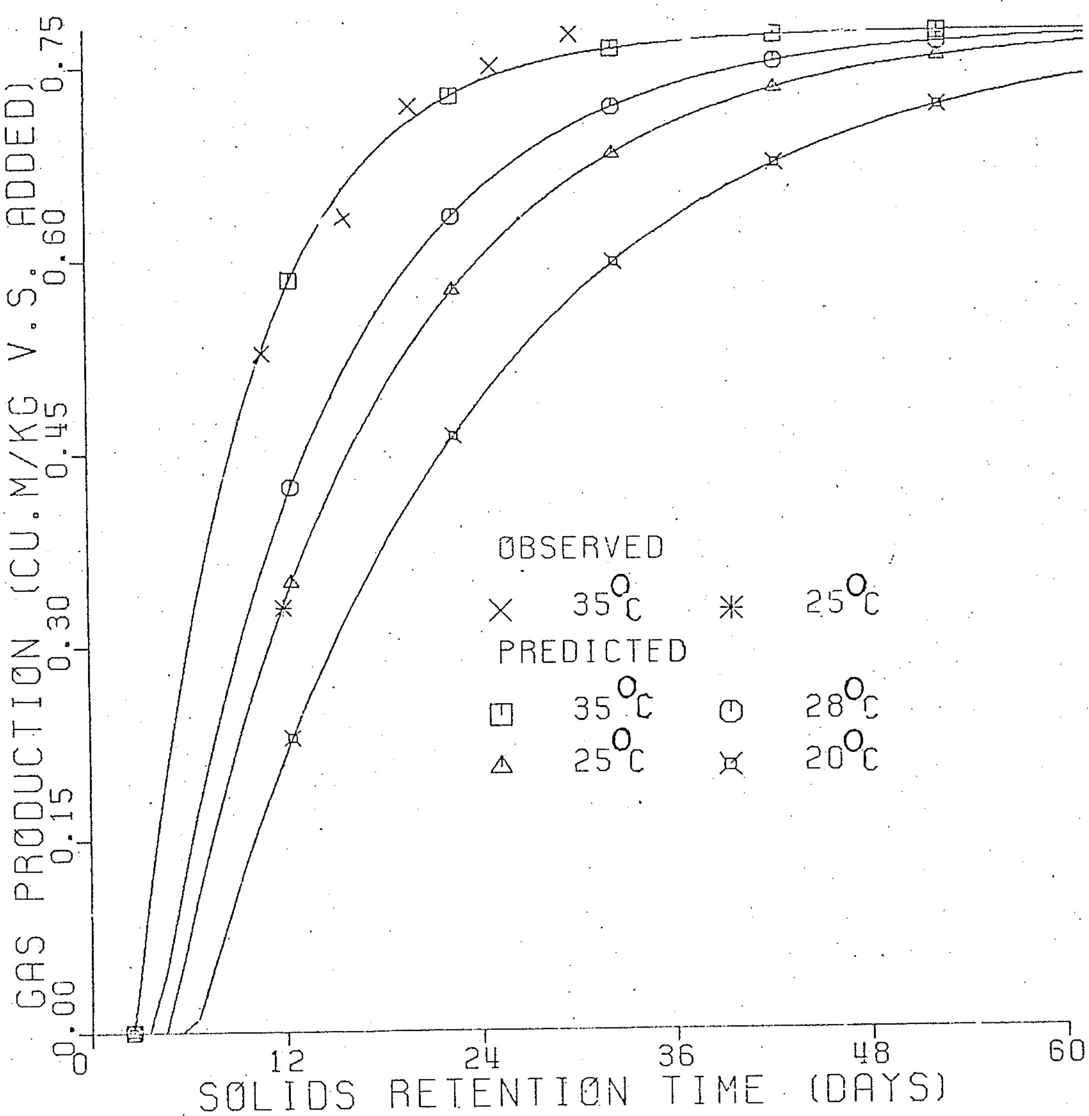


FIG. 4.5 PREDICTED AND ØBSERVED GAS PRØDUCTIØN AT VARIOUS DIGESTER ØPERATING TEMPERATURES

$$P = 9.804 \frac{\rho_w . V_a . H_L}{t_s} \tag{4.27}$$

where: P = power requirement for mixing (W)

ρ_w = specific weight of slurry column (kg m^{-3})

V_a = volume of gas recirculated (m^3)

H_L = depth of liquid in the digester (m)

t_s = time for mixing (s)

To calculate the value of P in Equation 4.27, ρ_w was taken to be same as the specific weight of water (1000 kg m^{-3}) assuming that the slurry has a constant specific weight for the total solids concentrations used in this study. V_a was computed from information given by Metcalf and Eddy (1972) to the effect that the daily amount of gas required for gas recirculation mixing is 1.8 m^3 per m^3 of digester volume at atmospheric pressure. The time of mixing (t_s) was taken as 24 hr day^{-1} to ensure uniform temperatures throughout the digester. The values of H_L was made to equal the liquid depth in the digester which was calculated from the digester size.

4.6 Model for Influent Temperature

The daily temperature of the digester influent varies according to the temperature in the manure storage pit. The manure storage pit temperature depends on the interaction among the type of storage facility, barn temperature, air temperature and soil temperature. Complete data for manure temperatures in storage pits under confinement barns were not available at the Glenlea Research Station of the University of Manitoba. However, estimates of the minimum and maximum temperatures were $-1.2^{o}C$ for the 1st of February and $18^{o}C$ for the 1st of August, respectively (Schulte)*. The nature of influent temperature variation will show a periodicity over a period of 365 days because the parameters affecting influent temperature (i.e. air and soil temperatures) are periodic in nature (Sections 4.1 and 4.2). However, the periodicity of influent temperature could not be analyzed by Fourier Series because of the limited data. Therefore, a simple sine wave function was developed to predict the influent temperature. The general sine wave function used to represent influent temperature is given in Equation 4.28

$$T_I = A_o + A_1 \cdot \mathrm{Sin}(\frac{2\pi}{365} \cdot \tau + \phi) \quad (4.28)$$

where: T_I = influent temperature (K)

τ = time (days)

ϕ = phase difference

A_o and A_1 are scalar constants

T_I in Equation 4.28 would have minimum value on the 1st of April if ϕ equals zero. To represent the actual situation, a phase difference of 60 days was introduced as shown in Equation 4.29.

$$T_I = A_o + A_1 \cdot \sin\{\frac{2\pi}{365} \cdot (\tau + 60)\} \quad (4.29)$$

The values of constants A_o and A_1 were determined by satisfying Equation 4.29 at the estimated minimum and maximum influent temperatures on their respective days and solving the resultant equations simultaneously. This procedure led to the following values for the constants.

---

*Schulte, D. D. 1976 10 ?. Personal communication. Department of Agricultural Engineering, University of Manitoba, Winnipeg, Manitoba.

$$A_o = 8.4^{o}C$$

and $$A_1 = -9.6^{o}C$$

The predicted daily influent temperatures calculated by Equation 4.28 are shown in Figure 4.6.

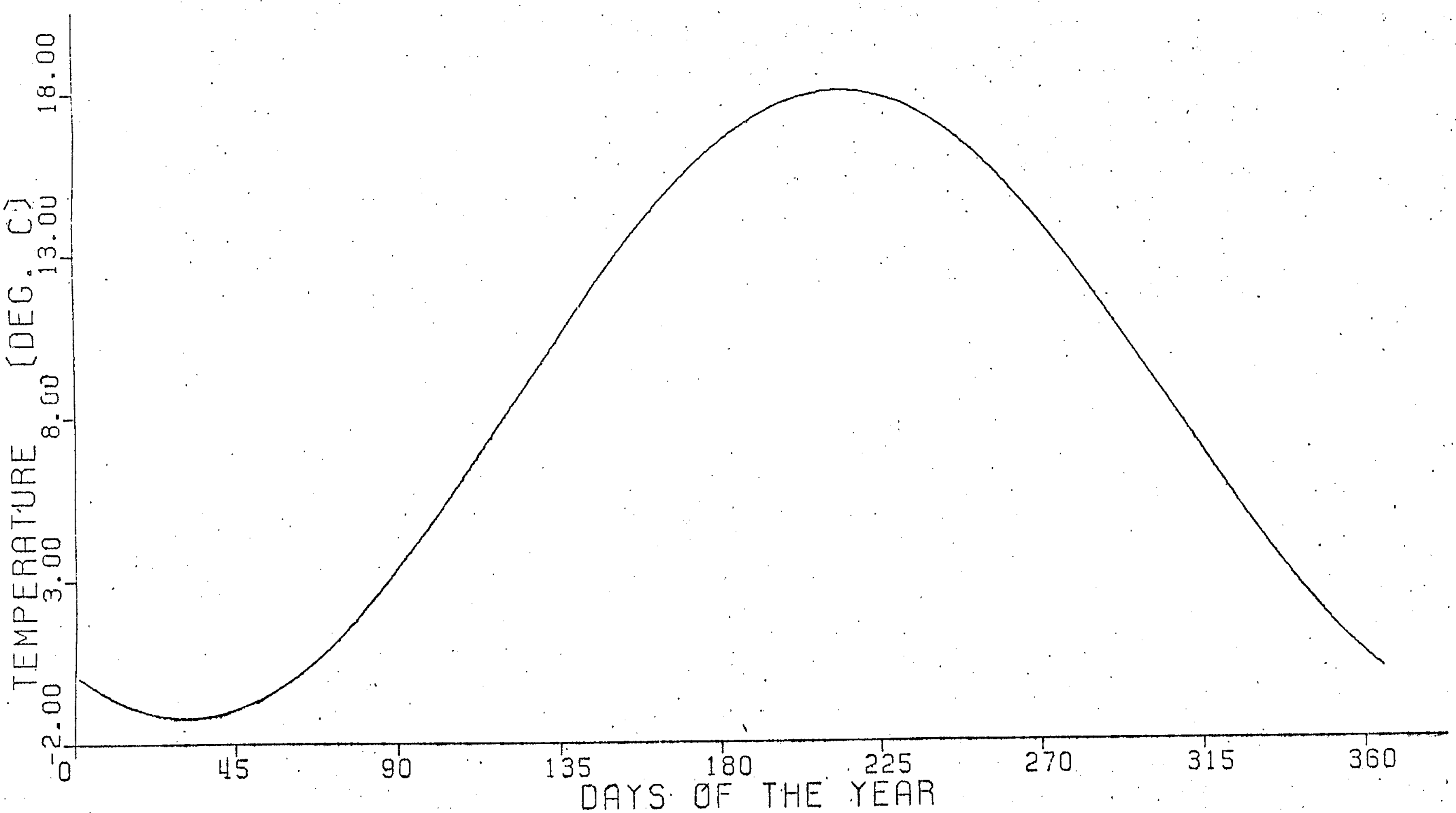
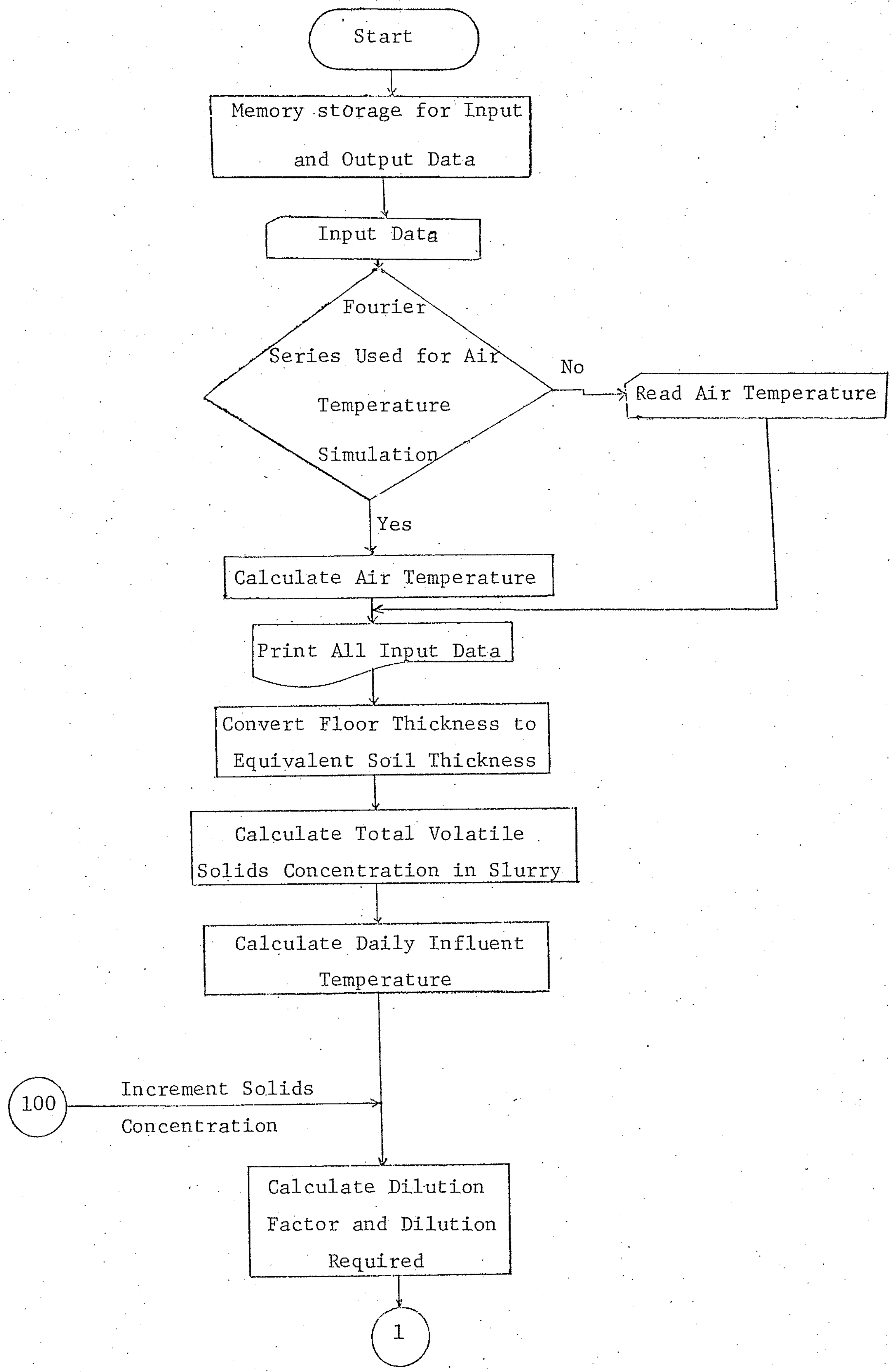
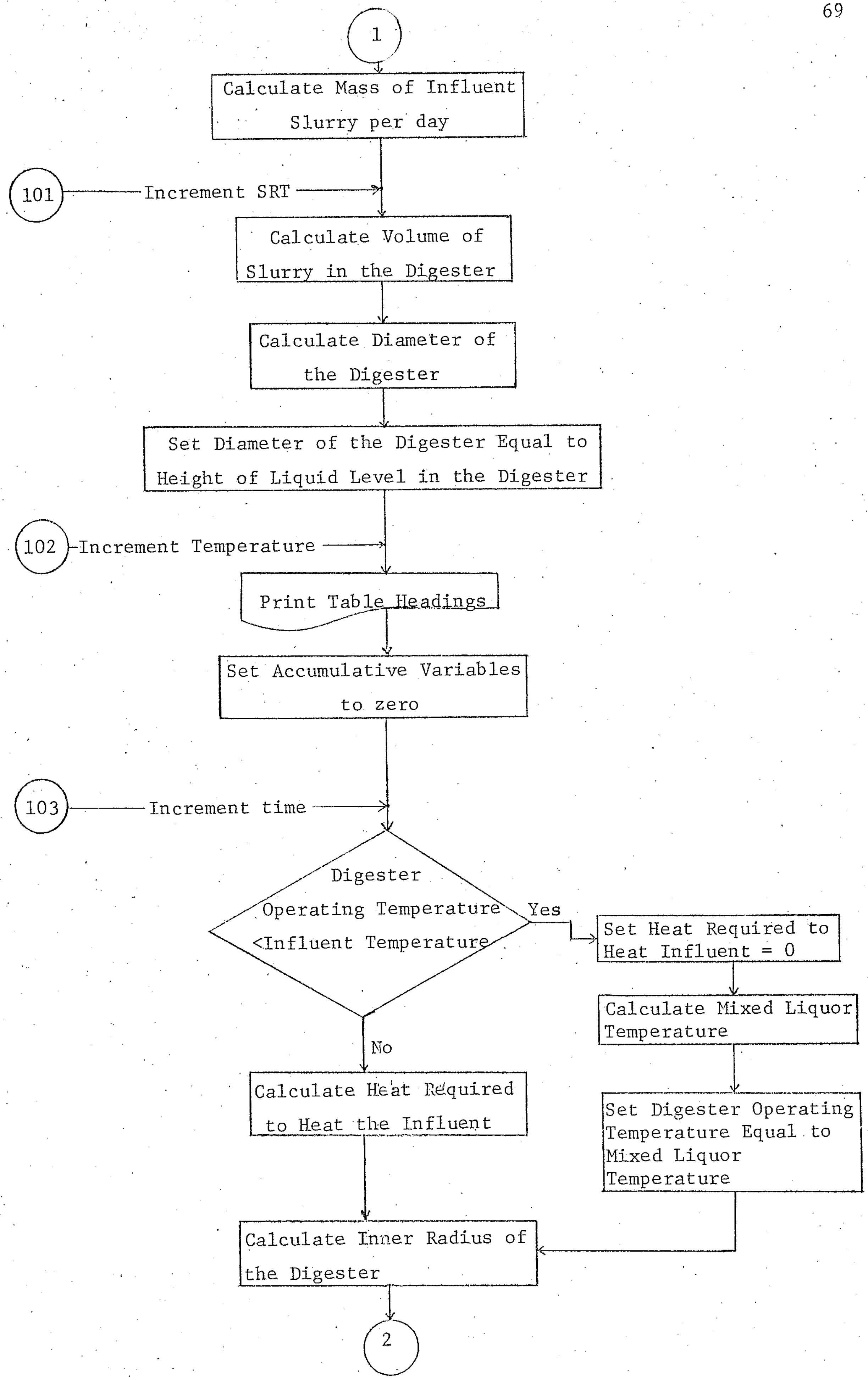
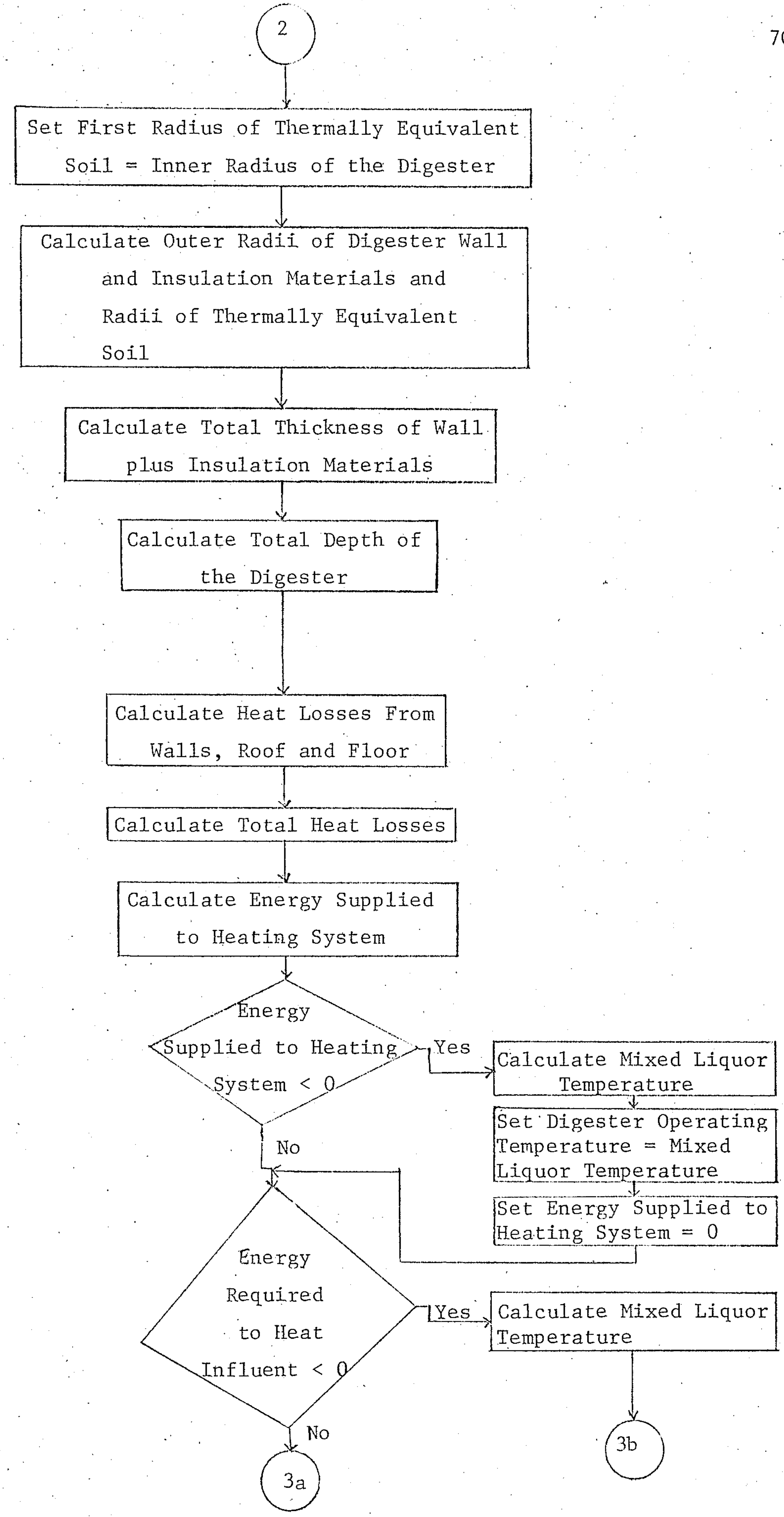


