ANAEROBIC TREATMENT ANALYSIS OF CONCENTRATED HOG WASTES

by

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A B S T R A C T

Due to the development of intensive livestock production methods - namely, high-density confinement feeding - animal wastes traditionally looked upon as "natural" or "background" wastes, are now being subject to the same restrictions, as regards disposal, as industrial wastes. As a result waste treatment of some nature has become necessary. Such treatment methods would reduce the amount of solids requiring disposal and make the liquid portion more acceptable for disposal to water courses or for re-use. Anaerobic lagooning is one such method of waste treatment of concentrated animal wastes.

An investigation on a laboratory-scale of the effects of various parameters on the anaerobic decomposition of hog waste was undertaken. Included in this study was the effect of varied detention times and temperatures on such waste characteristics as oxygen demand, solids, nutrients and gas composition and production. The final outcome of this program was to add some degree of optimization to the anaerobic waste treatment method and to develop improved design guidelines related to this specific field.

All recommendations presented are based on laboratory findings. Correlation between laboratory-scale results and field-scale results was not attempted in this portion of the study.

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CHAPTER I

INTRODUCTION

1.1 General Discussion

In the past decade, for a number of reasons, farmers have found it necessary to concentrate greater numbers of agricultural animals onto more confined land areas [1]. Along with the new concepts of farming, these farmers are confronted with new problems, one of which is disposal of the resulting animal wastes. Previous to this when large areas of land were available, traditional land disposal of animal wastes was a suitable solution. But land disposal methods for the newly developing high density, confinement farms are no longer acceptable due primarily to:

(i) the diminished relative value of animal wastes as a fertilizer;

(ii) the quantity of raw waste being too great for direct land disposal without creating nuisance conditions;

(iii) the pollution problems created by wastes reaching surrounding water courses or ground waters.

As a result, the need for waste management by alternate methods has become essential [2]. During the past ten years the alternative to waste disposal by traditional manure spreading has been biological waste treatment. Those waste treatment schemes which have been utilized successfully are:

(1) activated sludge systems

(2) oxidation ditches

(3) aerated lagoons (mechanical aeration)

(4) anaerobic lagoons.

Field studies on all of these treatment processes have shown that the effluent produced can conform to standards set by most regulatory agencies. It seems then that the trend in design for future "factory-farms" is well outlined. In order to comply to the standards of the appropriate regulatory agency, in cases where land disposal is no longer adequate, some form of biological waste treatment is necessary.

The National Hog Centre at Abbotsford, B.C. is the first large-scale high density hog-raising facility to be established in the Fraser Valley. From this installation 22,000 marketable hogs per year will be born, weaned, and finished within buildings whose total floor area is 100,000 sq. ft. The resulting volume and strength of waste from such an industry is considerable. As this waste is to be discharged into the Fraser River, the Provincial Pollution Control Branch (PPCB) stipulated that waste treatment be provided. However, because knowledge of the waste load or characteristics was lacking, the degree of treatment to be provided was not specifically stipulated. The National Hog Centre retained a consulting firm which studied numerous treatment schemes and derived a working arrangement which was agreeable to both the PPCB and National Hog. The firm's study of treatment schemes took into consideration anticipated waste characteristics, treatment efficiencies, land area requirements, initial capital outlay and present land values. The final proposal involved treatment by anaerobic lagoons. The overall plans included built-in versatility so that mechanical aeration devices could be installed if treatment efficiency had to be increased.

1.2 Design and Layout of Treatment Facilities

(a) Design

The treatment accepted by the PPCB, consisted of a three-cell system. The first two cells, or primary lagoons, are of 300,000 cu. ft. capacity each with a water depth of 15 feet. These were built to act as settling ponds with the added benefit of anaerobic biological activity. During routine farm operation the two primary ponds are used alternately one "resting" while the other is in service. Removal frequency of accumulated sludge from alternate cells was estimated to be every three to five years. This removed sludge would be well degraded, reduced in volume and suitable for land disposal.