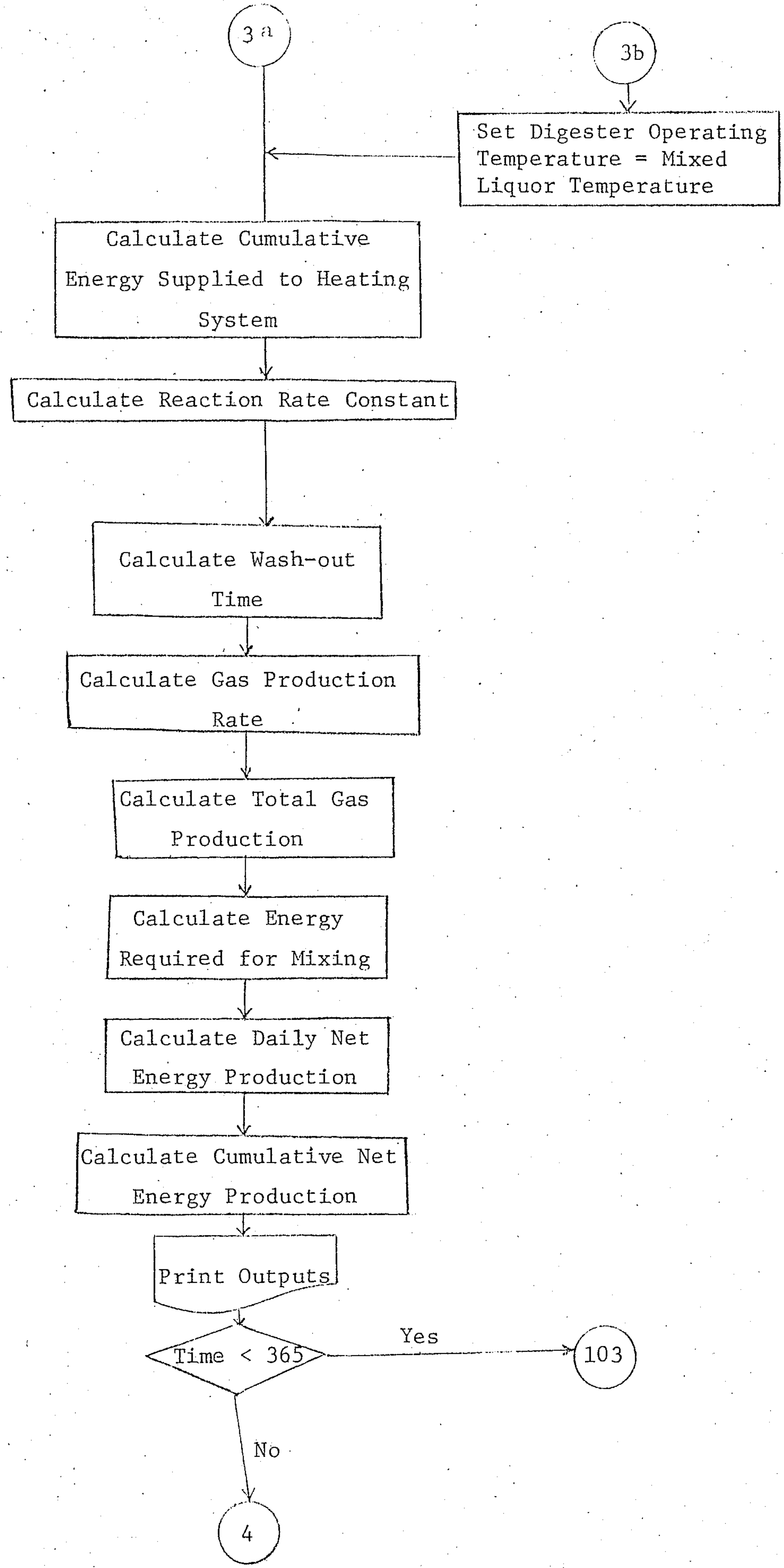
FIG. 4.6 PREDICTED DAILY INFLUENT TEMPERATURE

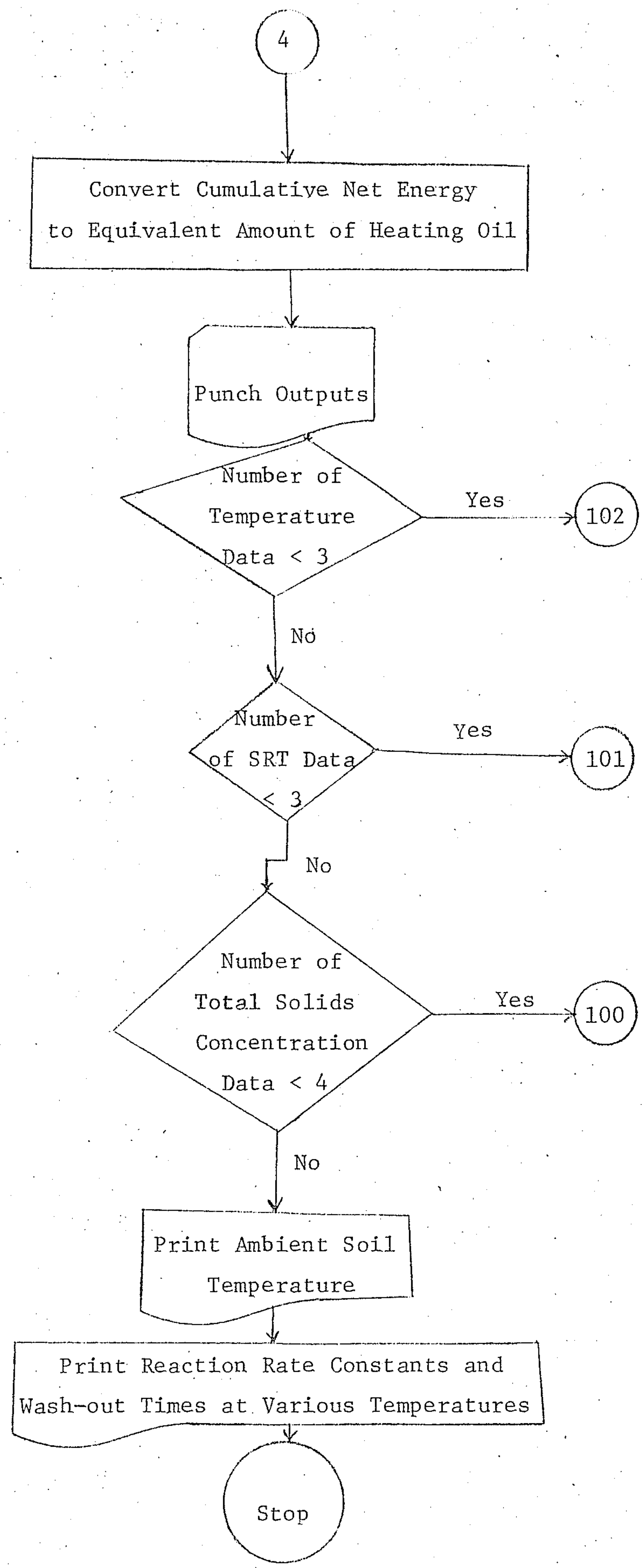
4.7 Flow Diagram




1
Calculate Mass of Influent Slurry per day
101
Increment SRT
Calculate Volume of Slurry in the Digester
Calculate Diameter of the Digester
Set Diameter of the Digester Equal to Height of Liquid Level in the Digester
102
Increment Temperature
Print Table Headings
Set Accumulative Variables to zero
103
Increment time
Digester Operating Temperature <Influent Temperature
Yes
Set Heat Required to Heat Influent = 0
Calculate Mixed Liquor Temperature
Set Digester Operating Temperature Equal to Mixed Liquor Temperature
No
Calculate Heat Required to Heat the Influent
Calculate Inner Radius of the Digester
2


2
Set First Radius of Thermally Equivalent Soil = Inner Radius of the Digester
Calculate Outer Radii of Digester Wall and Insulation Materials and Radii of Thermally Equivalent Soil
Calculate Total Thickness of Wall plus Insulation Materials
Calculate Total Depth of the Digester
Calculate Heat Losses From Walls, Roof and Floor
Calculate Total Heat Losses
Calculate Energy Supplied to Heating System
Energy Supplied to Heating System < 0
Yes
Calculate Mixed Liquor Temperature
Set Digester Operating Temperature = Mixed Liquor Temperature
Set Energy Supplied to Heating System = 0
No
Energy Required to Heat Influent < 0
Yes
Calculate Mixed Liquor Temperature
No
3a
3b


3a
3b
Set Digester Operating Temperature = Mixed Liquor Temperature
Calculate Cumulative Energy Supplied to Heating System
Calculate Reaction Rate Constant
Calculate Wash-out Time
Calculate Gas Production Rate
Calculate Total Gas Production
Calculate Energy Required for Mixing
Calculate Daily Net Energy Production
Calculate Cumulative Net Energy Production
Print Outputs
Time < 365
Yes
103
No
4


4
Convert Cumulative Net Energy to Equivalent Amount of Heating Oil
Punch Outputs
Number of Temperature Data < 3
Yes
102
No
Number of SRT Data < 3
Yes
101
No
Number of Total Solids Concentration Data < 4
Yes
100
No
Print Ambient Soil Temperature
Print Reaction Rate Constants and Wash-out Times at Various Temperatures
Stop

4.8 Experimental Design

Principal Variables

The experimental design in this study involved the following principal variables:

(i) Influent solids concentrations of 3, 6, 9 and 12%;

(ii) Solids retention times of 10, 30 and 60 days;

(iii) Digester operating temperatures of 20, 28 and 35°C.

Other variables which remained constant throughout the experiment were:

Materials	Dimension (Thickness, cm)	Thermal Conductivity ($W\ m^{-1}K^{-1}$)	Reference
Roof			
1. Concrete (dry)	15.0	0.933	Kreith(1967)
2. Urethane	7.5	0.02	*
3. Fir Plywood	0.64	0.11	*
Walls (a) Above ground surface			
1. Concrete(dry)	25.0	0.933	Kreith(1967)
2. Urethane	3.8	0.02	*
3. Fir Plywood	0.64	0.11	*
(b) Below ground level			
1. Concrete (10% moisture)	25.0	1.2096	Kreith(1967)
2. Urethane	3.8	0.02	*
3. Fir Plywood	0.64	0.11	*
Floor			
Concrete (10% moisture)	15.0	1.2096	Kreith(1967)

*Associate Committee on the National Building Code (1975).

Other Thermal Constants

	Reference
Unit surface conductance of air outside the digester at $6.7\ m\ s^{-1}$ speed, $h_o = 34.0\ W\ m^{-2}K^{-1}$	WPCF (1959)
Unit surface conductance of gas inside the digester, $h_i = 9.1\ W\ m^{-2}K^{-1}$	WPCF (1959)
Coefficient of conductance of gas $k_a = 6.28\ W\ m^{-2}K^{-1}$	WPCF (1959)
Thermal conductivity of soil $k_s = 1.205\ W\ m^{-1}K^{-1}$	Rosenberg (1974)
Specific heat of influent slurry $C = 4186.816\ J\ kg^{-1}K^{-1}$	WPCF (1959)

Size of Digester

The size of the digester was calculated from the volume of influent per day and the SRT assuming that the diameter of the digester was equal to the depth of liquid level in the digester. The total height of the digester was assumed to equal the depth of liquid in the digester plus a freeboard of 0.60 m (WPCF 1959). The portion of the digester was assumed to be buried under ground to a depth of 3 m.

Amount of Influent

The amount of influent per day was based on the following type of livestock enterprise:

Number of growing hogs = 1 000

Number of finishing hogs = 1 000

Live weight of growing hogs = 25 kg per hog

Live weight of finishing hogs = 75 kg per hog

Dry manure produced = 7.5 kg per 1 000 kg of live weight per day

Wet manure produced = 70 kg per 1 000 kg of live weight per day

Specific weight of diluted slurry = 1 000 kg m^{-3}

Ratio of volatile solids to total solids = 0.65

Gas Production Constants

The gas production model did not include the effect of influent solids concentration. However, the influent solids concentration was an important parameter to be considered for estimation of heat loss since it affects the loading rate and thus the size of the digester. The gas production model did take into account the effect of SRT and digester temperature. To run the gas production model, values of the minimum time to start gas production, reaction rate constant and maximum gas production in digestion period were taken from Figure 4.4. These values were

Minimum time to start gas production at 35 ^{o}C = 2.5 days

Reaction rate constant at 35 ^{o}C temperature = 0.14 day^{-1}

Maximum gas production during digestion period = 0.775 m^3 kg^{-1} v.s. added.

Temperature coefficient, θ = 1.063

Ratio of methane to total gas = 0.67

Heating value of methane = 37256973 J m^{-3}

Mixing constant = 1.8 m^3 per m^3 day^{-1} volume

"Thermal bulb effect" constants

While considering heat loss from the digester surfaces, one-dimensional steady-state conduction was assumed. Calculations showed that under extreme operating conditions digester temperature affected the ambient soil temperature up to a radial distance of 8 m from inner surface of digester walls and a vertical distance of 4.75 from the bottom of the digesters. These distances were taken as boundary conditions for heat loss through the buried portion of digester in this study.

Experimental Runs

The computer runs were made using daily time increments from 1 to 365. Day 1 corresponded to January 1 and the day 365 corresponded to December 31. A depth increment of 2 cm was selected for the buried portion of the digester to calculate heat losses through the walls. Each computer run was made by changing the value of one principal variable while keeping others constant.

V. RESULTS AND DISCUSSION

The objective of this investigation was to construct test and utilize a model with which to develop relationships between energy input and output for design and operation of anaerobic digesters, for animal manure, operating under a variety of conditions. The operating conditions selected to accomplish the objective were listed in Section 4.8 and were employed with the following assumptions:

(i) continuous loading of the digester and complete mixing of digester contents;

(ii) steady-state digester operation;

(iii) unidirectional heat flow from digester walls, floor and roof;

(iv) thermally homogeneous soil around the digester;

(v) bare and smooth soil surface;

(vi) no snow cover around the digester portion above the ground surface;

(vii) temperature dependent reaction rates and wash-out times having equal-valued temperature coefficients;

(viii) constant gas production temperature coefficient in the temperature range of 20 to 35^{o}C;

(ix) constant specific heat of influent in total solids concentration range of 3 to 12%;

(x) no heat generation by microorganisms;

(xi) air and soil temperatures for a normal year;

(xii) gas production rates governed by a first-order relationship to SRT for different temperatures;

(xiii) gas production rates independent of total solids concentration in influent slurry;

(xiv) gas production rates independent of temperature at infinite SRT;

(xv) 67% of total gas produced was methane;

(xvi) 65% of total solids in influent slurry were volatile;

(xvii) no heat losses from influent carrying pipes.

Discussion of the results of this study was divided into seven sections: (a) effect of digester operating temperature on soil temperature surrounding the digester; (b) predicting energy required for digester operation; (c) predicting net energy production under digester operating conditions; (d) annual net energy recovery for various digester operating conditions; (e) effect of major assumptions on results; (f) implications of results to design of anaerobic digester for farm-animal manure; (g) use of model for other situations.

5.1 Effect of Digester Operating Temperature on Soil Temperature Surrounding the Digester

The digester operating temperature developed a "thermal bulb" around the digester as discussed in Section 4.3. The extent of the "thermal bulb" depended on the digester operating temperature, digester size and ambient soil temperature. Rather than discussing the "thermal bulb effect" for all 36 operating conditions used in this study the following set of operating conditions was selected to show the importance of the "thermal bulb effect":

- digester operating temperature (DOT) of $35^{\circ}C$
- total solids concentration (TSC) in influent slurry of 6%
- solids retention time (SRT) of 30 days
- soil depths of 0.0, 1.5 and 3.0 m
- soil temperatures on January 1, April 1, July 1 and October 1.

5.1.1 Effect Around the Digester Walls at Various Depths

The DOT affected soil temperature to a radial distance of 5.0 m from the inner surface of the digester for the selected set of operating conditions and a maximum of 8.0 m from the inner surface of digester operating at 3% TSC and 60-day SRT. The effect was more prominent in cold weather and at the soil surface than in warm weather and at 3-m soil depth. For the selected set of digester operating conditions the temperature drop through the digester walls and insulation at the soil surface was 22.9 and 12.6^{o}C on January 1 and July 1, respectively. During other months of the year the temperature drop through the digester walls and insulation at the soil surface was in the range of 12.6 to 22.9^{o}C. The temperature drop radially away from the digester walls and insulation followed a logarithmic relationship with distance at all the depths until it reached the ambient soil temperature (Figure 5.1, 5.2 and 5.3). At all soil depths the temperature adjacent to the outer surface of the digester walls and insulations was greater than the ambient soil temperature throughout the year (Table 5.1).

TABLE 5.1 DIFFERENCE BETWEEN ELEVATED AND AMBIENT SOIL TEMPERATURES AT OUTER SURFACE OF DIGESTER WALLS AND INSULATION

Depth (m)	Day of the year			
	January 1	April 1	July 1	October 1
	Temperature (^{o}C)			
0.0	17.5	16.1	8.1	11.6
1.5	13.7	15.2	13.0	11.3
3.0	13.9	13.9	14.0	12.8