The third cell of the system was designed for 100,000 cu. ft. capacity with a water depth of 11 feet. It accepts the liquid overflow from whichever primary cell is in use and provides further detention for the supernatant. Anaerobic decomposition of the dissolved and colloidal organics continues in this cell. The overflow from this final cell is continually chlorinated and discharged to the Fraser River. It is to this third cell that mechanical aeration devices will be added if an increase in treatment efficiency becomes necessary.

(b) Layout

The plan and elevation views of the lagoon facilities are illustrated in Figure 1-1.

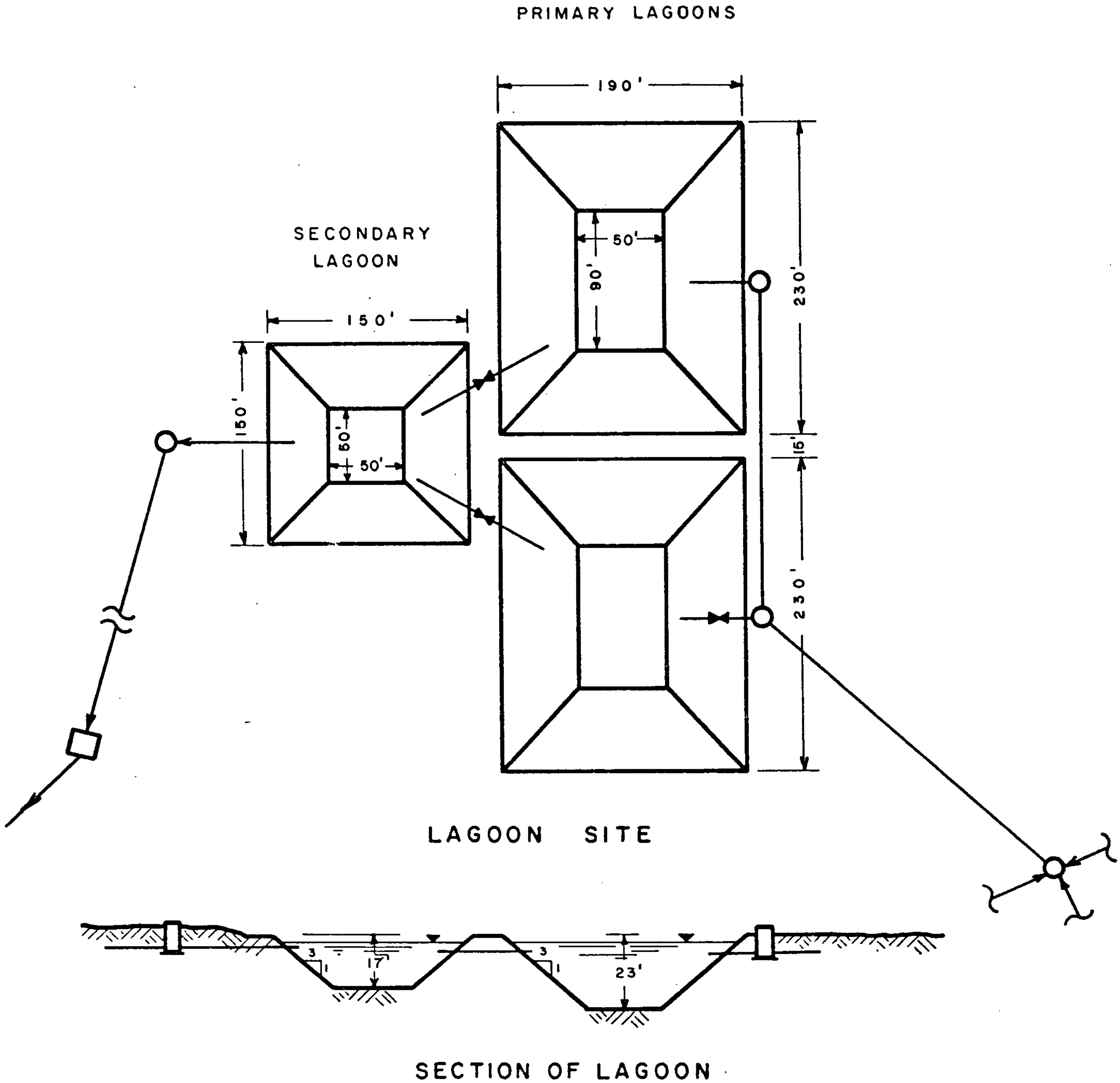


FIGURE 1-1

PLAN & ELEVATION VIEWS OF THE

LAGOON FACILITIES

1.3 Fundamentals of Anaerobic Lagoons

The object in lagooning of concentrated animal wastes is to stabilize to some degree the incoming organics by biological means. The biological anaerobic process may be generally described as three-phase

(i) Hydrolysis of complex material;

(ii) Acid production - conversion of complex organics in the raw waste to mostly acid intermediate-products by acid-forming bacteria;

(iii) Gas production - conversion of the acid intermediate-products to methane and carbon dioxide largely by methane forming bacteria.

In order for this system to be successful, the raw waste must have a high food value so as to sustain the metabolic activity of the bacteria. The food value is measured by the concentration of biochemical oxygen demand (BOD) and volatile suspended solids (VSS). The higher these values are the more suitable the food source is for anaerobic digestion.

Initially the solids in animal wastes are in suspension and a large portion of the solids settle out in the primary lagoon. However, as opposed to the usual separation and removal of settled solids, the settled solids are allowed to accumulate in the lagoon and the accumulated solids provide a suitable substrate for anaerobic breakdown. The overlying waste-water containing dissolved and colloidal solids blankets the settled solids and serves two important functions:

(i) it has a high oxygen demand which prevents diffusion of free oxygen to the bottom deposits, and;

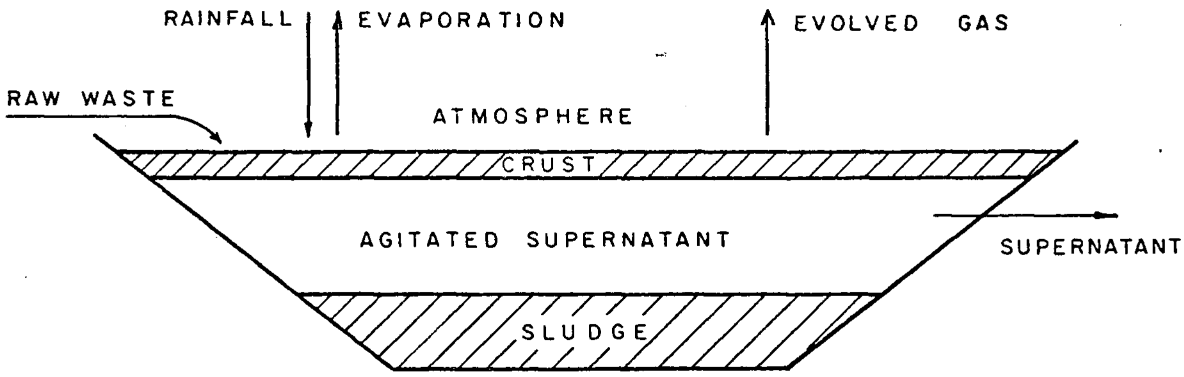
(ii) it provides a buffering mechanism through dilution and dispersion for shock waste loadings.

Under these conditions the anaerobic bacteria thrive in the lagoons and degrade the organic solids with consequent production of methane (CH_4), carbon dioxide (CO_2) and trace gases. The evolved gas bubbles to the surface and finally diffuses to the atmosphere.

Anaerobic lagooning then is a combined two-part process of (1) solids removal and concentration by settling and (2) organics reduction by biological means. It should be noted that the resulting effluent strength is still considerable due in part to resuspension of solids by gas agitation and to incomplete breakdown of the organics. A cross-section of a typical lagoon is shown in Figure 1-2.