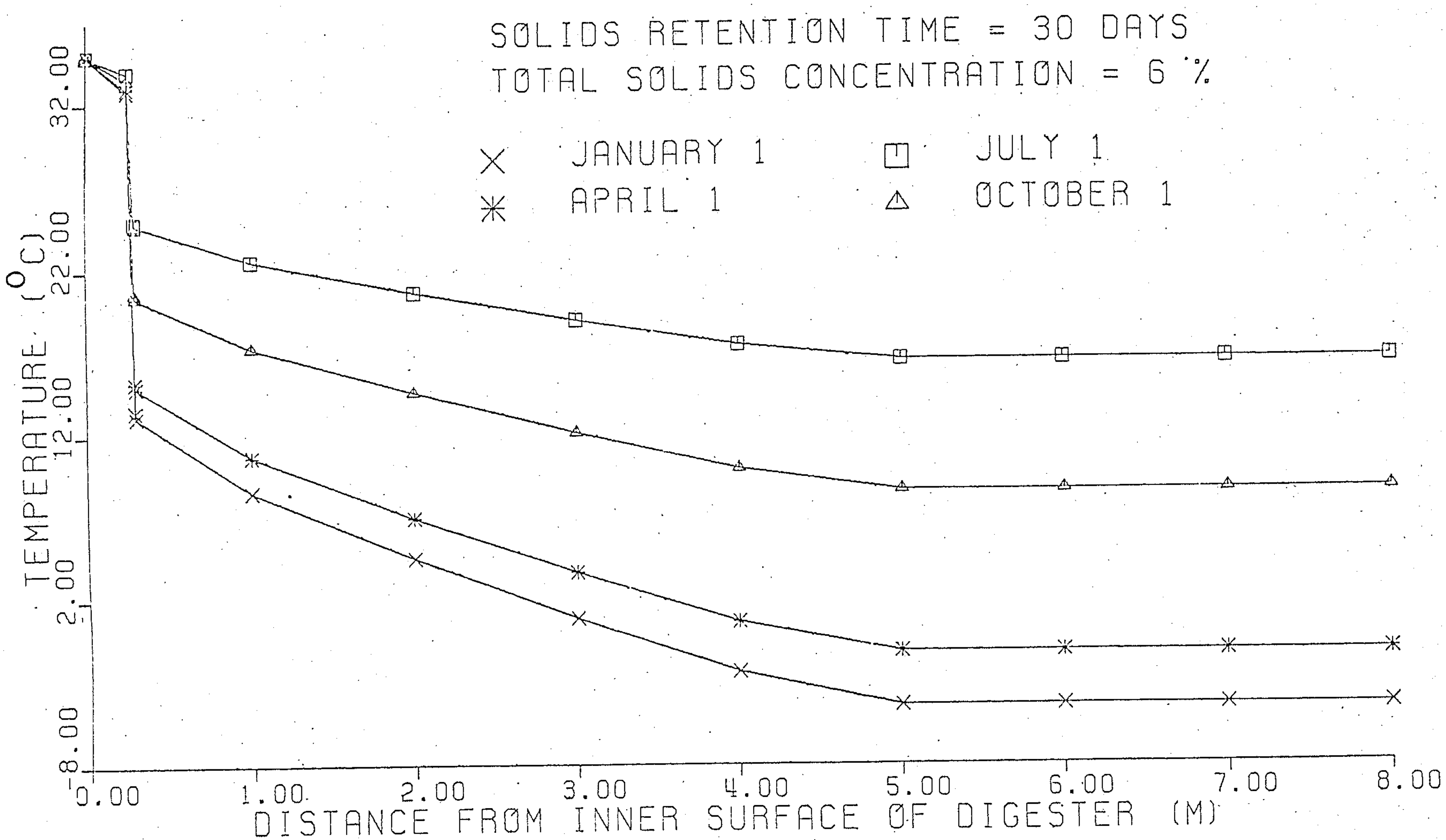


FIG. 5.1 EFFECT OF DIGESTER OPERATING TEMPERATURE ON SOIL TEMPERATURE AT SOIL SURFACE

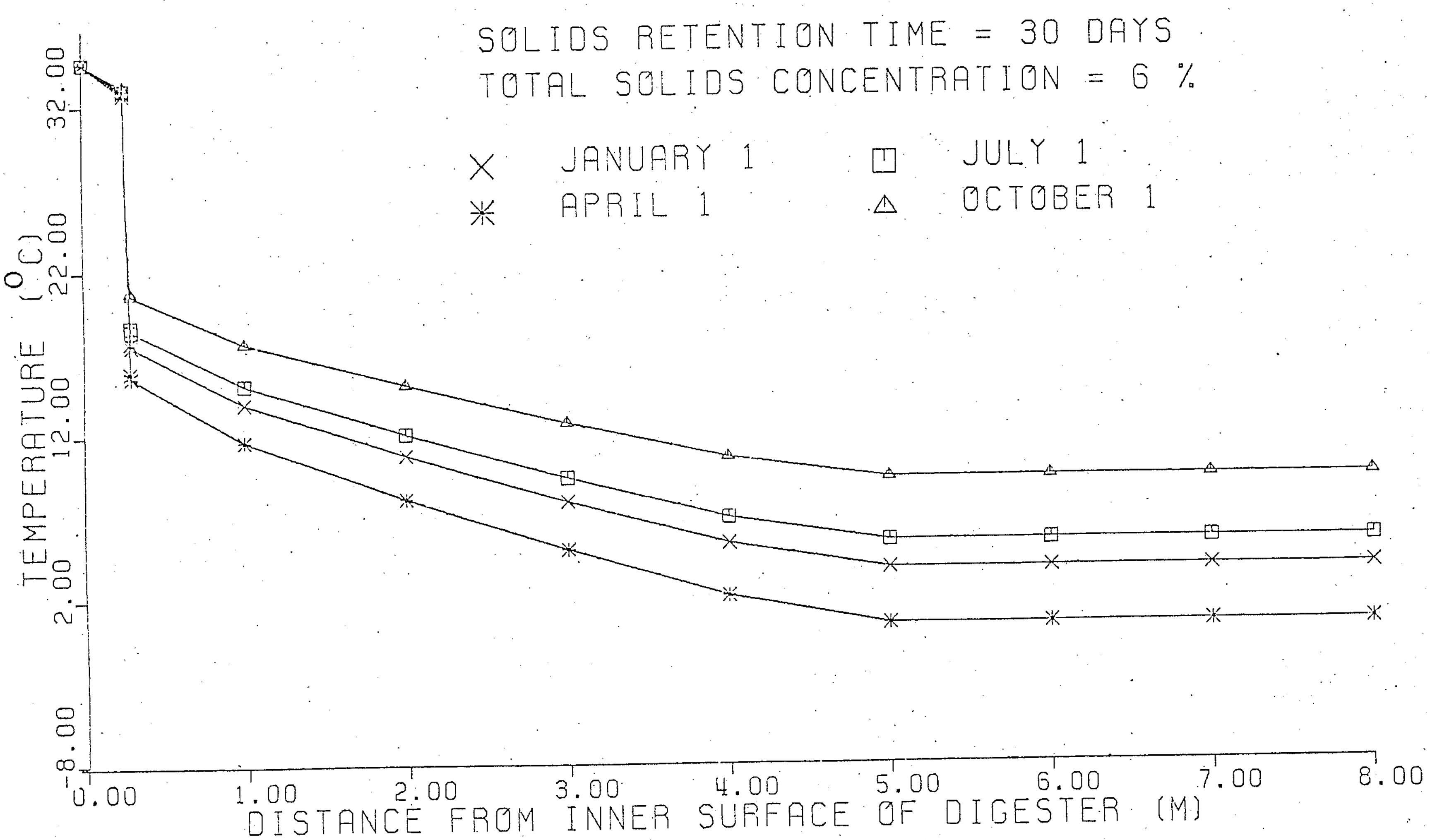


FIG. 5.2 EFFECT OF DIGESTER OPERATING TEMPERATURE ON SOIL TEMPERATURE AT 1.50 M SOIL DEPTH

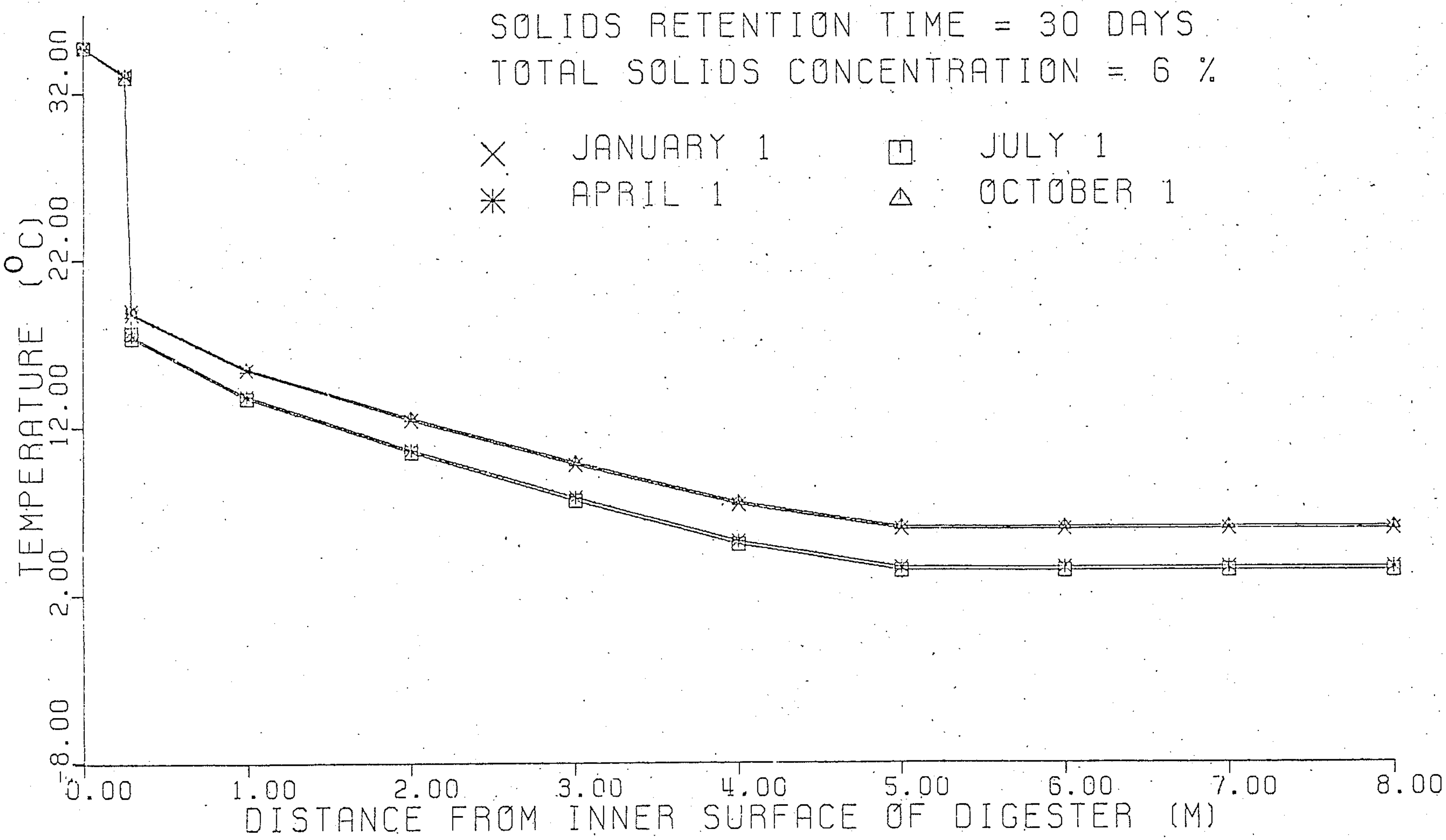


FIG. 5.3 EFFECT OF DIGESTER OPERATING TEMPERATURE ON SOIL TEMPERATURE AT 3.00 M SOIL DEPTH

At a soil depth of 1.5 m the temperature drop through the digester walls and insulation was 19.2 and 13.1^{o}C on April 1 and October 1, respectively (Figure 5.2). The temperature of soil surrounding the digester walls and insulation was elevated by 15.2^{o}C on April 1 and 11.3^{o}C on October 1 (Table 5.1). At this depth the temperature drop showed a phase difference of about 3 months with respect to temperature drop at the soil surface.

At the 3.0-m soil depth the temperature drops through digester wall and insulation were 16.1 and 17.5^{o}C on January 1 and July 1, respectively (Figure 5.3). The temperature of soil adjacent to outer surface of digester at the 3.0 m-depth was elevated by a maximum of 18.9^{o}C on January 1 and a minimum of 17.5^{o}C on July 1. At this depth the temperature drop showed a phase difference of 9 months as compared to that at the soil surface.

At greater depths the temperature drop through the digester walls and insulation would be time independent because the ambient soil temperature remains constant throughout year (Merva 1975). The phase difference in elevated soil temperature with respect to depth was due to phase difference in ambient soil temperature with respect to depth since the digester operating temperature was constant. At all soil depths the temperature of soil surrounding the digester walls was higher than the ambient soil temperature indicating that the DOT affected soil temperature regardless of time and depth.

5.1.2 Effect Under the Digester Floor

The DOT affected the soil temperature under the digester floor to a maximum depth of 4.75 m from the inner surface of the digester floor.

The soil temperature immediately adjacent to the digester floor was constant throughout the year for all the digester operating conditions. For the selected set of digester operating condition the soil temperature adjacent to the digester floor was 33.3°C while ambient soil temperatures at that depth varied from 3.1 to 6.6°C depending upon the time of the year. Evidently, the soil temperature adjacent to the digester floor was elevated by 26.7 to 30.2°C.

The elevated soil temperature would establish a lesser temperature gradient for heat transfer from the digester to the surrounding soil than that generally expected were ambient soil temperatures alone used to calculate heat losses to the soil. In the other words, the soil surrounding the digester acted as added insulation reducing the energy requirement to maintain the digester operating temperature.

5.2 Predicting Daily Energy Required for Digester Operation

The energy required for digester operation included energy required to heat the influent, energy required to maintain digester operating temperature and the energy required to provide adequate mixing of the digester contents. However, in an operating digester, energy would also be required to pump the influent and effluent, and to balance heat losses through influent pipes. Neither of these were included in this study because they were thought to be relatively unimportant compared to other components of energy required for digester operation.

All components of the energy required for digester operation were dependent on DOT, influent TSC, SRT, influent temperature, soil temperature, air temperature and day of the year.

Since influent TSC has a direct effect on the digester volume required at a given SRT and animal population the results in this section were organized according to the TSC in the influent (Figures 5.4, 5.5, 5.6 and 5.7).

At any selected combination of influent TSC, SRT and DOT, mixing energy was constant throughout the year because the mixing energy was based on the digester volume. Energy required to raise the influent temperature, energy required to maintain DOT and total energy required for digester operation varied daily for a fixed TSC, SRT and DOT. The time dependent components of energy required for digester operation were periodic in nature and had a maxima on January 27th and a minima on August 1st (Figures 5.4, 5.5, 5.6 and 5.7). The periodicity in the time dependent components of the energy required for digester operation was due to the aggregated effect of the periodic nature of air temperature, soil temperature and influent temperature. Values of maximum and minimum daily energy requirements for digester operation at extreme conditions of 10 and 60 day SRTs and of 20 and 35^{o}C DOTs are shown in Tables 5.2 and 5.3. The intermediate operating conditions for different combinations of 28^{o}C or 30 day SRT's had energy requirements for all components of digester operation between the stated extreme operating conditions.

The total energy required for a digester operating at 3% TSC reached a maximum of 5.6004 GJ day^{-1} on January 27 at a 35^{o}C DOT and 60 day SRT (Table 5.2) and the minimum of 0.3140 GJ day^{-1} on August 1 at a 20^{o}C DOT and 10 day SRT (Table 5.3). As the volume of digester increased, the total energy required for the digester operation increased at a given DOT. The change in digester volume was encountered either through changing SRT or TSC. As SRT increased from 10 to 60 days at a constant TSC and temperature, the digester volume increased which increased the