1.4 Comparison of Field Lagoon and Laboratory Digester

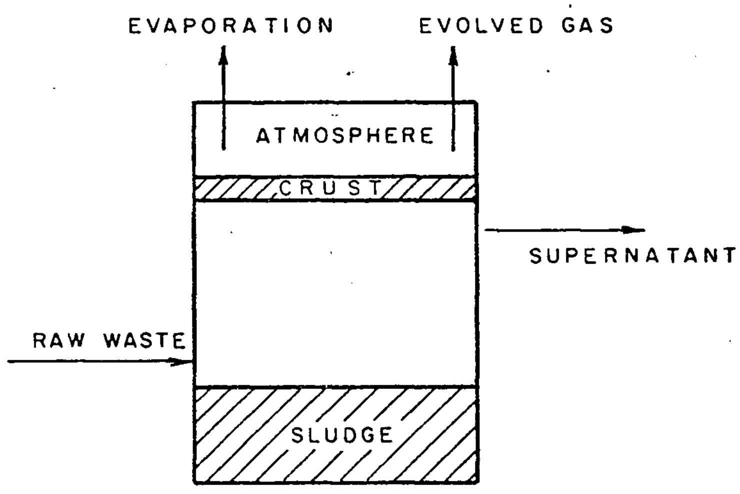
Laboratory-scale anaerobic reaction vessels were built to simulate the primary field lagoon. Following the work with lab digesters the subsequent step would be field studies which would be conducted to correlate the lab-scale and full-scale results. If successful in this area of the work it would become possible to test the anaerobic treatability of most animal wastes in the laboratory and determine with acceptable accuracy the design criteria that must be used on the full-scale installations to achieve a given treatment efficiency. A cross-section of the laboratory



Sludge — Consists of settled solids plus anaerobes
Agitated Supernatant — Includes dissolved and colloidal solids; re-suspended solids due to gas agitation; plus anaerobes
Crust — Consists of volatile matter plus grain hulls, hair, and wood fibres
Evolved Gas — Consists of CH_4, CO_2 plus trace gases
Atmosphere — O_2, N_2 plus trace gases

FIGURE 1-2

SECTION OF FIELD ANAEROBIC LAGOON



Atmosphere — CH_4, CO_2 plus trace gases

FIGURE 1-3

SECTION OF LABORATORY ANAEROBIC DIGESTER

digester is shown in Figure 1-3 and can be compared to the field facility illustrated in Figure 1-2. An aerial view of the farm and a photograph of the laboratory set-up are shown in Figures 1-4 and 1-5.

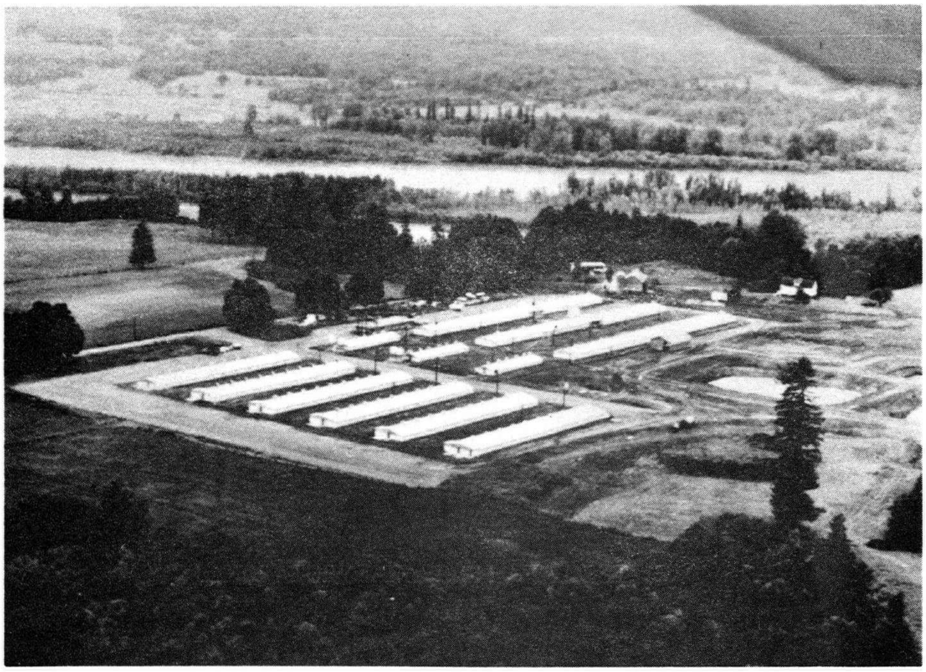
1.5 Need for Improved Design Criteria

Guidelines for the design of the anaerobic lagoons in use at the National Hog Centre were determined from knowledge of treatment efficiencies of operating facilities in the United States and from design guidelines which had evolved over the years from experience with these lagoons. With the many uncertainties involved in the design and operation of anaerobic lagoons for concentrated animal wastes and because of a lack of definite design parameters for lagoons, this laboratory study was undertaken to develop improved design guidelines.