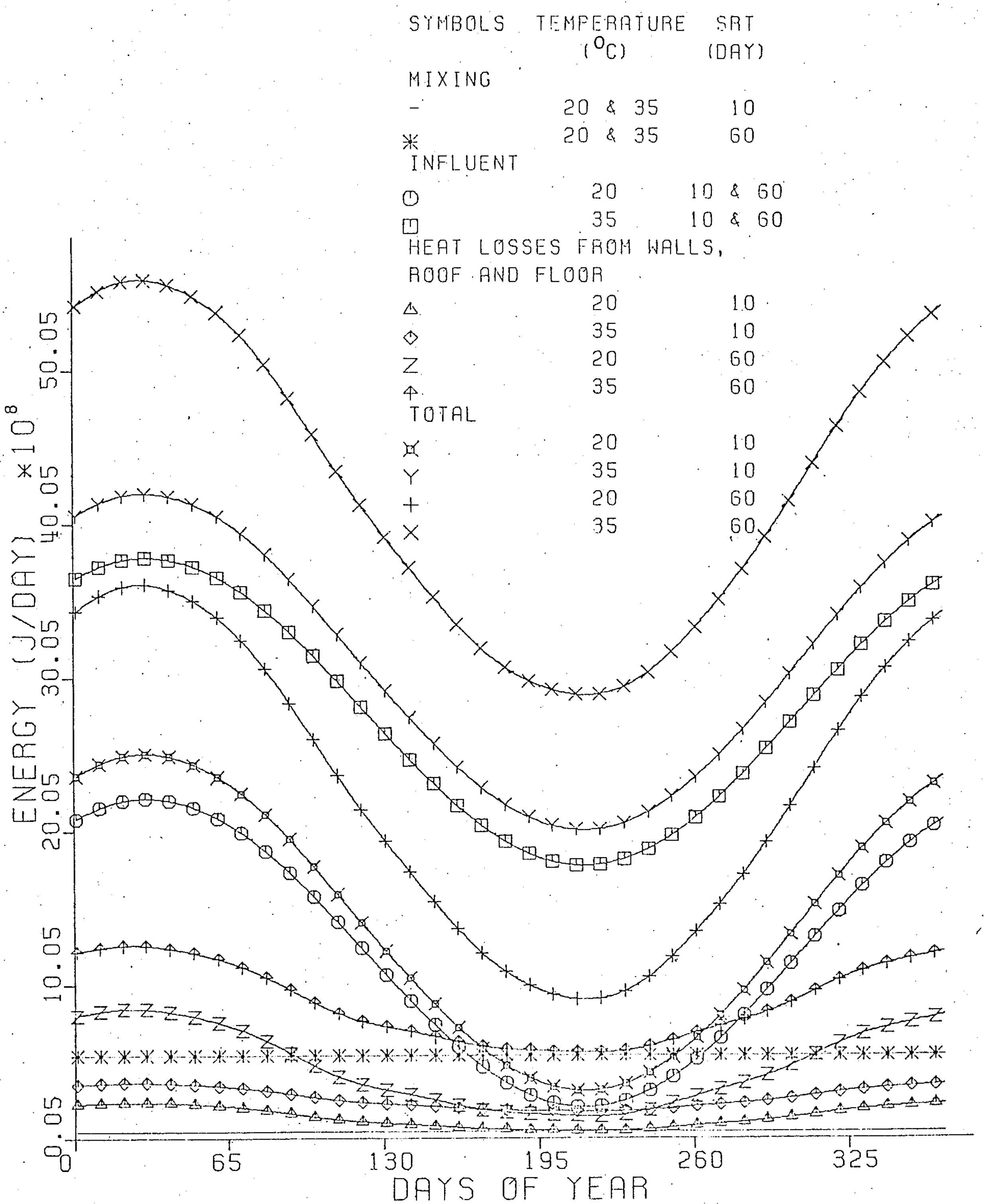


FIG. 5.4 PREDICTING ENERGY REQUIRED FOR DIGESTER OPERATION AT 3% TOTAL SOLIDS CONCENTRATION

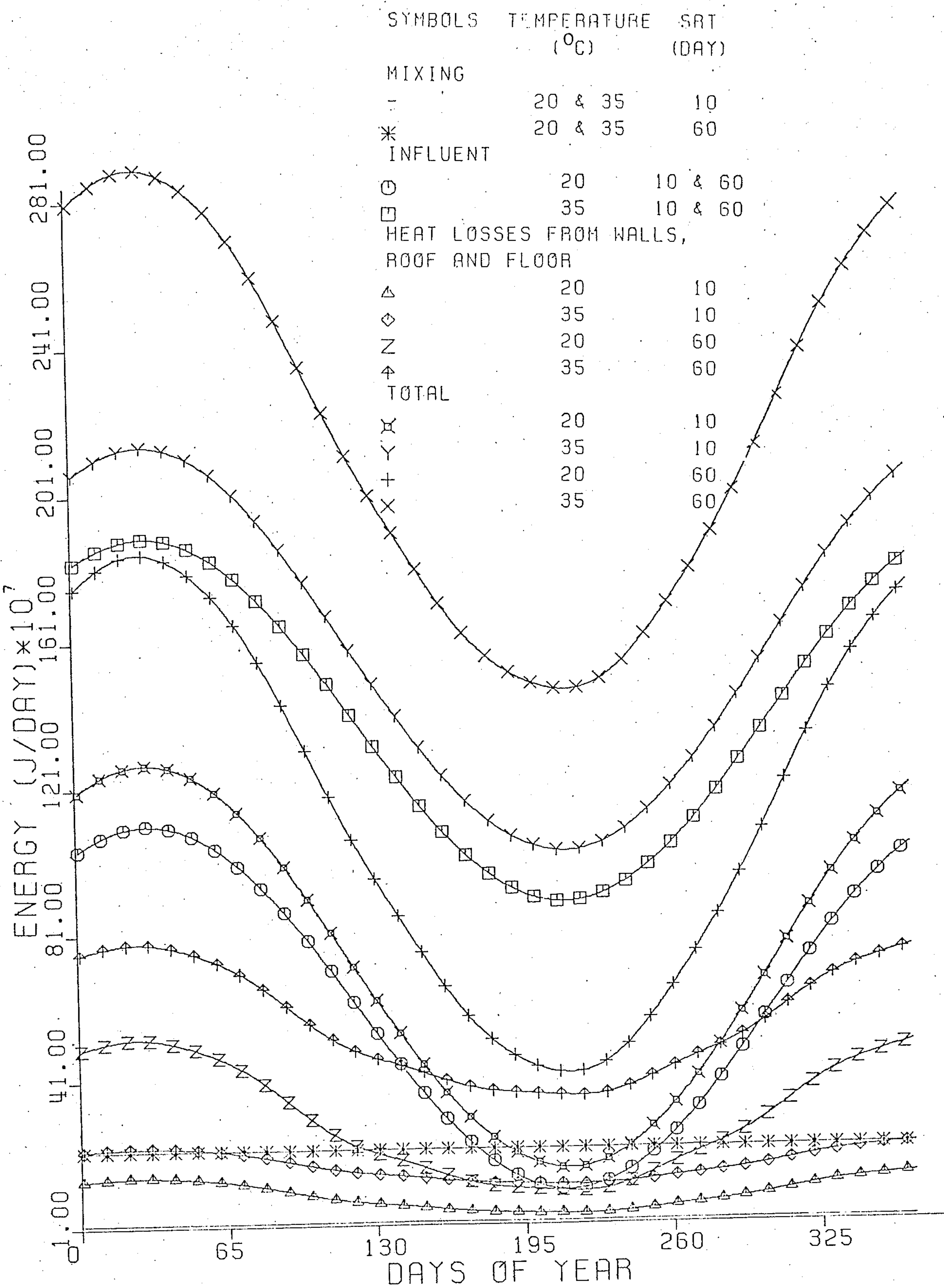


FIG. 5.5 PREDICTING ENERGY REQUIRED FOR DIGESTER OPERATION AT 6% TOTAL SOLIDS CONCENTRATION

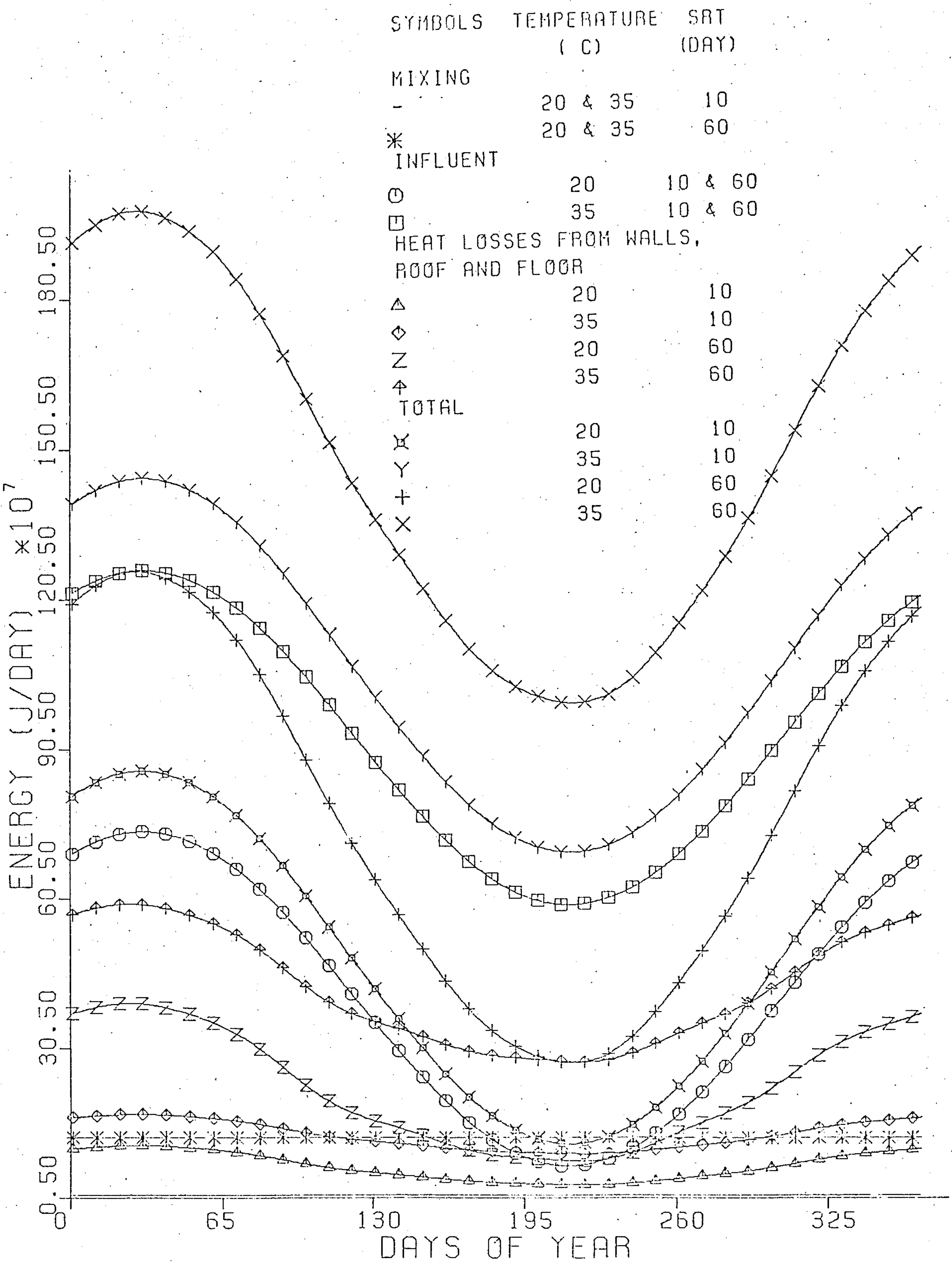


FIG. 5.6 PREDICTING ENERGY REQUIRED FOR DIGESTER OPERATION AT 9% TOTAL SOLIDS CONCENTRATION

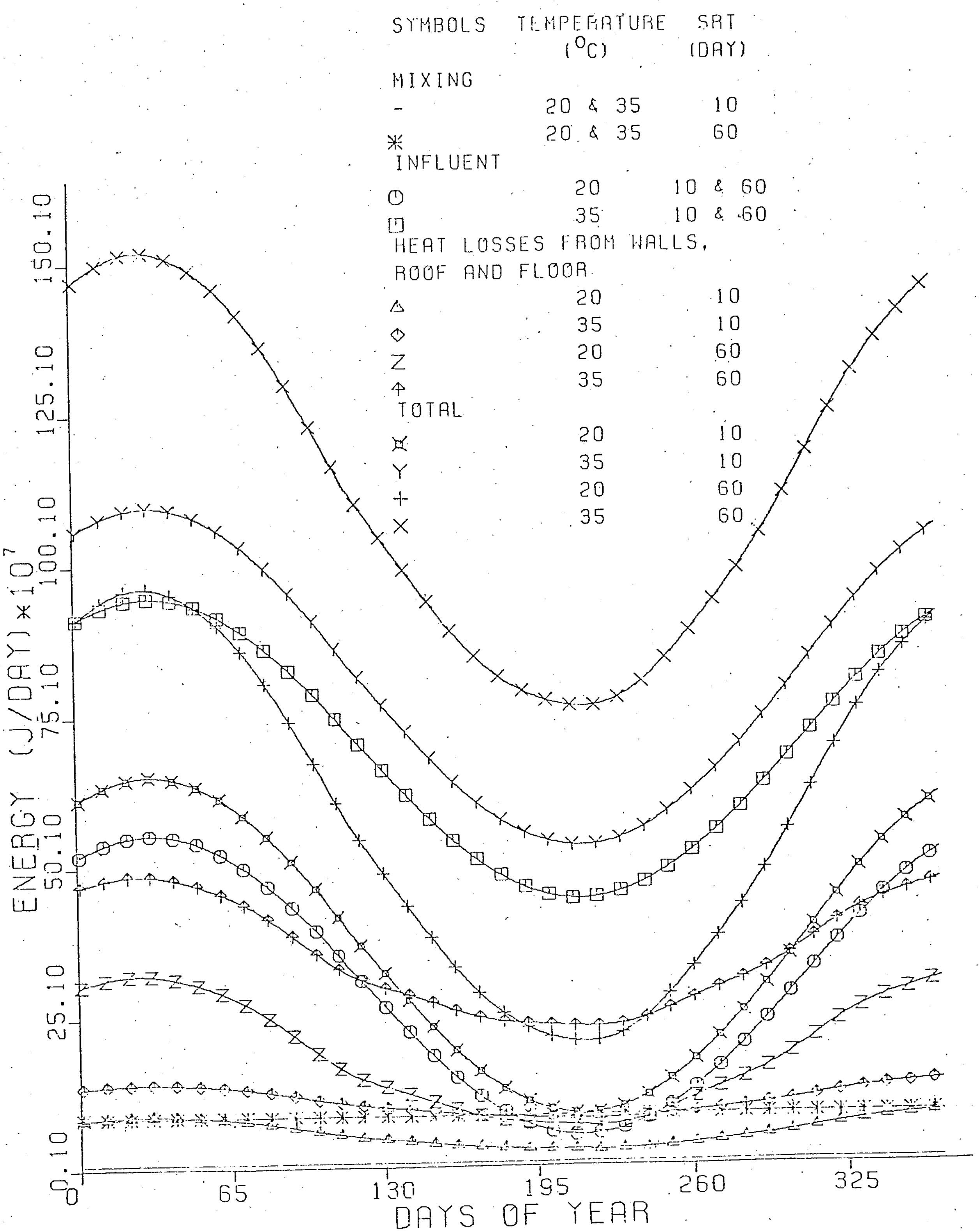


FIG. 5.7 PREDICTING ENERGY REQUIRED FOR DIGESTER OPERATION AT 12% TOTAL SOLIDS CONCENTRATION

TABLE 5.2 MAXIMUM* ENERGY REQUIREMENTS FOR DIGESTER OPERATION

Digester operation			Requirements						
Total solids concentration (%)	SRT (days)	Temperature (°C)	Influent heating		Heat losses from walls, floor and roof		Mixing		Total GJ day^{-1}
			GJ day^{-1}	% of total	GJ day^{-1}	% of total	GJ day^{-1}	% of total	
3	10	20	2.2190	88.4	0.2424	9.7	0.0502	2.0	2.5116
		35	3.7890	90.1	0.3686	8.8	0.0502	1.2	4.2078
	60	20	2.2190	61.3	0.8510	23.5	0.5474	15.1	3.6174
		35	3.7890	67.7	1.264	22.6	0.5474	9.8	5.6004
6	10	20	1.1110	86.9	0.1478	11.6	0.0199	1.6	1.2787
		35	1.8950	88.4	0.2285	10.7	0.0199	0.9	2.1434
	60	20	1.1110	60.0	0.5254	28.3	0.2172	11.7	1.8516
		35	1.8950	65.4	0.7856	27.1	0.2172	7.5	2.8978
9	10	20	0.7397	85.9	0.1103	12.8	0.0116	1.4	0.8616
		35	1.263	87.3	0.1729	11.9	0.0116	0.8	1.4475
	60	20	0.7397	58.6	0.3954	31.3	0.1265	10.0	1.2616
		35	1.263	63.7	0.5944	30.0	0.1265	6.4	1.9839
12	10	20	0.5548	85.1	0.0896	13.7	0.0079	1.2	0.6523
		35	0.9473	86.4	0.1419	12.9	0.0079	0.72	1.0971
	60	20	0.5548	57.6	0.3229	33.5	0.0862	8.9	0.9639
		35	0.9473	62.3	0.4876	32.1	0.0862	5.7	1.5211

*JANUARY 27

TABLE 5.3 MINIMUM* ENERGY REQUIREMENTS FOR DIGESTER OPERATION

Digester operation			Requirements						
Total solids concentration (%)	SRT (days)	Temperature (°C)	Influent heating		Heat losses from walls, floor and roof		Mixing		Total GJ day^{-1}
			GJ day^{-1}	% of total	GJ day^{-1}	% of total	GJ day^{-1}	% of total	
3	10	20	0.2094	66.7	0.0544	17.3	0.0502	16.0	0.3140
		35	1.7790	88.5	0.1870	9.0	0.0502	2.5	2.0099
	60	20	0.2094	23.1	0.1502	16.6	0.5474	60.4	0.9070
		35	1.7790	61.6	0.5631	19.5	0.5474	18.9	2.8895
6	10	20	0.1047	64.3	0.0383	23.5	0.0199	12.2	0.1629
		35	0.8897	86.5	0.1190	11.6	0.0199	1.9	1.0286
	60	20	0.1047	24.8	0.0999	23.7	0.2172	51.5	0.4218
		35	0.8897	60.6	0.3602	24.6	0.2172	14.8	1.4671
9	10	20	0.0698	61.8	0.0315	27.9	0.0116	10.3	0.1129
		35	0.5931	84.9	0.0941	13.5	0.0116	1.7	0.6988
	60	20	0.0698	25.3	0.0794	28.8	0.1265	45.9	0.2757
		35	0.5931	59.4	0.2784	27.9	0.1265	12.7	0.9980
12	10	20	0.0523	59.5	0.0277	31.5	0.0079	9.0	0.0879
		35	0.4449	83.5	0.0800	15.0	0.0079	1.5	0.5328
	60	20	0.0523	25.4	0.0677	32.8	0.0862	41.8	0.2062
		35	0.4449	58.3	0.2323	30.4	0.0862	11.3	0.7634

*AUGUST 1

digester surface area causing more heat loss from digester walls, roof and floor and increasing the mixing energy requirement to mix the increased volume of digester contents. Any change in the individual components of total energy requirement for digester operation changed total energy requirement.

When TSC in influent was increased at a constant SRT and DOT, the total energy required for digester operation, mixing energy and influent heating requirements were decreased (Figures 5.4, 5.5, 5.6 and 5.7). Due to the increased influent TSC at a constant SRT and DOT the temperature gradient for heat transfer from the digester and the difference between the digester and influent temperatures remained constant on any particular day of year but the digester volume and total amount of incoming influent decreased. The lower digester volume provided a lesser surface area for heat loss and lesser amount of incoming influent required lesser energy to raise the influent temperature.

The results shown in Figures 5.4, 5.5, 5.6 and 5.7 and Tables 5.2 and 5.3 indicated that, during cold months, influent heating constituted more than 50% of total energy required for digester operation. This is in agreement with the work of Cassell et al. (1974) and Stevens*. However it contradicts the work of Kroeker et al. (1975) who reported that energy requirements to replace heat losses from the digesters were much higher than energy required to heat the influent. However, Stevens* recalculated the results of Kroeker et al. (1975) and found errors in calculations which led to the conclusion contradicted by this study.

On August 1st, i.e. during warm months, the influent heating requirements were also above 50% of the total energy required for digester

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*Stevens, M. A. 1976 12 ?. Personal communication. Department of Agricultural Engineering, University of Manitoba, Winnipeg, Manitoba.

operation at all TSCs held at 10 and 30 day SRTs and 28 and 35°C DOTs. However, the digesters operating at 20°C DOT and 60 day SRT had influent heating requirements in the range of 23.1 to 25.4% of total energy required for digester operation on August 1 (Table 5.3). Under these operating conditions the influent heating requirements and heat losses from digester, as expected, were less than that usually observed during cold months because of a lesser temperature difference between the DOT and influent temperature and also because of a lesser temperature gradient for heat losses from the digester. Consequently, at the 20°C DOT and 60 day SRT on August 1, mixing energy constituted 40 to 60% of total energy required for the digester operation. At this operating condition the mixing energy is predominent because a 60-day SRT accumulates a larger volume of slurry to be mixed in the digester. Therefore, while a 20°C DOT during warm months kept influent heat requirements and heat losses low, mixing energy became the major component of the total energy required for digester operation.

It was also observed that for all the combinations of influent TSCs, SRTs and DOTs, both during cold and warm months of the year, energy required to maintain the DOT never exceeded a maximum of 33.5% of total energy required for digester operation (Tables 5.2 and 5.3). Evidently, the insulated digester walls and roof and the "thermal bulb effect" were responsible for this result. If an insulated digester and the thermal bulb effect were not considered in system design, estimates of the energy required to maintain the DOT would be much greater than that observed in this study.

Unfortunately there is not much information available regarding different components of energy requirements for field-scale digester operation with which to compare quantitatively the results of this study. Until such information is available from field-scale digester operation the results of this study must serve as the best practical estimate of those requirements.

5.3 Predicting Daily Net Energy Production Under Various Digester Operating Conditions

Net energy production in this study was calculated daily for each digester operating condition. Net energy was defined as the gross energy production from an anaerobic digester continuously loaded with manure produced from 2 000 head of growing and finishing hogs minus total energy required for the digester operation at a defined operating condition. Gross energy production in this study was estimated from the quantity of methane gas produced at any combination of stated operating conditions.

The results of this section are illustrated in Figures 5.8, 5.9, 5.10 and 5.11 which are based on influent TSC. At a given digester operating condition the gross energy production was constant throughout the year. Since the daily energy required for digester operation was periodic in nature over a period of 365 days, the net energy production also had a period of 365 days. Net energy had a maximum value on August 1 and a minimum on January 27 at any combination of stated digester operating conditions (Figures 5.8, 5.9, 5.10 and 5.11).

A minimum of -0.7252 GJ day^{-1} net energy was produced from the digester operating at 3% TSC, 10 days SRT and 20°C DOT on January 27 and a maximum of 8.8710 GJ day^{-1} was produced from the digester operating at 12% TSC, 60 days SRT and 28°C DOT (Table 5.4). An increase in DOT from 20 to 35°C increased net energy production from the digester

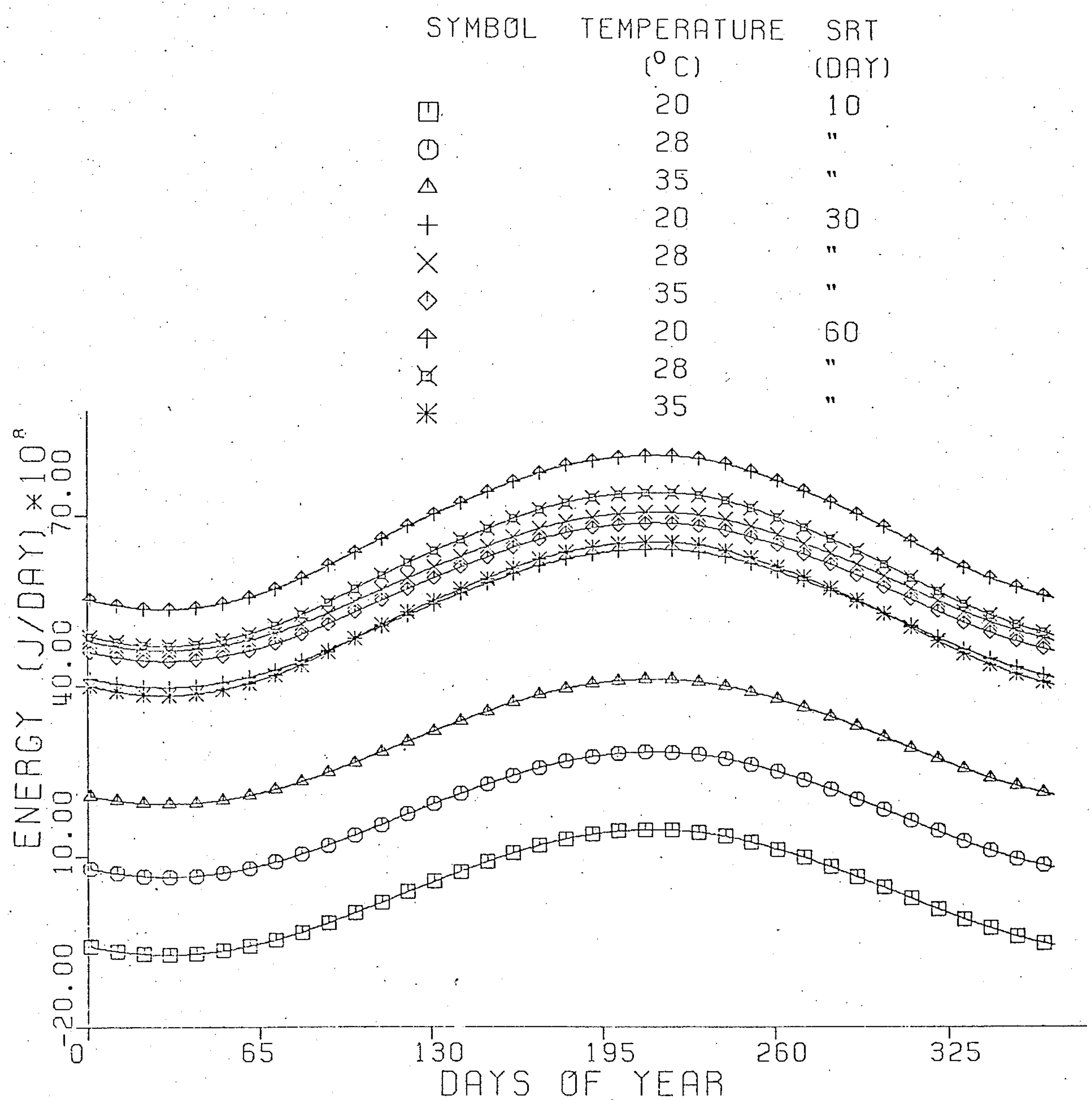

FIG. 5.8 PREDICTING NET ENERGY PRODUCTION RATE AT 3% TOTAL SOLIDS CONCENTRATION

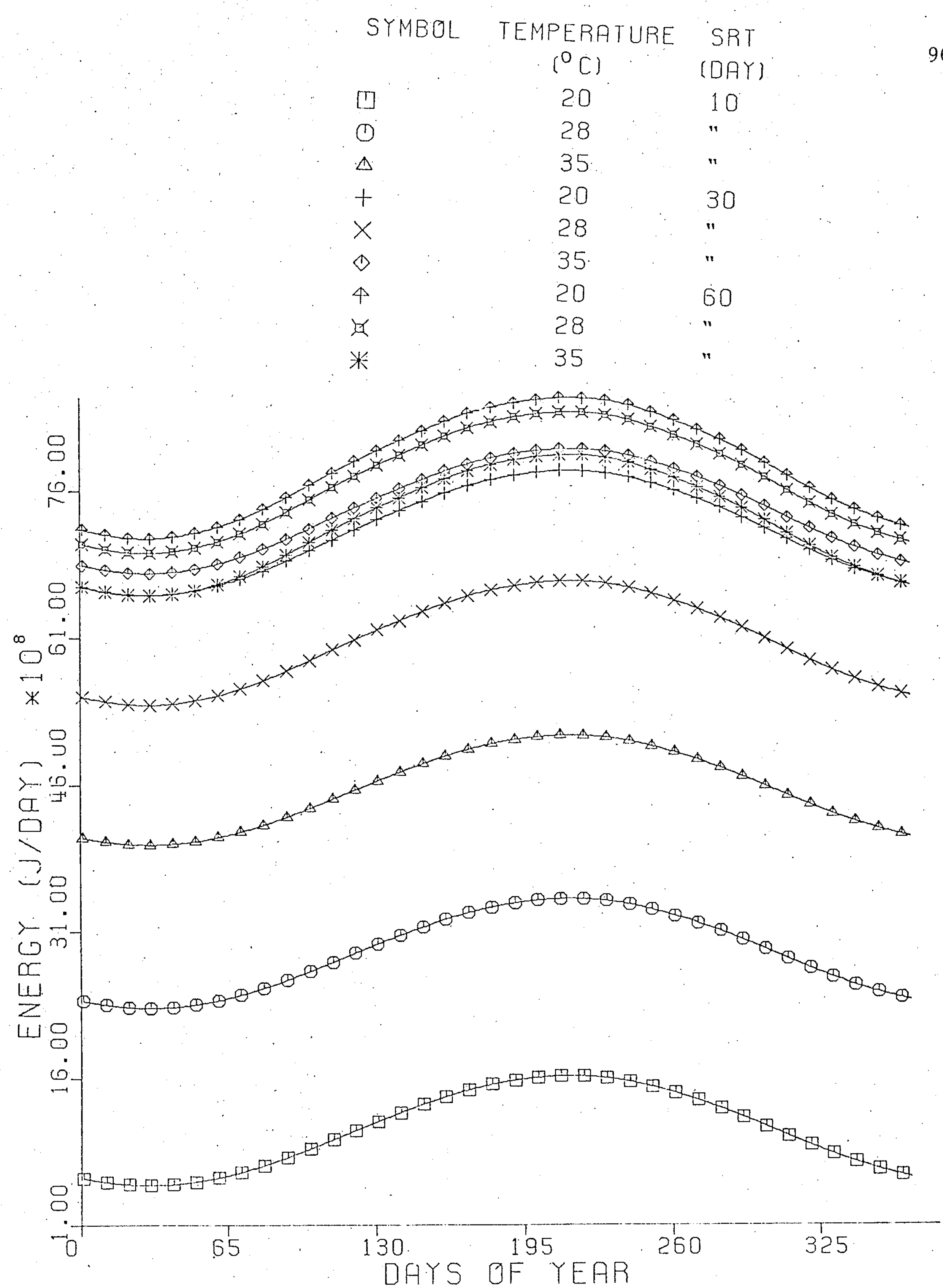

FIG. 5.9 PREDICTING NET ENERGY PRODUCTION RATE AT 6% TOTAL SOLIDS CONCENTRATION

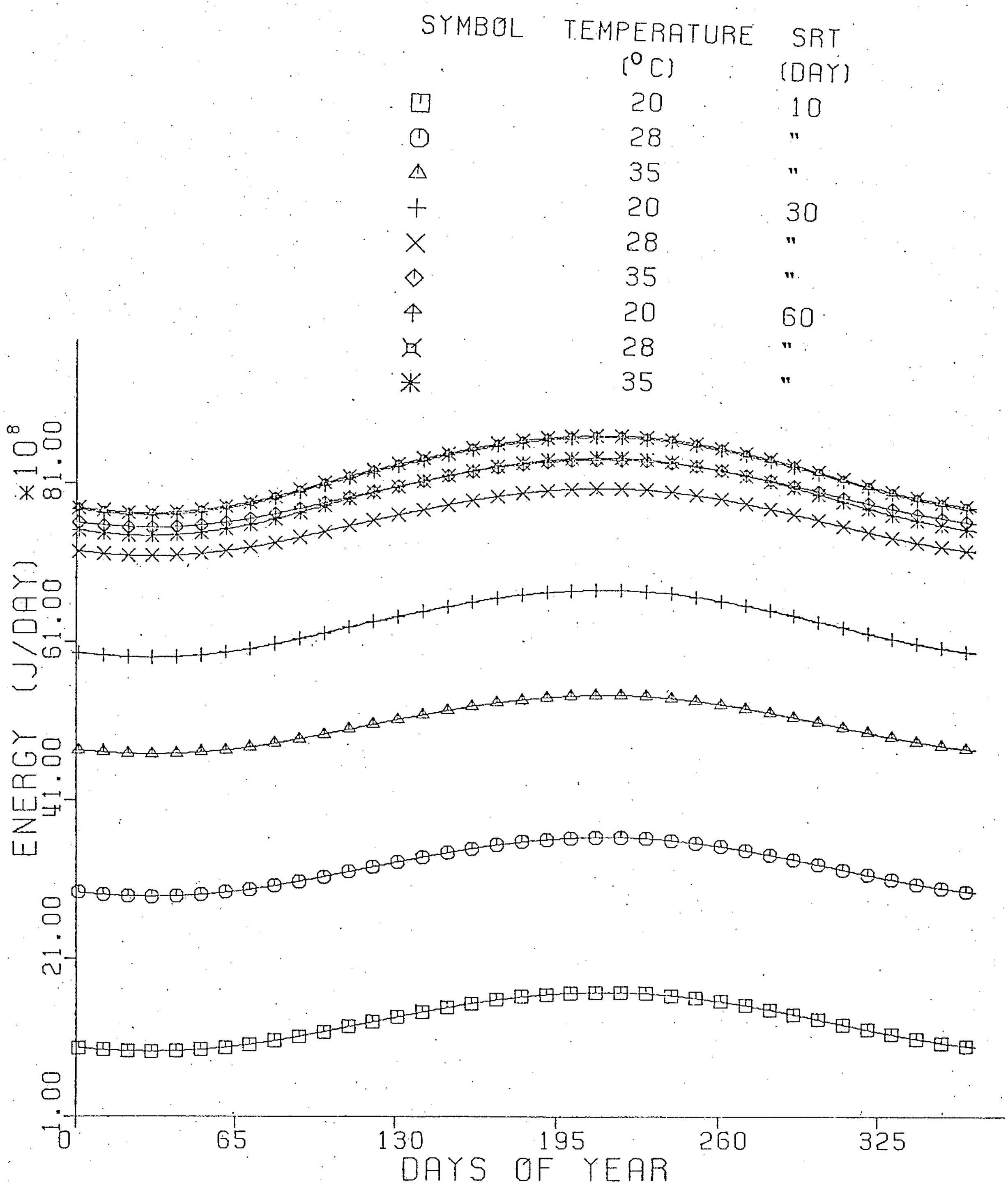

FIG. 5.10 PREDICTING NET ENERGY PRODUCTION RATE AT 9% TOTAL SOLIDS CONCENTRATION

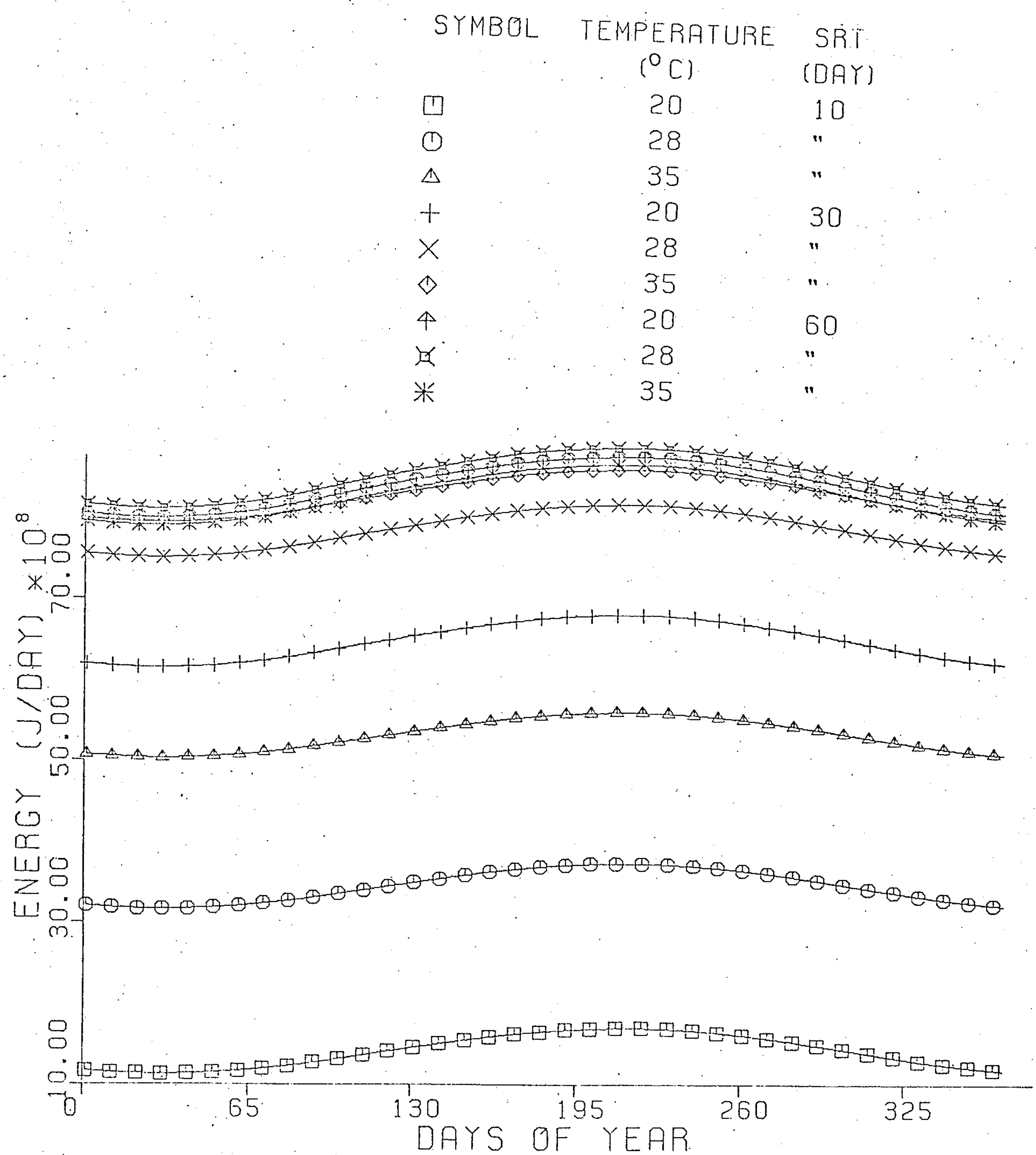

FIG. 5.11 PREDICTING NET ENERGY PRODUCTION RATE AT 12% TOTAL SOLIDS CONCENTRATION

TABLE 5.4 MAXIMUM* AND MINIMUM+ NET ENERGY PRODUCTION

Digester operation			Net Energy				Gross energy[2)]
Total solids concentration (%)	SRT (days)	Temperature (^oC)	Maximum GJ day^{-1}	Maximum % Recovery[1)]	Minimum GJ day^{-1}	Minimum % Recovery	GJ day^{-1}
3	10	20	1.4710	82.4	-0.7252	-40.6	1.7860
		35	4.1200	67.2	1.9230	31.4	6.1310
	60	20	8.0580	89.9	5.3510	59.7	8.9660
		35	6.5370	69.3	3.8300	40.6	9.4280
6	10	20	1.6230	90.9	0.5088	18.5	1.7860
		35	5.1020	83.2	3.9880	65.1	6.1310
	60	20	8.5430	95.3	7.1150	79.4	8.9660
		35	7.9600	84.4	6.5320	69.3	9.4280
9	10	20	1.6730	93.7	0.9243	51.8	1.7860
		35	5.4320	88.6	4.6830	76.4	6.1310
	60	28	8.7140	93.0	7.7290	82.4	9.3750
		35	8.4290	89.4	7.4450	79.0	9.4280
12	10	20	1.6970	95.0	1.1340	63.5	1.7860
		35	5.5980	91.3	5.0340	82.1	6.1310
	60	28	8.8710	94.6	8.1150	86.6	9.3750
		35	8.6640	91.9	7.9070	83.9	9.4280

*August 1

+January 27

1) $\% \text{ Recovery} = \frac{\text{Net energy}^{3)}}{\text{Gross energy}} \times 100$

2) Gross energy = energy equivalent to methane gas produced

3) Net energy = gross energy production—total energy required for digester operation

operating at a 10-day SRT and all TSCs used in this study. This increase was due to the fact that gross energy production increased with increasing temperature at a greater rate than that of total energy required for digester operation. This, in turn, was because mixing energy was temperature independent and also because the digester surface area for heat transfer remained constant.

At a 60-day SRT and TSC of 3 or 6% the increase in temperature from 20 to 35^{o}C decreased the daily net energy production (Table 5.4). This was due to the fact that at 60 day SRT there is not much effect of temperature on gross energy production but heat losses from the digester and influent heating requirements were increased with a temperature increase from 20 to 35^{o}C. At influent TSCs of 9 and 12% and a 60-day SRT the interaction between gross energy production and total energy required for digester operation was such that net energy production increased with a temperature increase from 20 to 28^{o}C and decreased with a temperature increase from 28 to 35^{o}C throughout the year. Maximum net energy production occurred at the 28^{o}C DOT during cold as well as during warm months of the year (Table 5.4).

As influent TSC increased from 3 to 12% the daily net energy production increased at all SRTs and DOTs. This was because of the fact that the greater TSCs needed lesser digester volume which reduced digester heat losses and mixing energy requirements and also required a lesser volume of influent to be heated.

At a constant TSC and constant DOT as SRT was changed from 10 to 60 days the daily net energy production increased throughout the year. By increasing SRT at constant DOT and TSC, influent heating requirements remained constant. However, energy required to maintain DOT increased because of a larger surface area of digester for heat losses. Also, increased energy was required to mix the digester contents due to larger volume of slurry in the digester. However, gross energy production also increased with increasing SRT at constant DOT with the resultant effect that net energy production always increased with increase in SRT.

The results also indicated that, at any influent TSC, a digester operating at a 10-day SRT and 35°C DOT produced less net energy than one operating at 20 or 28°C DOT and a 60-day SRT. This made it clear that a 10 day SRT did not produce as much gross energy even at 35°C DOT as a 60-day SRT produced at 20 or 28°C DOT.

As previously discussed, negative net energy was recorded from a digester operating at 3% TSC, 10 day SRT and 20°C DOT. This is in agreement with the work of Kroeker et al. (1975) who observed negative net energy production in cold months at Winnipeg. Cassell et al. (1974) reported positive net energy recovery from cow manure when digester was operated at 20 and 35°C but at 55°C the net energy recovery was negative. Cassell also reported that they could not recover enough net energy from cow manure during cold weather even from well-insulated digesters. The reason might be that they assumed 45% efficiency of heating systems and probably they did not consider the thermal bulb effect for underground digester installations. This study assumed 100% efficiency of the heating system and a 60% efficiency for the mixing unit. The consideration of 100% efficiency for heating systems is very optimistic. According to the WPCF (1959), heating system efficiencies in the range of 75 to 80% can be attained for anaerobic digesters. Cassell et al. (1974) reported a realistic figure for heating systems efficiency to be 65%.

Consequently, the % energy recovery figures in Table 5.4 are somewhat higher than that which might ordinarily be expected. On the other hand, the assumption of 45% efficient heating system by Cassell et al. (1974) was very pessimistic in relation to net energy production from an anaerobic digester. If the assumption of a 100% efficient heating system was not made, a lower range of % recovery than that in Table 5.4 would have been observed.

The results of this study and of Cassell et al. (1974) showed that an elevated DOT is not necessary for greater net energy production than that at lower DOT. In this study at all digester operating conditions a 10-day SRT and 35°C DOT produced less net energy than that at 60-days SRT and 20 or 28°C DOT. Therefore, for design considerations, an optimum combination of SRT and DOT should be selected.

5.4 Annual Net Energy Recovery For Various Digester Operating Conditions

The annual net energy was defined as the cumulative sum of daily net energy production over a period of 365 days for the normal year. It was observed in Section 5.3 that daily net energy production was dependent on DOT, SRT, TSC and day of the year.

5.4.1 Effect of DOT on Annual Net Energy Recovery

At all TSCs (3, 6, 9 and 12%) at a 10-day SRT the annual net energy production followed a linear increase with increase in DOT (Figure 5.12). At a 30-day SRT, the annual net energy recovery at all influent TSCs increased rapidly (though less rapidly than at a 10-day SRT) in the DOT range 20 to 28°C. However, the rate of increase in annual net energy production was less in the DOT range of 28 to 35°C. At a 60-day SRT, at all the stated TSCs, annual net energy production

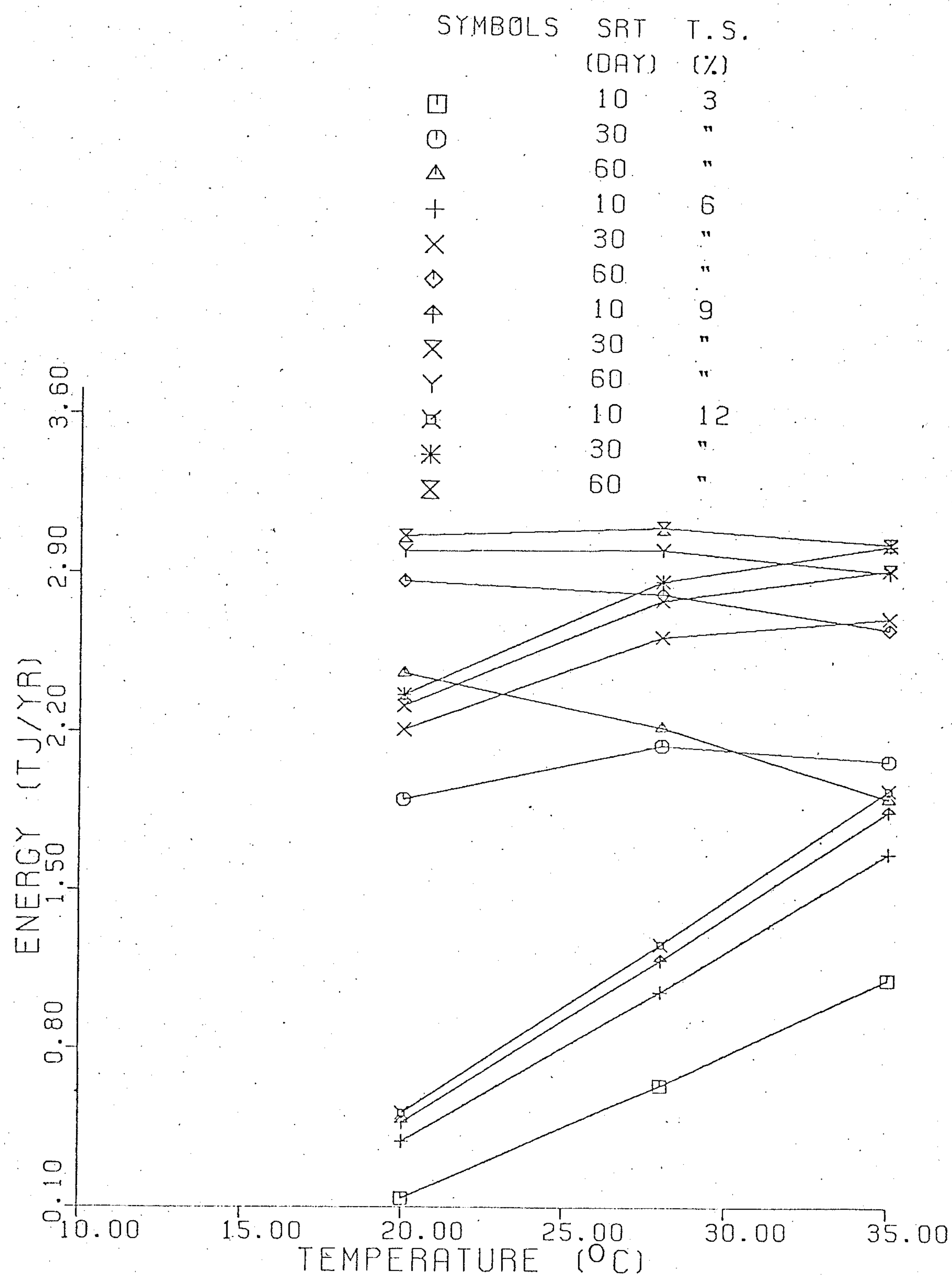

FIG. 5.12 EFFECT OF TEMPERATURE ON CUMULATIVE NET ENERGY PRODUCTION

either decreased or showed no significant change in net annual energy production with DOT (Figure 5.12).

5.4.2 Effect of Loading Rate on Annual Net Energy Recovery

For purposes of comparison, volatile solids loading rates were calculated from the SRTs and TSCs used in this study. As a result loading rates in the range of 0.33 to 7.80 kg v.s. m^{-3} day^{-1} were determined to have occurred in this study. The variation in annual net energy production with loading rates at various DOTs are shown in Table 5.5. Since loading rates were calculated from the independent parameters of SRT and TSC, no trend in net energy recovery was found with respect to loading rate. For example, a digester operating at 3% TSC and a 10-day SRT had a loading rate of 1.95 kg v.s. m^{-3} day^{-1} as did the digester operating at 9% TSC and a 30-day SRT. However, the net energy production for these digesters were quite different (Table 5.5). The digesters having the same loading rates but operating at different SRT and TSC had different annual net energy production because a digester operating at 3% TSC and a 10-day SRT produced less daily gross energy than at a 9% TSC and 30-day SRT. Gross energy production was directly related to SRT at a fixed DOT. Furthermore, the energy required to heat the influent for the digester at 3% TSC was greater than that at 9% TSC. Here it should be noted that loading rate might be a quite misleading design parameter if the net energy is the criteria for success. Therefore, a design engineer should base his design on SRT, DOT and TSC rather than the more traditional criteria of loading rate and DOT.