The general design of a lagoon can be simple if no consideration is given to the workings within the lagoon. The designer, given the average characteristics and flow of the raw waste, the required effluent quality (as set by the regulatory agency) and the field study data collected on similar existing facilities can determine a workable lagoon volume for adequate treatment. Considering only the "in" and "out" waste values is not wholly adequate. Essential items which are missing in such a design method are:

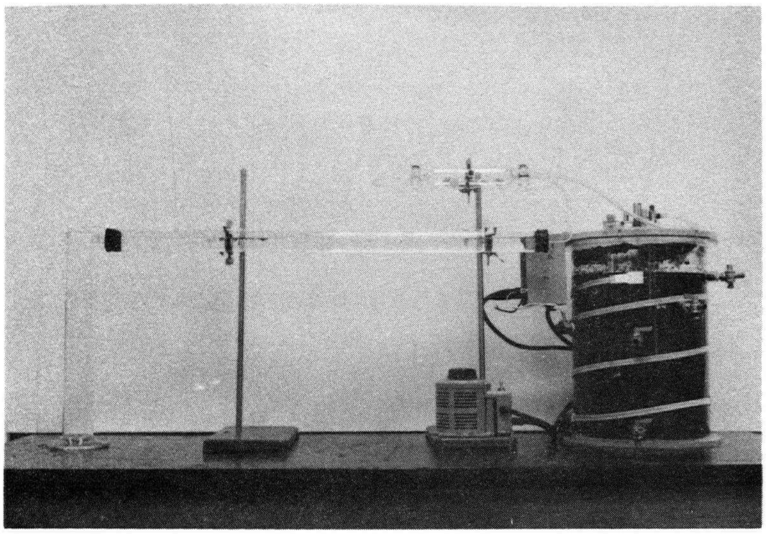
(i) the rate of build-up of solids and hence the required frequency of sludge removal;

(ii) the rate of organic solids destruction by anaerobic bacteria;



AERIAL VIEW OF HOG BARNS AND
ANAEROBIC LAGOONS

FIGURE 1-4



LABORATORY ANAEROBIC DIGESTER

FIGURE 1-5

(iii) the effect of solids build-up on treatment efficiencies;

(iv) the effect of temperature on the waste treatment operation;

(v) the effect of gas evolution in mixing the lagoon contents and on the quality of the lagoon effluent.

These then were some of the specific points which this research study centered on. Included with the study and related to the above points were the effects of such parameters as raw waste loading rate and nutrient concentration. In the final analysis the purpose of this study was to provide information which would assist in optimizing criteria for the design of anaerobic treatment for concentrated animal wastes.

CHAPTER II

LITERATURE REVIEW

2.1 General Discussion

Early manure lagoons were often mistakenly patterned after aerobic lagoons without due consideration to the animal waste characteristics or the principles involved in treating such wastes. Recent literature on design criteria for lagoons specifically states that manure pond design should be based on volume considerations rather than on surface relationships so commonly used to design waste water ponds [3,4,5,6,7,8,9]. As anaerobic bacteria need neither sunlight nor oxygen for survival, surface area requirements need not even be considered in this scheme of treatment design. Consequently, present design methods have been developed on a volumetric basis. Some of the parameters which have been quoted for designing lagoon facilities are:

(i) cu. ft. of lagoon/lb. of animal;

(ii) lb. BOD/cu. ft. of lagoon/day;

(iii) lb. volatile solids (VS)/cu. ft. of lagoon/day.