For comparative purposes the annual net energy production was converted to an equivalent amount of heating oil per animal. Results of this method of expression of annual net energy production are given in

TABLE 5.5 EFFECT OF LOADING RATE ON CUMULATIVE NET ENERGY PRODUCTION

TSC (%)	SRT (days)	Loading rate (kg v.s. m^{-3} day^{-1})	Temperature (^oC) 20	28	35
			cumulative net energy production (TJ yr^{-1})		
3	10	1.95	0.1391	0.6387	1.1060
	30	0.65	1.9020	2.1400	2.0710
	60	0.33	2.4580	2.2220	1.9030
6	10	3.99	0.3905	1.0520	1.6600
	30	1.30	2.2110	2.6210	2.7020
	60	0.65	2.8640	2.8100	2.6510
9	10	5.87	0.4750	1.1910	1.8470
	30	1.95	2.3140	2.7820	2.9140
	60	0.98	2.9970	3.0050	2.9020
12	10	7.80	0.5174	1.2610	1.9410
	30	2.60	2.3660	2.8640	3.0220
	60	1.30	3.0630	3.1040	3.0280

Table 5.6. Naturally, these results followed the same trend with respect to digester operating conditions as the annual net energy recovery shown in Table 5.5. The results shown in Table 5.6 were helpful in making a comparison of the results of Lapp et al.(1974) and those of this study. Lapp et al.(1974) estimated an annual net equivalent heating oil recovery of 43.80 $dm^3\ yr^{-1}\ hog^{-1}$ from a digester loaded with manure from 1 000 head of hogs having an average mass of 45.0 kg hog^{-1}. Digester operating conditions were in the range of 32 to 35^{o}C DOT at a 40-day SRT and an influent TSC of approximately 13%. From Table 5.6 it is evident that the equivalent net heating oil production obtained through computer simulation was approximately 37.805 $dm^3\ yr^{-1}\ hog^{-1}$ for digesters operating at a 12% TSC and 30-or 60-day SRTs and 35^{o}C. The results of Lapp et al.(1974) were slightly higher than the results in this study. However, influent temperature and air temperature were not mentioned in the study by Lapp et al.(1974) and the energy requirement for digester operation and consequently the net annual heating oil production was simply a crude estimation of net energy recovery in their study (Schulte*). Through computer simulation the net energy production was calculated on the basis of a realistic consideration of air temperature, influent temperature and soil temperature, hence the results proposed by Lapp et al.(1974) seemed realistic under the assumptions in this study.

5.4.3 Relationships Between Annual Net Energy Production and Digester Operating Conditions

In order to develop relationships between annual net energy production and digester operating conditions a multilinear regression

*Schulte, D. D. 1976 12 17. Personal communication. Department of Agricultural Engineering, University of Manitoba, Winnipeg.

TABLE 5.6 EQUIVALENT HEATING* OIL TO ANNUAL NET ENERGY RECOVERY PER HOG

TSC (%)	SRT (days)	DOT (^{o}C) 20	28	35
		Equivalent heating oil to annual net energy ($dm^3\ yr^{-1}\ hog^{-1}$)		
3	10	1.737	7.975	13.805
	30	23.745	26.720	25.855
	60	30.690	27.735	23.760
6	10	4.876	13.130	20.730
	30	27.605	32.720	33.730
	60	35.760	35.080	33.100
9	10	5.930	14.865	23.060
	30	28.890	34.735	36.385
	60	37.415	37.520	36.275
12	10	6.460	15.740	24.230
	30	29.535	35.750	37.725
	60	38.235	38.745	37.805

*heating value of heating oil was taken as 40.05 GJ m^{-3}

was performed at each of the DOTs (20, 28 and 35^{o}C) on annual net energy production, SRT and TSC. The following relationships were developed.

$$CNEP_{20} = -0.15083 + 0.04711\ (SRT) + 0.05180\ (TSC) \quad (5.1)$$

$$CNEP_{28} = 0.45217 + 0.03271\ (SRT) + 0.07978\ (TSC) \quad (5.2)$$

$$CNEP_{35} = 0.93198 + 0.01795\ (SRT) + 0.10426\ (TSC) \quad (5.3)$$

where: $CNEP_{20}$ = cumulative net energy production at 20^{o}C digester operating temperature (TJ yr^{-1})

$CNEP_{28}$ = cumulative net energy production at 28^{o}C digester operating temperature (TJ yr^{-1})

$CNEP_{35}$ = cumulative net energy production at 35^{o}C digester operating temperature (TJ yr^{-1})

SRT = solids retention time (days)

TSC = total solids concentration in influent slurry (%).

Coefficients of determination for Equations 5.1, 5.2 and 5.3 are given in Table 5.7. All the coefficients of determination (r^2) in Table 5.7 were above 0.83 which indicated a good fit of the equations to the data. It is clear from the Table 5.7 that the equations are capable of explaining at least 83% of the observed variation in annual net energy production at a given DOT in the range of 20 to 35^{o}C. From Equations 5.1, 5.2 and 5.3 it was clear that as DOT increased from 20 to 35^{o}C the effect of TSC on annual net energy recovery increased relative to the effect of SRT. Also, at an constant DOT between 20 and 35^{o}C, the effect of TSC on annual net energy was greater than that of SRT.

A multilinear regression was also performed on annual net

TABLE 5.7 VALUES OF COEFFICIENT OF DETERMINATION FOR ANNUAL NET ENERGY PRODUCTION AND DIGESTER OPERATING CONDITIONS

Digester operation		Coefficient of determination
Temperature (^oC)	Variables entered	(r^2)
20	SRT, TSC	0.927
28	SRT, TSC	0.864
35	SRT, TSC	0.834
T_ℓ*	SRT, TSC, T_ℓ	0.850

*T_ℓ = mixed liquor temperature in digester

energy production including not only SRT and influent TSC but also DOT as independent variables (Equation 5.4). The coefficient of determination of Equation 5.4 was 0.85 which simply means that 85% of the total variation in annual net energy production could be explained by a linear relationship between annual net energy production and digester operating conditions. The remaining 15% of the total variation is probably due to the fact that a linear relationship is oversimplification of the situation.

$$\text{CNEP} = -0.52405 + 0.0338\ T_{\ell} + 0.03259\ (\text{SRT}) + 0.07861\ (\text{TSC}) \tag{5.4}$$

where: CNEP = cumulative net energy production (TJ yr^{-1})

T_{ℓ} = mixed liquor temperature in digester (^{o}C)

Apparently, the net effect of the DOT and SRT, which have nonlinear effects (Figure 4.5) on gas production (gross energy production), and SRT and TSC which have nonlinear effects on energy required for digester operation (Figures 5.4, 5.5, 5.6 and 5.7), can be approximated by a linear relationship between annual net energy production and digester operating conditions. Also from Equation 5.4 it is evident that the effects of digester operating conditions on annual net energy production were (in the order of relative influence): TSC > DOT > SRT.

5.5 Effect of Major Assumptions on Results

Unidirectional heat flow from digester walls, roof and floor resulted in less heat loss than normally would occur by consideration of three-dimensional heat loss from a digester. A three-dimensional heat transfer model would predict more energy requirement to maintain the DOT than would a unidirectional heat transfer model. Therefore, a three-dimensional heat transfer model will predict reduction in the net energy production on any day of year and at any combination of digester operating conditions.

The thermally homogeneous soil considered around the digester at all depths resulted in a constant rate of heat flow through the soil but in reality soil differs in thermal characteristics both horizontally and vertically. Consequently, the thermal conductivity and thermal diffusivity would not be constant and would oversimplify the soil temperature model thus affecting heat losses from digester walls and floor. It is beyond the scope of this study to determine to what extent such variations would influence net energy production.

The smooth and bare soil surface allowed more heat losses from the soil surrounding the digester than would a soil having vegetative cover. Generally, field soils are not bare and smooth and vegetative cover acts as insulation. Also, snow-cover during cold months would add extra insulation to the soil surface and around the digester wall. These were not considered in this study. Vegetation and snow cover would reduce the heat losses from a digester resulting in increased net energy production.

The accuracy of the value of the temperature coefficients for wash-out time and rates of gas production could not be tested directly. Other values of these coefficients would affect gross energy production and thus may affect the net energy production. Furthermore, utilization of constant temperature coefficients in the range of 20 to 35°C DOT might not always be accurate. If the value of the temperature coefficient at 20°C DOT were different than that at 35°C, the net energy production observed at 20°C DOT would be different than that predicted by this study.

More research is needed to establish comparative reaction rate coefficients especially at lower DOTs.

The assumption of temperature independent gas production rates at an infinite SRT resulted in a lesser difference in gas production rates at a long SRT (operating at 20^{o}C as opposed to 35^{o}C) than that of a short SRT operating at those temperatures. If gas production rates were temperature dependent at an infinite SRT, the trend of results in this study might well be reversed at 60 day SRT.

The assumption of complete-mixing of digester contents for 24 hr day^{-1} may not be necessary in practice but was made to insure uniform mixed-liquor temperature at any location in the digester. The assumption insured steady-state heat transfer from the digester to surrounding soil. However, consideration of complete-mixing throughout the day would possibly require more mixing energy per day than if mixing were accomplished only once per day.

Steady-state digester operation insures uniform production of gross energy but in actual practice digesters may not perform at steady-state levels because of the various inhibitory agents discussed in Chapter II. Consequently, gross energy production would be impaired. Also, the assumption of steady-state operation does not consider the reduced energy production rates expected during the start-up period of digester operation which will also reduce the net energy recovery from the digester. However, digesters are not generally designed to take consideration of negative effects of inhibition and start-up. Were such effects considered the results would be difficult to compare to future studies where it is unlikely that similar inhibition or start-up problems would be duplicated.

The assumption of cold manure temperatures during cold months required more energy to heat influent than might normally be required, for example, to heat the influent from a manure storage pit inside a barn. By changing management practices inside the barn it may be possible to reduce the influent heating requirements and thus cause an increase in net energy production.

The assumption of 100% efficiency for the heating system was quite optimistic. As mentioned earlier, influent pumping requirements and heat losses from influent carrying pipes were ignored which also kept energy required for digester operation at a lower level than would normally be expected. The consideration of these energy losses and a lower efficiency of heating systems than 100% would simply lower the magnitude of net energy than that of this study but the relative trend of difference digester operating conditions would remain the same.

Heat generation by microorganisms was not permitted in this study but in practice microorganisms may produce some heat which would reduce the heat required to maintain DOT and thus an increase in net energy production. Unfortunately, no information was available in the literature which indicated that this source of heat was of practical significance.

The assumption of constant specific heat of influent slurry was made in the TSC range of 3 to 12% because within this range thermal characteristics of manure will not change much and also no other information was available with which to develop a model for change in manure thermal properties.

The assumption of a normal year was made to enable the determination of the effects of digester operating conditions on net energy recovery without the confounding influence of extremes in air temperature during the year. The net energy production in different year than a normal year would depend on nature of the year. However, any year could be used in the simulation model.

It appears that some assumptions made in this study resulted in increased net energy production while others decreased net energy production from the digester. Without quantitatively verifying the effects of assumptions on net energy recovery, it is not possible to conclude whether the effects would be balanced or would influence the net energy production significantly. However, the major effects of DOT, insulation, the "thermal bulb effect", SRT, TSC and influent temperature have been accounted for and it is probable that the net effect of the major assumptions on the model results are relatively small.

5.6 Implications of Results to Design of Anaerobic Digesters for Farm Animal Manures

In general practice, anaerobic digesters are designed for specific operating temperature, capacity, size of mixing system, capacity of heating system, dimensions of digester walls and insulation materials and loading rate. For farms this would include the manure produced from a fixed number of animals. As discussed in Section 5.4 designing a system solely on the basis of organic loading rate might be a misleading criteria in relation to net energy recovery unless the SRT and TSCs are specified.

The effect of a well-insulated digester and the "thermal bulb effect" reduced the energy required to maintain the DOT which was favourable to net energy recovery from the digester. Also the results discussed in Section 5.4 showed that the 9 and 12% TSCs recovered more energy than did the 3 and 6% TSC's at equivalent SRTs and digester operating temperatures.

A TSC of 12% in influent manure slurries can easily be maintained by preventing leakage, water spillage and lesser use of water for washing than normally done in the barn (Loehr 1974). However, the pumping characteristics of slurries having high TSC's (9 and 12%) are quite different than at lower TSC's such as 3 and 6% (Miner and Smith 1975).

The results also indicated that the greatest net energy recovery occurred with long SRT's. However, a net energy production figure may be quite misleading if used without reference to the cost per unit of net energy recovered. A 60-day SRT, for example, would require more digester volume than that of a 10-day SRT thus increasing the cost of installation. An added advantage of long SRT's could, in some cases, be the possibility of using the digester as a manure storage tank. Before recommending operating conditions for anaerobic digesters for farm manures a cost analysis per unit net energy recovery should be completed. If possible, the operating conditions selected for digester design should be those which maximize net benefits to the farmer.

5.7 Use of Model for Other Situations

The computer simulation model developed to predict net energy recovery from anaerobic digesters is given in Appendix A. The model was written in FORTRAN IV. The results of this study were merely the results of the computational procedure involved in the model at a selected set of input data. The model can be used for any other type of manure, other soils, other climates, any combination of wall and insulation materials, a square digester configuration, and any set of operating conditions of a digester.

The input data on the manure characteristics were: (a) live-weight per animal for growing and finishing animals, (b) number of growing and finishing animals; (c) average dry and wet manure produced per unit liveweight of animal; (d) % of total solids in influent slurry on dry weight basis which are volatile; (e) specific weight of influent slurry. To use the model for different types of manure the input data for manure characteristics must be changed.

To use the model for a digester surrounded by soil other than that of in this study, the input data for thermal conductivity of soil should be changed for predicting heat losses through the new soil media. Use of the model in other climates might be restricted because of the soil temperature model which was developed for Winnipeg. However, if a soil temperature model for a different place can be developed following the procedure in Chapter IV, the simulation model could be used for that place.

Air temperature does not impose any locational restriction on the model because daily air temperature data for any year can be utilized by the computer program. The influent temperature model may be restricted for use in different climates but this restriction can be overcome by introducing a statement in the computer program to skip the influent temperature model and to read influent temperatures from a data deck similar to that possible with the air temperature model.

To use the model for any other type of digester, wall and insulation materials would have to be changed as well as the film coefficients for heat transfer between the interior digester walls and digester gas and the insulation materials and outside air. The thickness of the digester wall and insulation materials are variable and any number of wall or insulation materials with different thicknesses can be accepted by the model.

To use the model for square or rectangular digester configuration, the simulation model would need some modification in the equation which converts the digester wall and insulation materials to thermally equivalent soil. The new equation will be of the type used for changing the floor thickness to thermally equivalent soil. The equations previously used in Chapter III to calculate heat losses from the digester walls, roof and floor will be unchanged for square or rectangular digester configuration.

The digester operating conditions can be changed by changing the input data to reflect any combination of influent TSC, SRT and DOT.

Values of gross energy production can be changed for different situations by changing the maximum gas production rate, the reaction rate constant or temperature coefficient. Thus the net energy production can be predicted for almost any possible situation.

Energy required to mix the digester contents can also be changed for more or less vigorous mixing by changing volume of gas required per unit volume of digester. The efficiency of the heating system and mixing units may also be changed depending upon type of heating and mixing units desired.

VI. CONCLUSIONS

The simulation results in this study indicated the following:

(1) Digester operating temperatures (DOT) developed a thermal bulb region in the surrounding soil which elevated the soil temperature around the digester walls and floor. For example, on January 1st a digester operating at 35°C DOT, 6% total solids concentration (TSC) and 30-day solids retention time (SRT) had the soil temperature adjacent to its outer insulation elevated by 17.5°C at the soil surface and by 13.9°C at the 3.0-m depth.

(2) The extent of thermal bulb region reached a maximum of 8.0 m from the inner surface of digester walls in the radial direction and 4.75 m downward from inner surface of digester floor.

(3) At all the digester operating conditions during cold months influent heating constituted over 50% of total energy required for digester operation. During warm months the influent heating requirement also exceeded 50% of the total in all cases except for the digester operating at a 60-day SRT and 20°C DOT where it was less than 25.4% of the total energy required for digester operation.

(4) Energy required to replace heat losses from the walls, floor and roof of the digesters were in the range of 8.8 to 33.5% of total energy required for the digester operation throughout the year.

(5) Mixing energy requirements were always less than 19% of total energy required for digester operation throughout the year except for digesters operating at a 60-day SRT and 20°C DOT during the warm months where it was in the range of 41.8 to 60.4% of total energy required.

(6) The worst operating condition in relation to net energy recovery occurred on January 27th at a DOT of 20°C, 10-day SRT and a 3% TSC when a -40.6% energy recovery occurred. Except for this case all other operating conditions gave positive net energy recovery.

(7) The best operating condition in relation to net energy recovery occurred at 12% TSC, 60-day SRT and a 28°C DOT throughout the year. The annual net energy recovery per hog for this operating condition was equivalent to 38.745 $dm^3\ yr^{-1}$ of heating oil.

(8) DOT had a positive effect on net energy production from digesters operating at 10-and 30-day SRTs but at a 60-day SRT, in most cases, the effect of increased digester operating temperature was either insignificant or negative.

(9) Loading rate as a design parameter was misleading in relation to net energy recovery without knowledge of the SRT and the influent TSC. Therefore, a design engineer should base his design on SRT, DOT and TSC rather than the more traditional criteria of loading rate and DOT.

(10) Annual net energy production showed a multilinear relationship among digester operating temperature, SRT and influent TSC. The effects of digester operating conditions on annual net energy recovery were (in order of relative influence): TSC > DOT > SRT.

The previous results and the model presented in Chapter IV and Appendix A fulfill the objective stated in Chapter I that a model be constructed, tested and utilized with which to develop relationships between energy input and output for design and operation of anaerobic digesters for farm-animal manure.

VII. RECOMMENDATIONS FOR FURTHER STUDY

Computer simulation of energy recovery from animal manures should be extended in the following areas:

(i) A three-dimensional heat transfer approach should be developed to calculate heat losses from digester walls, floor and roof.

(ii) The model could be modified to be used at fluctuating digester operating conditions in regard to pH, alkalinity, un-ionized volatile acids and inhibitory substances.

(iii) The value of the temperature coefficient for gas production used in this model should be verified experimentally and new temperature coefficients should be developed for DOT ranges other than that used in this study. Also, values of the temperature coefficient for washout time should be developed.

(iv) Optimization techniques should be used to determine the optimum digester operating conditions in relation to the cost of digester installation and operation.

(v) The model should be adapted for other types of manure, soil, wall and insulation materials and climatic conditions.

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APPENDICES

APPENDIX A

APPENDIX A.1 MODEL NOTATION AND FORTRAN VARIABLES

Model notation	FORTRAN Variables	Model notation	FORTRAN Variables
a_o, $a_1 \ldots a_6$	A0, A1...A6	k_f	KF
A_{o_a}	AI	k_j	K(I)
A_r	AR	k_s	CDSOL
A_s	AS, AGS	k_{T_1}	RK35
A_{w_a}	AGA	k_{T_2}	RK(L)
A_o^1	A0	ℓn	ALOG
A_o	AI0	n	NWS, NR
A_{o_a}	AI	P	RME
A_1	AI1	Q_f	QF
$b_1 \ldots b_6$	B1...B6	Q_r	QR
C	C	Q_{w_a}	QWA
D	DI	Q_{w_s}	QWS
g_t	GPR1	Q_{w_1}	QW1
G_m	GPRM	Q_{w_2}	QW2
h_i	HI	Q_{L_s}	QLS
h_o	HO	Q_{L_A}	QLA
H_L	HL	r_i	R1
H_S	HS	r_j	R(I)
H_T	HT	r_{n+1}	RSN, RWS(NWS+1), R(M+1)
k	K		
k_a	KA		

r_{os}	RSD
r_s	RS
R_g	RK
S_f	SF
SRT	SRT
t	D
t_o	SRTO
t_{T_1}	SRTO35
t_{T_2}	SRTO(L)
T_a	T2, TA
T_i	T1
T_ℓ	T1, T3, TML, TMLL
T_s	TS
T_{sa}	TSOIL
T_z	TSF
T_I	TI
TSC	DCS
U_a	UA
U_f	UF
U_r	UR
U_s	US
U_{w_a}	UGA
U_{w_s}	UGS
V_a	V
W_I	W
x_f	XF
x_j	XR(I)
z_a	SDFT
θ	THETA
ρ_w	SPWS
ω_n	AR1...AR6
π	PI

APPENDIX A.2 ALPHABATICAL INDEX OF FORTRAN NOTATION USED IN THE SIMULATION MODEL

A	Dilution factor
AA	Outer surface area of walls above liquid level normal to heat flow between levels H_S and H_L (m^2)
AD1...AD6	Constants for soil temperature model
AF	*
AGA	*
AGS	*
AI	*
AI0	*
AI1	*
ALOG	*
AMBST	Array to store ambient soil temperatures
AO	*
AR	*
AR1....AR6	Constants for air temperature and soil temperature models (rad day^{-1})
AS	*
AS0	Fourier constant for soil temperature (^oC)
AS1,...AS6	Fourier coefficients with cosine terms for soil temperature model (^oC)
A0	Fourier constant for air temperature model (^oC)
A1....A6	*
BS1...BS6	Fourier coefficients with sine terms for soil temperature model (^oC)
B1....B6	*
C	*
CDSOL	*

*Cross notation between Appendix A.1 and list of symbols.