In the first case, all that is required to determine the lagoon volume is the total weight of animals to be accommodated while the second and third design procedures require some knowledge of the animal waste characteristics and the amount of waste produced per day. Of these three design parameters, the first two are gaining wider acceptance. This is due to the fact that livestock manures usually contain large quantities of hay stems, grain hulls and similar non-biodegradable but volatile matter. Thus the lb. VS/cu. ft. of lagoon/day is inappropriate and less reliable in determining adequate lagoon sizes. Some of the values obtained from field research and which have been used for design are outlined in Table I.

Removal efficiencies reported on a few of the above lagoons by these same researchers show:

75-80% total solids (TS) removal,

85-90% VS and chemical oxygen demand (COD) removal,

60-70% BOD removal.

It should be noted however that these values are misleading and one must not lose sight of the fact that lagooning essentially affords primary treatment for the incoming waste and the effluent is still rather potent.

2.2 Solids

Related to the high per cent removal of VS for concentrated animal wastes is the decrease in effective waste retention capacity of the lagoon due to solids accumulation [9]. The sludge build-up rate has been found to be a function of both the loading rate of VS, the rate of biological degradation of VS and also to some extent to the washout of VS. But even a balanced microbial population will not reduce all the organic material to gaseous end-products and inevitably a finite service life for waste lagoons will be reached (i.e. solids build-up will become a problem). Two alternative solutions to this problem offered by present design

TABLE I

FIELD STUDY DESIGN PARAMETERS FOR ANAEROBIC LAGOONS TREATING HOG WASTES

Reference #	Researcher	Required Lagoon Volume
3	Hart & Turner	2.5-5.0 lb VS/1000 ft^3/day
	Clark	475 ft^3/hog
	Dornbush & Anderson	130-170 ft^3/hog
	Hart & Turner	124 ft^3/animal
4	Ricketts	0.3 ft^3/lb animal
	Willrich	1.6 ft^3/lb animal
	Anon	0.9 ft^3/lb animal
	Willrich	1.8 ft^3/lb animal
	Eby	0.4-1.4 ft^3/lb animal
	Willrich	1.0-2.0 ft^3/lb animal
5	Curtis	75-100 ft^3/hog
8	White	10-20 lb BOD/1000 ft^3/day
9	Dornbush	15-20 lb BOD/1000 ft^3/day
	Dornbush & Anderson	5-10 lb VS/1000 ft^3/day

procedure are:

(1) periodic dredging without consideration of sludge depth;

(2) designing a given sludge storage life into the lagoons by estimating the cu. ft. of sludge produced/100 lb. animal/year [3], and the rate of solids degradation. From this a dredging frequency of the lagoon could then be calculated based on a predetermined level for maximum solids build-up.

The second estimate assumes a constant solids concentration for the sludge. This is a rough estimate only, for as the sludge accumulates within the pond it compacts and occupies less space. This would alter any original design estimate for cleanout frequency.

2.3 Temperature

Biological activity under anaerobic conditions is extremely temperature sensitive [3,5,8,9]. As reported from laboratory studies and verified by field studies, anaerobic action is vigorous under summer temperature conditions (25-35°C) with little activity under winter temperature conditions (0-10°C).

Of equal concern is the rate at which temperature fluctuations occur within the treatment system. It has been determined that a slow rate of temperature change allows anaerobic bacteria to adjust somewhat to the new conditions and to continue biological activity. On the other hand, rapid temperature fluctuations have been found to completely arrest anaerobic action [12]. In order to provide protection and insulation against rapid temperature changes, lagoon design criteria should include minimizing exposed surface area and maximizing depth.

2.4 pH and Nuisance Odours

During the operation of a successful lagoon the pH should be maintained near neutral with an optimum range from 6.8-7.2. Variances from these conditions result in malodourous conditions and decreased biological activity. Dornbush [9] describes this situation:

> "Meager information seems to point the accusing finger at sludge accumulations on the bottom of lagoons as being a major source of nuisance odors. With low temperatures or an inadequate population of methane formers, the first stage of digestion, that of acid formation, will proceed within the sludge accumulations. The resulting organic acids would quickly exceed the limited buffering within the sludge deposits and the pH would begin to drop to further limit the performance of the methane formers.
>
> Organic acids would be expected to accumulate and an acid sludge bank or "pocket" would develop. It is hypothesized that these acid sludge banks are a major source of odors in lagoons. Odors will be produced in the acid sludge until this localized "pickling" environment is altered either through dispersion by mixing, pH adjustment, or development of an adequate population of methane formers to break down the acids."

2.5 Gas Production and Composition

McCarty [11] outlines the relationship between waste stabilization and methane gas formation as:

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

From this equation it is theoretically possible to predict the quantity of methane produced from a knowledge of the waste chemical composition during complete breakdown of the waste.

The ultimate oxygen demand of methane gas may be described as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (2)$$

Equation (2) allows prediction of COD or BOD_L (ultimate BOD) stabilization from the volume of methane produced. This chemical equation shows one mole of methane is equivalent to two moles of oxygen. Further calculation shows that 5.62 cu. ft. CH_4 (STP) will be produced per lb. of oxygen utilized. Measured values for methane production per pound of COD or BOD_L stabilization for a wide variety of wastes from pure laboratory substrates to complex wastes have shown the validity of this relationship and the close accuracy with which it can be used to predict methane production [10,11].

Gas agitation is also important. Gas agitation appears to improve the lagoon action by redistributing and making available undigested organic material for bacterial utilization [3,4,5]. Design for mechanical mixing is therefore usually not necessary if vigorous biological activity can be maintained. Gas mixing within the lagoon is indicated by the constant raising of bottom sludge to the lagoon surface [7].

With regard to gas composition, the gaseous end-products consist of methane, carbon dioxide and trace gases. Taiginides [6], studying anaerobic digestion of hog wastes at 35°C, reported that during successful anaerobic treatment of swine wastes 59% of the gas was methane and 40% carbon dioxide.

2.6 Detention Time

In addition to the organic loading to the lagooning system mentioned in section 2.1, the waste retention time must also be given consideration. Eckenfelder [10] states that:

> "...sufficient time must be available in the reactor to permit growth of the organisms or they will be washed out of the system."

It has been determined that the methane bacteria growth rate governs and that for detention times of less than 7 days some organisms will begin to be washed out of the treatment system.

2.7 Successful Lagoon Design and Operation

Recommended general procedures for hog waste lagoon design and operation are summarized from the available literature [5,8,9,10] and are as follows:

(a) Design -

(i) volume requirements should be based on 3/4-1½ cu. ft./lb. animal; 10-20 lb. BOD/1000 cu. ft./day or 3.5-7.0 lb. VS/1000 cu. ft./day with consideration for sludge volume build-up (15-20 cu. ft./100 lb. hog/year);

(ii) rapid temperature fluctuations which adversely affect methane producing bacteria should be minimized in the lagoon by minimizing the exposed surface area and maximizing the depth;

(iii) in order to avoid severe retardation of biological activity the temperature in the lagoon should not drop below a specified minimum (i.e. 20°C);

(iv) in order to prevent the possible contamination of surrounding water supplies the soil characteristics and location of the lagoon should be considered with regard to infiltration, ground water table and uncontrolled runoff due to storms;

(v) the retention banks of the lagoon should be sloped adequately to ensure soil stability;

(vi) the raw waste should be discharged into the central area of the lagoon through submerged inlets. Baffles should be provided at the outlets to decrease the possibility of short-circuiting;

(vii) a fence should be provided around the lagoon as a safety precaution.

(b) Operation -

(i) if possible the operation of the lagoon should commence in late spring or early summer to take advantage of the natural warming trend to aid in establishing a viable bacteria culture;

(ii) the pH range should be between 6.8 and 7.4 since the bacteria are most active at neutral pH;

(iii) the design water level should be maintained so that the solids are covered at all times and not in direct contact with atmospheric oxygen. This allows immediate and continuous anaerobic digestion of solids.

CHAPTER III

EXPERIMENTAL PROCEDURE

3.1 General Discussion

All necessary initial preparations had been completed in advance of the starting time for this study. This included a literature investigation on hog waste characteristics and treatment, a program for the field collection of raw wastes and design of a tentative set of experiments for the analysis of both raw waste and effluent samples. The experimental procedures used are outlined in Standard Methods [15] and further explained in Chemistry for Sanitary Engineers [16]. Additional preparations included the assembly of four model digesters of 25 litre capacity constructed from transparent acrylic plastic (Figure 1-5), the design of a gas collection apparatus and the design of a suitable method for gas analysis.