CEMP	Efficiency of mixing unit (%)
CFS	Concentration of tresh manure produced (%)
CHECK	Subroutine used to calculate ambient and elevated soil temperatures at desired depths
CUMTHA	Cumulative sum of total heat losses (W)
D	*
DCS	*
DI	*
DM	Dry manure produced (kg per 1 000 kg liveweight)
DREQD	Dilution required
EFCHN	Efficiency of heating system (%)
ELEVST	Array used to store elevated soil temperatures
EMA	Array used to store mixing energy requirements
ENPA	Array used to store net energy production
EPR	Energy production rate (J day^{-1})
FB	Free board (m)
GMP	Volume of methane produced (m^3 day^{-1})
GPR	Total gas produced (m^3 day^{-1})
GPR1	*
GRM	Volume of gas required for mixing (m^3 day^{-1})
GROEA	Array used to store cumulative gross energy production
HI	*
HIEA	Array used to store influent heating requirements
HL	*
HO	*
HOIL	Equivalent amount of heating oil to annual net energy production (dm^3 yr^{-1})
HS	*

HT	*
HVM	Heating value of methane (J m^{-3})
HVOIL	Heating value of heating oil (J dm^{-3})
I	Dummy variable
IHD	Soil depth around digester walls between levels H_S and H_L (cm)
IHL	Depth of liquid level in digester (cm)
IHS	Depth of digester below soil surface (cm)
II	Dummy variable
IK	Dummy variable
IN	Dummy variable
INCD	Increment in days of year for one run of model (day)
INDAY	Starting day of run (day)
IR	Dummy variable
ITS	Increment in soil depth around digester walls to compute heat losses (cm)
IW	Dummy variable
IWA	Dummy variable
J	Dummy variable to change total solids concentration
JIM	Dummy variable
JJ	Dummy variable to change solids retention time
JO	Dummy variable
K	*
KA	*
KF	*
KK	Dummy variable
KR	*
KWS	Thermal conductivity of digester wall and insulation materials below soil surface (W m^{-1} K^{-1})

L	Dummy variable to change temperature
LDD	Array used to store consecutive days of year
M	Number of digester wall and insulation materials above soil surface
MAXD	Maximum day of run
MM	Dummy variable
NEP	Net energy production rate (J day^{-1})
NR	Number of roof materials
NSC	Number of total solids concentration data
NSRT	Number of solids retention time data
NTV	Number of digester operating temperature data
NWS	Number of digester wall and insulation materials under soil
NYEAR	Code for normal year
N1	Number of growing hogs
N2	Number of finishing hogs
PI	3.141559
PMG	Fraction of methane in total gas produced
PMGP	Percentage of methane in total gas produced (%)
PRODEA	Array used to store energy production rate
QF	*
QI	*
QL	Heat loss from digester (J day^{-1})
QLA	*
QLS	*
QR	*
QT	Total energy required to maintain digester operating temperature (J day^{-1})

QTH	Total heat losses from digester walls, roof and floor (J day^{-1})
QWS2	Heat loss from digester walls below liquid level when $H_L < H_S$ (W)
QW1	*
QW2	*
R	*
RK	*
RK35	*
RME	*
RS	*
RSD	*
RSN	*
RS(1)	*
RTA1	Thermal resistance of digester walls above soil surface (m^2 K W^{-1})
RTA2	Thermal resistance of digester walls above soil surface (m^2 K W^{-1})
RTA3	Thermal resistance of digester walls above soil surface (m^2 K W^{-1})
RTA11	Thermal resistance of digester walls above soil surface and below liquid level (m^2 K W^{-1})
RTA22	Thermal resistance of digester walls above soil surface and below liquid level (m^2 K W^{-1})
RTA33	Thermal resistance of digester walls above soil surface and below liquid level (m^2 K W^{-1})
RTR	Thermal resistance of roof (m^2 K W^{-1})
RTR1	Over-all thermal resistance for heat transfer from roof (m^2 K W^{-1})

RTS1	Thermal resistance of digester walls below soil surface (m^2 K W^{-1})
RTS2	Thermal resistance of digester walls below soil surface (m^2 K W^{-1})
RTS3	Thermal resistance of digester walls below soil surface (m^2 K W^{-1})
RTS22	Over-all thermal resistance of digester wall below soil surface (m^2 K W^{-1})
RVST	Ratio of volatile to total solids in the manure slurry
RWS	Radius of digester wall and insulation materials below soil surface (m)
R1	*
R(1)	*
SDFT	*
SF	*
SINGH	Subroutine used to calculate mixed liquor temperature
SPWS	*
SRT	*
SRTO	*
SRTO35	*
STEEL	Subroutine used to calculate ambient and elevated soil temperatures at desired depths
STEMP	Subroutine used to calculate ambient soil temperature at any depth
STUF	Soil temperature under floor (K)
SUMGEP	Sum of gross energy production (J day^{-1})
SUMHLW	Sum of heat losses from walls (J day^{-1})
SUMNEP	Sum of net energy production (J day^{-1})
SUMTHL	Sum of total heat losses (J day^{-1})

TA	*
TAIR	Array used to store air temperature
TDS	Total mass of dry solids produced (kg day^{-1})
TEMPS	Subroutine used to calculate elevated soil temperature at any depth
THETA	*
TI	*
TINF	Influent temperature (^{o}C)
TINFL	Array used to store influent temperature
TML	*
TMLL	*
TOHLA	Array used to store total energy required for digester operation
TONEA	Array used to store cumulative net energy production
TS	*
TSF	*
TSFF	Array used to store temperature under floor
TSOIL	*
TWH	Total mass of hogs (kg)
TWS	Total mass of manure slurry produced (kg day^{-1})
T1	*
T1L	Mixed liquor temperature (^{o}C)
T1LL	Array used to store digester operating temperature
T2	*
T3	*
U	*
UA	*
UF	*

UGA	*
UGS	*
UR	*
US	*
UU	Over-all coefficient of heat transfer from digester walls above soil surface and below liquid level ($W\ m^{-2}\ K^{-1}$)
V	*
VLS	Amound of volatile solids produced (kg day^{-1})
W	*
WHLA	Array used to store cumulative heat required to heat influent
WM	Mass of wet manure produced (kg per 1000 kg of liveweight)
W1	Mass of growing hogs (kg hog^{-1})
W2	Mass of finishing hogs (kg hog^{-1})
X	*
XFLOOR	Thickness of floor materials (cm)
XR	*
XRF	Thickness of roof (cm)
XWA	Thickness of digester wall and insulation materials above ground level (m)
XWNS	Thickness of digester wall and insulation materials below ground level (m)
XWS	Thickness of digester wall and insulation materials above ground level (cm)
XWSL	Thickness of digester wall and insulation materials below ground level (cm)
Z	Soil depth (cm)

APPENDIX A.3 MATHEMATICAL MODEL IN FORTRAN STATEMENTS

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C     SIMULATION OF ENERGY RECOVERY FROM LIVESTOCK MANURES
C     THROUGH ANAEROBIC DIGESTION
C     THESE ARRAYS STORE INFORMATION REQUIRED FOR DATA PUNCHING
      DIMENSION AMBST(365,13),ELEVST(365,13)
      DIMENSION LDD(365)
C     LDD IS AN ARRAY TO STORE NUMBER OF DAYS
      DIMENSION TSFF(365)
      DIMENSION WHLA(365),HIEA(365),TOHLA(365),CUMTHA(365),EMA(365)
      DIMENSION GROEA(365)
      DIMENSICN PRODEA(365),ENPA(365),TONEA(365)
C     ***     ***  ***   ***   ***   ***   ***   ***   **  **  **   ****
      DIMENSION TINFL(365),TAIR(365)
      DIMENSION RK(5)  ,SRTO(5)
      DIMENSION R(10),K(10),X(10),RS(10),RWS(10)
C     RWS=RADIUS OF WALL MATERIAL UNDER SOIL IN M.
      DIMENSION DCS(5),SBT(5),T1(5)
      INTEGER SDFT ,D,Z
      REAL KWS(10),XWS(10)  ,KR(10),XR(10)
C     KWS=THERMAL CONDUCTIVITY OF WALL MATERIALS UNDER SOIL(W/M.K)
C     XWS=THICKNESS OF WALL MATERIALS UNDER SOIL(M.)
C     KR=THERMAL CONDUCTIVITY OF ROOF MATERIALS (W/M.K)
C     XR=THICKNESSES OF ROOF MATERIALS IN M.
C     NWS=NUMBER OF WALL MATERIALS UNDER SOIL
      DIMENSION XRF(5),XWSL(5),XWA(5)
      REAL  K,KA,KF
      REAL NEP
C     **********         ***********           ***********
      READ171,HI
C     HI=IN SIDE FILM COEFFICIENT (W/SQ.M-K)
      READ171,HO
C     HO=OUT SIDE FILM COEFFICIENT (W/SQ.M-K)
      READ171,KA
C     KA=COEFFICIENT OF CONDUCTANCE FOR GAS (W/SQ.M-K)
      READ171,CDSOL
C     CDSOL=THERMAL CONDUCTIVITY OF SOIL (W/M-K)
      READ171,C
C     C=SPECIFIC HEAT OF SLURRY IN J/KG.-K
      READ172,SDFT
C     SDFT=SOIL DEPTH UNDER FLOOR WHERE DIGESTER TEMP HAS NO EFFECT IN CM.
      READ171,RSD
C     RSD=RADIUS OF SOIL SLAB WHERE DIGESTER TEMPERATURE IS NOT HAVING
C     ANY EFFECT ON SOIL TEMPERATURE (M.)
      READ171,THETA
C     THETA=TEMPERATURE COEFFICIENT
      READ171,RVST
C     RVST=RATIO OF VOLATILE SOLIDS TO TOTAL SOLIDS
      READ171,RK35
C     RK=REACTION RATE CONSTANT CALCULATED FROM FINAL REPORT DATA
      READ171,PMG
C     PMG=FRACTION OF METHANE IN GAS PRODUCED(0.67)
      READ171,HS
C     HS=HEIGHT OF TANK UNDER SOIL
      READ172,ITS
C     ITS=INCREMENT IN THE THICKNESS OF SOIL
      READ171,FB
C     FB IS FREE BOARD OVER LIQUID SURFACE WHICH IS GENERALLY 0.60 M.
      READ171,CEPM
C     CEPM=COMBINED EFFICIENCY OF PUMP AND MOTOR (60%)
      READ171,EFCHN
C     EFCHN=EFFICIENCY OF HEATING UNIT(%)
      READ171,SRTO35
C     SRTO35=WASH-OUT TIME FOR 35(DEG. C) TEMPERATURE
      READ171,GRM
C     GRM=GAS REQUIRED TO MIX THE SLURRY IN ONE HOUR(CU.M/1000 CU.M OF VOLUME)
      READ171,DM
C     DM=DRY MANURE PRODUCED IN KG/1000KG OF LIVE WEIGHT
```

```
      READ171,WM
C     WM=WET MANURE PRODUCED BY HOGS KG/1000KG LIVE WEIGHT
      READ171,GPRM
C     GPRM=MAXIMUM GAS PRODUCTION L./GM.VS-ADDED
      READ171,SPWS
C     SPWS=SPECIFIC WEIGHT OF SLURRY (KG/CU.M)
      READ172,N1
C     N1=NUMBER OF GROWING PIGS
      READ172,N2
C     N2= NUMBER OF FINISHING HOGS
      READ171,W1
C     W1=AVERAGE WEIGHT OF GROWING HOGS
      READ171,W2
C     W2=AVERAGE WEIGHT OF FINISHING HOGS(KG.)
      READ173,NR,(KR(J),J=1,NR),(XR(J),J=1,NR)
C     NR=NUMBER OF ROOF MATERIALS
      READ193,NWS,(KWS(I),I=1,NWS),(XWS(I),I=1,NWS)
      READ193,M,(K(I),I=1,M),(X(I),I=1,M)
      READ174,XF,KF
C     XF=THICKNESS OF FLOOR  IN M.
C     KF=THERMAL CONDUCTIVITY OF FLOOR (W/M.K)
      READ175,NSC,NSRT,NTV
C     NSC=NUMBER OF SOLIDS CONCENTRATION VARIABLES
C     NSRT=NUMBER OF SRT VARIABLES
C     NTV=NUMBER OF TEMPERATURE VARIABLES
      DO 32 IN=1,NSC
 32   READ176,DCS(IN)
      DO 33 JO=1,NSRT
 33   READ176,SRT(JO)
      DO 34 JIM=1,NTV
 34   READ176,T1(JIM)
C     INDAY=INITIAL DAY TO START RUNS
C     MAXD=MAXIMUM DAY OF RUNS
C     INCD=INCREMENT IN DAY
      READ172,INDAY
      READ172,MAXD
      READ172,INCD
      READ172,NYEAR
      IF(NYEAR.NE.1) READ133,(TAIR(D),D=INDAY,MAXD,INCD)
 133  FORMAT(13F6.1)
 171  FORMAT(F10.3)
 172  FORMAT(I5)
 173  FORMAT(I2,5X,4(F7.5,1X))
 193  FORMAT(I2,5X,6(F7.5,1X))
 174  FORMAT(5X,2(F7.5))
 175  FORMAT(3(I2,2X))
 176  FORMAT(4X,(F4.,1X))
      DATA AR1,AR2,AR3,AR4,AR5,AR6/.0172,.03442,.05163,.06884,.08605,
     -.10326/
      DATA A0,A1,A2,A3,A4,A5,A6,B1,B2,B3,B4,B5,B6/1.877,-18.277,-1.41,
     10.724,0.114,0.043,0.272,-6.027,-1.259,-0.241,0.494,0.1,-0.426/
      DATA AI0,AI1/8.4,-9.6/
C     *********          ***********         **********            ********
      PI=3.141559
C     ***********             ************          ********       *******
C     GAS PRODUCTION IS A FUNCTION OF SRT AND TEMPERATURE
C     GPR1=DAILY GAS PRODUCTION RATE L./GM.-VS ADDED
C     GPR=TOTAL DAILY GAS PRODUCTTON (CU.M)
      HVM=37256973.39
C     HVM=HEATING VALUE OF METHANE (37256973.39 J/CU.M)
C     ************            *************         *********       **********
      PMGP=PMG*100
      DO 350 IR=1,NR
 350  XRF(IR)=XR(IR)*100
      DO 351 IW=1,NWS
 351  XWSL(IW)=XWS(IW)*100
```

```
      DO 352 IWA=1,M
352   XWA(IWA)=X(IWA)*100
      XFLOOR=XF*100
      PRINT400
400   FORMAT('1',50X,'EXPERIMENTAL DESIGN')
      PRINT401
401   FORMAT(' ',50X,19('-'))
      PRINT402
402   FORMAT('0',25X,'MATERIALS',10X,'THICKNESS',5X,'THERMAL CONDUCTIVIT
     $IES')
      PRINT403
403   FORMAT('0',46X,'(CM)',15X,'(W/M-K)')
      PRINT404
404   FORMAT(' ',25X,'---------',10X,'---------',5X,'-------------------
     $---')
      PRINT170
170   FORMAT('0',5X,'ROOF')
      PRINT405,XRF(1),KR(1)
405   FORMAT('0',20X,'1. CONCRETE (DRY)',10X,F5.2,12X,F6.4)
      PRINT406,XRF(2),KR(2)
406   FORMAT('0',20X,'2. URETHANE',16X,F5.2,12X,F4.2)
      PRINT177
177   FORMAT('0',5X,'WALLS')
      PRINT178
178   FORMAT('0',5X,'(1) BELOW GROUND LEVEL')
      PRINT408,XWSL(1),KWS(1)
408   FORMAT('0',20X,'1. CONCRETE(10%M.C.)',7X,F5.2,12X,F6.4)
      PRINT406,XWSL(2),KWS(2)
      PRINT407,XWSL(3),KWS(3)
      PRINT180
180   FORMAT('0',5X,'(2) ABOVE GROUND LEVEL')
      PRINT405,XWA(1),K(1)
      PRINT406,XWA(2),K(2)
      PRINT407,XWA(3),K(3)
407   FORMAT('0',20X,'3. FIR PLYWOOD',13X,F5.2,12X,F4.2)
      PRINT179
179   FORMAT('0',5X,'FLOOR')
      PRINT408,XFLOOR,KF
      PRINT409
409   FORMAT('0',5X,80('-'))
      PRINT410
410   FORMAT('0',50X,'OTHER PARAMETERS')
      PRINT401
      PRINT444,EFCHN
444   FORMAT('0',6X,'THIS STUDY ASSUMES ',F5.1,'% EFFICIENCY OF THE HEAT
     $ING SYSTEMS')
      PRINT445,CEPM
445   FORMAT('0',6X,'COMBINED EFFICIENCY OF PUMP AND MOTOR IS ',F5.1,'%
     $FOR  GAS RECIRCULATION MIXING')
      PRINT411,SDFT
411   FORMAT('0',6X,'SOIL DEPTH UNDER FLOOR WHERE DIGESTER TEMP. HAS NO
     $EFFECT=',I3,' CM.')
      PRINT428,RSD
428   FORMAT('0',6X,'DISTANCE FROM INNER SURFACE OF DIGESTER WHERE DIGES
     $TER TEMPERATURE HAS NO EFFECT=',F3.,' M.')
      PRINT412,THETA
412   FORMAT('0',6X,'TEMPERATURE COEFFICIENT=',F .3)
      PRINT413,RVST
413   FORMAT('0',6X,'RATIO OF VOLATILE SOLIDS TO TOTAL SOLIDS=',F4.2)
      PRINT414,RK35
414   FORMAT('0',6X,'REACTION RATE CONSTANT AT 35(C) TEMPERATURE=',F4.2)
      PRINT415,RMGP
415   FORMAT('0',6X,'PERCENTAGE OF METHANE IN GAS PRODUCED(%)=',F5.1)
      PRINT416,HS
416   FORMAT('0',6X,'HEIGHT OF DIGESTER UNDER SOIL=',F2.,' M.')
      PRINT417,ITS
```

```
417   FORMAT('0',6X,'INCREMENT IN THE THICKNESS OF SOIL=',I3,' CM.')
      PRINT418,DM
418   FORMAT('0',6X,'DRY MANURE PRODUCED=',F4.1,' KG/1000KG OF LIVE WEIG
     $HT')
      PRINT419,WM
419   FORMAT('0',6X,'WET MANURE PRODUCED=',F4.1,' KG/1000KG OF LIVE WEIG
     $GT')
      PRINT420,GPRM
420   FORMAT('0',6X,'MAXIMUM GAS PRODUCED DURING DIGESTION TIME=',F5.3,
     $' CU.M./KG V.S. ADDED')
      PRINT421,SPWS
421   FORMAT('0',6X,'SPECIFIC WEIGHT OF SLURRY=',F6.1,' KG/CU.M')
      PRINT422,N1
422   FORMAT('0',6X,'NUMBER OF GROWING PIGS=',I5)
      PRINT423,N2
423   FORMAT('0',6X,'NUMBER OF FINISHING HOGS=',I5)
      PRINT424,W1
424   FORMAT('0',6X,'AVERAGE WEIGHT OF GROWING PIGS=',F4.1,' KG PER HEAD
     $')
      PRINT425,W2
425   FORMAT('0',6X,'AVERAGE WEIGHT OF FINISHING HOGS=',F5.1,' KG PER HE
     $AD')
      PRINT426,CDSOL
426   FORMAT('0',6X,'THERMAL CONDUCTIVITY OF SOIL=',F5.3,' W/M-K')
      PRINT427,C
427   FORMAT('0',6X,'SPECIFIC HEAT OF SLURRY=',F8.3,' J/KG-K')
      PRINT701,HI
701   FORMAT('0',6X,'INSIDE FILM COEFFICIENT=',F5.2,' W/SQ.M-K')
      PRINT429,HO
429   FORMAT('0',6X,'OUT SIDE FILM COEFFICIENT=',F6.2,' W/SQ.M-K')
      PRINT430,KA
430   FORMAT('0',6X,'COEFFICIENT OF CONDUCTANCE FOR GAS=',F5.2,' W/SQ.M-
     $K')
C     **********          ***********          **********          **********
C     FLOOR IS MADE OF ONLY ONE MATERIAL ,CONCRETE
      SF=XF/KF*CDSOL
C     SF=SOIL THICKNESS EQUIVALENT TO FLOOR MATERIAL
C     **********          **********           *********           **********
      TWH=(N1*W1+N2*W2)
C     TWH=TOTAL WEIGHT OF HOGS (KG)
      TDS=TWH*DM/1000
C     TDS=TOTAL DRY SOLIDS IN KG
      TWS=TWH*WM/1000
C     TWS=TOTAL WEIGHT OF SLURRY WITHOUT DILUTION   (KG)
      VLS=RVST*TDS
C     VLS=VOLATILE SOLIDS PER DAY (KG)
      CFS=100.*DM/WM
C     CFS=CONCENTRATION OF FRESH SLURRY
      IF(NYEAR.NE.1) GO TO 900
      DO 35 D=INDAY,MAXD,INCD
      TAIR(D)=273+A0+A1*COS(AR1*D)+A2*COS(AR2*D)+A3*COS(AR3*D)+A4*COS(AR
     14*D)+A5*COS(AR5*D)+A6*COS(AR6*D)+B1*SIN(AR1*D)+B2*SIN(AR2*D)+B3*SI
     2N(AR3*D)+B4*SIN(AR4*D)+B5*SIN(AR5*D)+B6*SIN(AR6*D)
35    CONTINUE
900   CONTINUE
      DO 55 D=INDAY,MAXD,INCD
      TINFL(D)=273+AI0+AI1*SIN(AR1*(D+60))
55    CONTINUE
      DO 500 J=1,NSC
      PRINT70,DCS(J)
      PUNCH300,DCS(J)
70    FORMAT('1',6X,'DESIRED TOTAL SOLIDS CONCENTRATION OF MANURE(%)=',
     $F4.)
300   FORMAT(6X,'TOTAL SOLIDS CONCENTRATION IN SLURRY(%)=',F4.)
      A=CFS/DCS(J)
C     DCS=DESIRED CONCENTRATION OF SLURRY
```

```
      PRINT450,CFS
450   FORMAT('0',6X,'TOTAL SOLIDS CONCENTRATION OF MANURE AS RECEIVED(%)
     $=',F5.2)
      DREOD=A-1
      PRINT360,DREOD
360   FORMAT('0',6X,'DILUTION REQUIRED(CU.M/CU.M OF WET MANURE)=',F4.2)
      W=TWS*A
C     W=TOTAL WEIGHT OF SLURRY COMING DAILY IN THE DIGESTER    KG.
      DO 499 JJ=1,NSRT
      PRINT71,SRT(JJ)
      PUNCH301,SRT(JJ)
71    FORMAT('0',6X,'SOLIDS RETENTION TIME(DAYS)=',F4.)
301   FORMAT(6X,'SOLIDS RETENTION TIME(DAYS)=',F4.)
      V=W*SRT(JJ)/SPWS
C     V=TOTAL DIGESTER VOLUME REQUIRED   (CU.M)
C     FOR MINIMUM HEAT LOSS DI SHOULD BE EQUAL TO HL
C     AS  V=PI/4*(DI)**3
C     WHEN DI IS EQUAL TO HL , V=PI*(DI)**2*HL/4 WILL BE
      DI=(4.*V/PI)**(1/3.)
      HL=DI
      PRINT201,DI
      PUNCH302,DI
201   FORMAT('0',6X,'DIAMETER OF DIGESTER(M.)=',F5.2)
302   FORMAT(6X,'DIAMETER OF DIGESTER(M.)=',F5.2)
      DO 100 L=1,NTV
      T1L=T1(L)-273
      PRINT210,T1L
210   FORMAT('0',6X,'DESIRED OPERATING TEMPERATURE OF DIGESTER=',F4.,' D
     $EGREE CELSIUS')
      PUNCH303,T1L
303   FORMAT(6X,'DESIRED OPERATING TEMPERATURE OF DIGESTER(C.)=',F4.)
      PRINT72
72    FORMAT('0','-----------------------------------------------------
     $-----------------------------------------------------------------
     $----------')
      PRINT21
      PRINT22
      PRINT23
      PRINT31
31    FORMAT(' ','-----------------------------------------------------
     $-----------------------------------------------------------------
     $----------')
21    FORMAT(' ',' HEAT LOSS |ENERGY USED|TOTAL HEAT |  SUMTHL   |ENERGY
     $ FOR |ENERGY PRO-|   SUMGEP  | NET ENERGY|   SUMNEP  | DAY| AMB. |
     $DIGE-|INFLU.')
22    FORMAT(' ',' THROUGH    | TO HEAT   |  LOSS      |            | MIXIN
     $G    |  DUCTION  |           |PRODUCTION |           | OF |TEMP. |
     $STER |TEMPE-')
23    FORMAT(' ','  WALLS     |INFLUENT   |            |            |
     $     |   RATE    |           |   RATE    |           |YEAR|OF AIR|
     $TEMP.|RATURE')
C     **********          **********          *********         **********
      SUMHLW=0
C     SUMHLW=SUM OF HEAT LOSSES THROUGH WALL
      SUMTHL=0
C     SUMTHL=SUM OF TOTAL HEAT LOSSES
      SUMGEP=0
C     SUMGEP=SUM OF GROSS ENERGY PRODUCTION
      SUMNEP=0
C     SUMNEP=SUM OF NET ENERGY PRODUCTION
      DO 99 D=INDAY,MAXD,INCD
      LDD(D)=D
C     TI=INFLUENT TEMPERATURE
      TI=TINFL(D)
      IF(T1(L).LT.TI)GO TO 101
C     PROGRAM CALCULATES ENERGY LOSSES OVER ONE DAY PERIOD
```

```
      QI=F*C*(T1(L)-TT)
C     QI=ENERGY REQUIRED TO HEAT INFLUENT IN JOULES
      GO TO 102
C     IF TEMPERATURE OF DIGESTER IS LESS THAN THE TEMPERATURE OF INFLUENT,
C    1 THIS PROGRAM FINDS OUT THE NEW MIXTURE TEMPERATURE BASED ON STEADY STATE
 101  QI=0
      TML=(TI+T1(L)*(SRT(JJ)-1))/SRT(JJ)
C     TML=TEMPERATURE OF MIXED LIQUOR SLURRY
      T1(L)=TML
 102  CONTINUE
      T3=T1(L)
      R(1)=DI/2.
      RS(1)=R(1)
      R1=R(1)
      DO 5   I=1,M
 5    R(I+1)=R(I)+X(I)
      RWS(1)=R(1)
      DO 6  II=1,NWS
 6    RWS(II+1)=RWS(II)+XWS(II)
      XWNS=RWS(NWS+1)-R(1)
      T2=TAIR(D)
C        ********************            *****************           ************
C     THIS PROGRAM CONVERTS THICKNESS OF INSULATION MATERIALS EQUIVALENT TO
C     SOIL  THICKNESS  UNDER-GROUND
      DO 4 I=1,NWS
      RS(I+1)=RS(I)*((RS(I)+XWS(I))/RS(I))**(CDSOL/KWS(I))
 4    CONTINUE
C     RS=RADIUS OF EQUIVALENT SOIL THICKNESS
      RSN=RS(NWS+1)
C     **********          ********         *********          ***********
      HT=HL+FB
      IF(HL-HS)2,2,3
 2    CONTINUE
      RTS1=0
      DO 10 I=1,NWS
 10   RTS1=RTS1+(RWS(NWS+1)*ALOG(RWS(I+1)/RWS(I))/KWS(I))
      U=1./RTS1
      IHL=HL*100
C     IHL=HEIGHT OF LIQUID LEVEL IN THE DIGESTER IN CM.
      QW1=0
      KK=1
      DO 41 Z=1,IHL,ITS
      AO=2.*PI*RWS(NWS+1)*ITS/100
      CALL TEMPS(D,Z,T3,R1,RSN,RSD,TSOIL,TS)
      CALL CHECK(KK,D,Z,AMBST,ELEVST,T3,R1,RSN,RSD,TSOIL,TS)
      QW1=QW1+U*AO*(T1(L)-TS)
 41   CONTINUE
      AGA=2.*PI*R(M+1)*(HT-HS)
      RTA1=0
      DO 11  I=1,M
      RTA1=RTA1+R(M+1)*ALOG(R(I+1)/R(I))/K(I)
 11   CONTINUE
      RTA11=RTA1+R(M+1)/(HI*R(1))+1./HO
      UGA=1./RTA11
      RTS2=0
      DO 12 I=1,NWS
      RTS2=RTS2+RWS(NWS+1)*ALOG(RWS(I+1)/RWS(I))/KWS(I)
 12   CONTINUE
      RTS22=RTS2+RWS(NWS+1)/(HI*R(1))
      UGS=1./RTS22
      IHD=(HS-HL)*100
C     IHD=DIFFERENCE LIQUID HEIGHT AND SOIL HEIGHT IN CM.
      QWS2=0
      IF(IHD.EQ.0) GO TO 60
      KK=1
      DO 42 Z=1,IHD,ITS
```

```
      AGS=2.*PI*RWS(NWS+1)*ITS/100
      CALL TEMPS(D,Z,T3,R1,RSN,RSD,TSOIL,TS)
      CALL CHECK(KK,D,Z,AMBST,ELEVST,T3,R1,RSN,RSD,TSOIL,TS)
42    QWS2=QWS2+UGS*AGS*(T1(L)-TS)
60    CONTINUE
      QW2=QWS2+UGA*AGA*(T1(L)-T2)
      GO TO 40
3     CONTINUE
      AA=2.*PI*R(M+1)*(HL-HS)
      AI=2.*PI*R(M+1)*(HT-HL)
      RTS3=0
      DO 25 I=1,NWS
      RTS3=RTS3+RWS(NWS+1)*ALOG(RWS(I+1)/RWS(I))/KWS(I)
25    CONTINUE
      US=1./RTS3
      RTA3=0
      DO 20  I=1,M
20    RTA3=RTA3+R(M+1)*ALOG(R(I+1)/R(I))/K(I)
      RTA2=RTA3
      RTA22=RTA2+1./HO
      UA=1./RTA22
      RTA33=RTA3+R(M+1)/(HI*R(1))+1./HO
      UU=1./RTA33
      IHS=HS*100
C     IHS=SOIL DEPTH IN CM.
      QLS=0
      KK=1
      DO 43 Z=1,IHS,ITS
      AS=2.*PI*RWS(NWS+1)*ITS/100
      CALL TEMPS(D,Z,T3,R1,RSN,RSD,TSOIL,TS)
      CALL CHECK(KK,D,Z,AMBST,ELEVST,T3,R1,RSN,RSD,TSOIL,TS)
      QLS=QLS+US*AS*(T1(L)-TS)
43    CONTINUE
      QLA=UA*AA*(T1(L)-T2)
      QW1=QLS+QLA
      QW2=UU*AI*(T1(L)-T2)
40    CONTINUE
      AR=(PI*DI**2)/4.
C     AR=AREA OF ROOF
      AF=AR
C     AF=AREA OF FLOOR
      RTR=0
C     RTR IS THERMAL RESISTANCE OF ROOF
      DO 13 I=1,NR
13    RTR=RTR+XR(I)/KR(I)
      RTR1=RTR+1./HI+1./KA+1./HO
      UR=1./RTR1
      QR=AR*(T1(L)-T2)*UR
C     EFFECT OF DIGESTER TEMPERATURE ON FLOOR
C     NO INSULATION IS NEEDED FOR UNDER GROUND AND FLOOR
      UF=1./(XF/KF)
C     UF=HEAT TRANSFER COEFFICIENT THROUGH FLOOR
C     TSF=SOIL TEMPERATURE UNDER FLOOR
      CALL STEMF(D,SDFT,STUF)
      TSF=((SDFT/100.-SF-HS)*T1(L)+STUF*SF)/(SDFT/100.-HS)
      TSFF(D)=TSF-273
      QF=AF*(T1(L)-TSF)*UF
C     QF=HEAT LOSS THROUGH FLOOR
      QL=(QR+QW1+QW2+QF)*24*3600
C     QL IS HEAT LOSS IN JOULES PER DAY
      QTH=QL+QI
C     QTH=TOTAL HEAT LOSSES WITHOUT EFFICIENCY FACTOR
      QT=QTH*100/EFCHN
C     QT=TOTAL HEAT LOSSES WITH EFFICIENCY FACTOR
      IF(QT.LT.0) CALL SINGH(QT,TMLL,SRT,W,C,T1,L,JJ)
      IF(QL.LT.0) CALL SINGH(QT,TMLL,SRT,W,C,T1,L,JJ)
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      RK(L)=RK35*THETA**(T1(L)-308)
      SRTO(L)=SRTO35*THETA**(308-T1(L))
      GPR1=GPRM*(1-EXP(-RK(L)*(SRT(JJ)-SRTO(L))))
      IF(GPR1.LT.0.0) GPR1=0.0
      GPR=GPR1*VLS
C     ENERGY REQUIRED FOR MIXING (1 HOUR DAILY)
      RME=GPM*V*HL*9.804*100/CEPM
C     RME=REQUIREMENT OF MIXING ENERGY (J)
      GMP=PMG*GPR
C     GMP=VOLUME OF METHANE PRODUCED (CU.M)
      EPR=HVM*GMP
C     EPR=ENERGY PRODUCTION RATE PER DAY (J)
      NEP=EPR-QT-RME
C     NEP=NET ENERGY PRODUCTION (J)
      SUMHLW=SUMHLW+QL
      SUMTHL=SUMTHL+QT
      SUMGEP=SUMGEP+EPR
      SUMNEP=SUMNEP+NEP
      Z=300
      CALL STEEL(D,Z,AMBST,ELEVST,T3,R1,RSN,RSD,TSOIL,TS)
      T1LL=T1(L)-273
      TA=T2-273
      TINF=TI-273
      WHLA(D)=QL
      HIEA(D)=QI
      TOHLA(D)=QT
      CUMTHA(D)=SUMTHL
      EMA(D)=RME
      PRODEA(D)=EPR
      GROEA(D)=SUMGEP
      ENPA(D)=NEP
      TONEA(D)=SUMNEP
      PRINT19,QL,QI,QT,SUMTHL,RME,EPR,SUMGEP,NEP,SUMNEP,D,TA,T1LL,TINF
 19   FORMAT('0',9(E11.4,1X),1X,I3,2X,F5.1,1X,F5.1,F5.1)
 99   CONTINUE
      PRINT72
C     SUM OF NET ENERGY IS BEING CONVERTED TO EQUIVALENT AMOUNT OF HEATIG OIL
C     THE HEATING VALUE OF HEATING OIL WAS TAKEN AS 40.05 E 09(J/CU.M)
C     HOIL=EQUIVALENT AMOUNT OF HEATING OIL (LITRE)
C     HVOIL=HEATING VALUE OF HEATING OIL
      HVOIL=40.05*(10**6)
      HOIL=SUMNEP/HVOIL
      PRINT498,HOIL
 498  FORMAT('0','THE SUM OF NET ENERGY PRODUCTION IS EQUIVALENT TO=',
     $E11.4,' LITRES OF HEATING OIL')
      PRINT77
      PUNCH304
 304  FORMAT(10X,'HEAT LOSS THROUGH WALLS')
      PUNCH306,(WHLA(D),D=INDAY,MAXD,INCD)
 306  FORMAT(3X,7(E11.4))
      PUNCH501
 501  FORMAT(15X,'INFLUENT HEAT LOSS')
      PUNCH306,(HIEA(D),D=INDAY,MAXD,INCD)
      PUNCH373
 373  FORMAT(15X,'TOTAL HEAT LOSS')
      PUNCH306,(TOHLA(D),D=INDAY,MAXD,INCD)
      PUNCH375
 375  FORMAT(15X,'MIXING ENERGY ')
      PUNCH306,(EMA(D),D=INDAY,MAXD,INCD)
      PUNCH376
 376  FORMAT(15X,'ENERGY PRODUCTION RATE')
      PUNCH306,(PRODEA(D),D=INDAY,MAXD,INCD)
      PUNCH378
 378  FORMAT(15X,'NET ENERGY PRODUCTION RATE')
      PUNCH306,(ENPA(D),D=INDAY,MAXD,INCD)
      PRINT78,XWNS
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78    FORMAT('0',5X,'DAY OF      ELEVATED SOIL TEMPERATURE (C) AT A DISTA
     $NCE OF=',F5.2,' M. FROM INNER SURFACE OF WALLS')
      PRINT74
      PRINT75
      PRINT76
      PRINT77
90    FORMAT('0',6X,I3,9X,13F6.1)
      DO 81 D=INDAY,MAXD,INCD
81    PRINT90,D,(ELEVST(D,MM),MM=1,13)
      PRINT77
      PRINT85,SF
85    FORMAT('0',15X,' ELEVATED TEMPERATURE UNDER FLOOR(DEG. CELS.)AT=',
     $F4.2,' M. BELOW FLOOR TOP')
      PRINT77
      PRINT86,(LDD(I),I=INDAY,MAXD,INCD)
      PRINT74
      PRINT87,(TSFF(I),I=INDAY,MAXD,INCD)
      PRINT77
86    FORMAT('0',5X,'DAY',5X,15(1X,I3,2X))
87    FORMAT('0','TEMPERATURE',2X,15(F5.1,1X))
100   CONTINUE
499   CONTINUE
500   CONTINUE
      PRINT73
73    FORMAT('0',5X,'DAY OF',20X,'AMBIENT SOIL TEMPERATURE IN DEG. CELSI
     $US')
      PRINT74
74    FORMAT(' ',6X,'YEAR',6X,'-----------------------------------------
     $----------------------------------------')
      PRINT75
75    FORMAT(' ',45X,'SOIL DEPTHS (CM.)')
      PRINT76
76    FORMAT(' ',20X,' 0     25     50     75    100    125    150    175    2
     $00    225    250    275    300')
      PRINT77
77    FORMAT(' ','--------------------------------------------------------
     $--------------------------------------------')
      DO 80 D=INDAY,MAXD,INCD
80    PRINT90,D,(AMBST(D,II),II=1,13)
      PRINT77
      PRINT505
505   FORMAT('0'10X,'EFFECT OF DIGESTER OPERATING TEMPERATURE ON REACTIO
     $N RATE AND WASH-OUT TIME')
      PRINT77
      PRINT502
502   FORMAT('0',15X,'TEMPERATURE',5X,'REACTION RATE',5X,'WASH-OUT TIME'
     $)
      PRINT77
      DO 504 L=1,3
504   PRINT503,T1(L),RK(L),SRTO(L)
503   FORMAT('0',18X,F6.1,12X,F6.3,12X,F4.1)
      PRINT77
      STOP
      END
C     ***********        **********         *********        ***********
C     THIS IS FIRST SUBROUTINE SUBPROGRAM
      SUBROUTINE STEMP(D,Z,TSOIL)
      INTEGER D,Z
      DATA AR1,AR2,AR3,AR4,AR5,AR6/.0172,.03442,.05163,.06884,.08605,
     -.10326/
      DATA AD1,AD2,AD3,AD4,AD5,AD6/.00644,.0091,.0112,.013,.0144,.016/
      DATA AS0,AS1,AS2,AS3,AS4,AS5,AS6,BS1,BS2,BS3,BS4,BS5,BS6/4.894,
     1-10.919,1.157,-.0908,.03134,.5188,.02733,-5.129,.5735,.1188,
     2-.3651,.3319,.06805/
      TSOIL=273+AS0+EXP(-AD1*Z)*(AS1*COS(AR1*D-AD1*Z)+BS1*SIN(AR1*D-AD1*
     1Z))+EXP(-AD2*Z)*(AS2*COS(AR2*D-AD2*Z)+BS2*SIN(AR2*D-AD2*Z))+EXP(-A
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     2D3*Z)*(AS3*COS(AR3*D-AD3*Z)+BS3*SIN(AR3*D-AD3*Z))+EXP(-AD4*Z)*(AS4
     3*COS(AR4*D-AD4*Z)+BS4*SIN(AR4*D-AD4*Z))+EXP(-AD5*Z)*(AS5*COS(AR5*D
     4-AD5*Z)+BS5*SIN(AR5*D-AD5*Z))+EXP(-AD6*Z)*(AS6*COS(AR6*D-AD6*Z)+
     5BS6*SIN(AR6*D-AD6*Z))
      RETURN
      END
C     ***********          **********          *********          ***********
C     THIS IS SECOND SUBROUTINE SUBPROGRAM
      SUBROUTINE TEMPS(D,Z,T1,R1,RSN,RSD,TSOIL,TS)
      INTEGER D,Z
      CALL STEMP(D,Z,TSOIL)
      IF(RSN.GT.(R1+RSD)) GO TO 59
      TS=(TSOIL-T1)*ALOG(RSN/R1)/ALOG((R1+RSD)/R1)+T1
      GO TO 61
 59   TS=TSOIL
 61   RETURN
      END
C     ***********          **********          *********          ***********
C     THIS IS THIRD SUBROUTINE SUBPROGRAM
      SUBROUTINE SINGH(OL,TMLL,SRT,W,C,T1,L,JJ)
      DIMENSION SRT(5),T1(5)
C     TMLL=MIXED LIQUOR TEMPERATURE AFTER EFFECT OF SOIL HEAT FROM OUTSIDE
      TMLL=ABS(OL)/(W*SRT(JJ)*C)+T1(L)
      T1(L)=TMLL
      OL=0
      RETURN
      END
C     ***********          **********          *********          ***********
C     THIS IS FOURTH SUBROUTINE SUBPROGRAM
      SUBROUTINE STEEL(D,Z,AMBST,ELEVST,T3,R1,RSN,RSD,TSOIL,TS)
      DIMENSION AMBST(365,13),ELEVST(365,13)
      INTEGER D,Z
      IF(Z.NE.1) GO TO 3
      Z=0
      IK=1
      CALL TEMPS(D,Z,T3,R1,RSN,RSD,TSOIL,TS)
      Z=IK
      GO TO 5
  3   CONTINUE
      IK=Z/25+1
  5   AMBST(D,IK)=TSOIL-273
      ELEVST(D,IK)=TS-273
      RETURN
      END
C     ***********          **********          *********          ***********
C     THIS IS FIFTH SUBROUTINE SUBPROGRAM
      SUBROUTINE CHECK(KK,D,Z,AMBST,ELEVST,T3,R1,RSN,RSD,TSOIL,TS)
      DIMENSION AMBST(365,13),ELEVST(365,13)
      INTEGER D,Z
      IF(Z/25-KK+1)5,2,5
  2   CALL STEEL (D,Z,AMBST,ELEVST,T3,R1,RSN,RSD,TSOIL,TS)
      KK=KK+1
  5   RETURN
      END
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