Three of the digester units were temperature controlled while the temperature of the fourth digester was allowed to maintain ambient room temperature (18°-23°C). External heating tapes regulated by a thermostat mechanism were used to maintain two of the digester temperatures (25°C and 30°C). Since the ambient laboratory temperature was continually above 18°C, the 10°C digester unit was cooled by internal cooling coils. The type of thermostat mechanism used with this unit was identical to that in the heated digesters. In this case however the thermostat simply activated a cooling water circulation pump as required.

With the 25 litre capacity of the digester units to work with, some range of detention times had to be decided upon. An upper limit of 50 days was chosen because it represented a realistic figure in terms of the field lagoons at Abbotsford. Working from this upper limit, the detention times were to be decreased over a period of months in a stepwise manner to some lower limit. This lower limit was expected to be the point at which treatment efficiency would be markedly reduced. The initial detention time represented a daily feeding rate of ½ litre of raw waste to each digester.

Equipped with this outline the aim then was to collect sufficient and satisfactory experimental data through the various detention periods. This represented daily and weekly waste sampling, completing experiments in duplicate and triplicate, and re-running experiments where large changes or discrepancies in the raw waste or effluent characteristics occurred. It was anticipated that this testing program would determine the effects of settling, temperature, and detention time on the anaerobic digestion process.

For clarity the experimental procedure is divided into four major headings:

(i) establishing and operating the model digester units;

(ii) digester temperatures;

(iii) testing procedure for the effluent and influent;

(iv) testing procedure for the evolved gas.

3.2 Establishing and Operating the Model Digester Units

A number of months were required to establish a viable culture of anaerobic bacteria in the digesters which would act predictably to imposed loadings. During those months, familiarity was gained with the waste characteristics and with the required lab techniques. The first attempt at culturing the anaerobes failed due to an excessive raw waste feeding rate. In order to rectify this situation without the aid of chemicals the digestors were allowed to "sit" with no further addition of raw waste until the anaerobes were active again. Once the bacteria re-established themselves a feeding program was begun. Initially a low feeding rate was used. The feeding rate was increased progressively until the digesters operated successfully at 400 mg BOD_5/litre of digester/day. There was no comprehensive data gathering attempted at this time.

During the intensive test period that followed, feeding of the digesters was done daily with the exception of double doses on Fridays and Mondays in order to compensate for the lack of feeding on the weekends. Feeding was done in a manner which essentially excluded entry of atmospheric oxygen to the digester. This was accomplished by simultaneously draining off a volume of effluent and adding an equal volume of raw waste. The digester gas line was closed during this operation in order to maintain positive pressure within the digester.

Since mechanical mixing was not used on any of the units in order to simulate field conditions, the solids accumulation was quite noticeable. The solids accumulation however gave little trouble during the feeding or sampling procedure. Any attempts to directly measure solids build-up proved fruitless because of gas lens formations which separated and lifted the sludge continually, and because of crust formations at the liquid surface.

3.3 Digester Temperatures

Of the three digester units initially on-line, two were temperature controlled by thermostat units. Using the previously described arrangement for temperature control, the temperature and temperature sensitivity for those two digester units was 25±1°C and 30±1°C.

The third unit was operated at room temperature with no thermost control. For this unit, through the Spring and Summer months of testing the average temperature of the digester contents gradually increased and then through late Summer and Fall months slowly fell off. The minimum-maximum digester temperatures recorded during this period were 17°C and 25°C with the usual range of 18-23°C.

The fourth digester unit was completed later, and was identical to the other three except that cooling coils of copper tubing lined the inside perimeter of the digester. Cooling water was forced through these lines by a thermostatically controlled pump. The controlled temperature was maintained at 10±1°C.

The one difficulty encountered with this unit was thermal layering between the bottom sludge and the overlying liquid layer. This problem was caused by poor vertical positioning of the cooling coils. In order to remedy this situation, the digester contents were occasionally stirred.

During the start-up of the fourth digester, seeding material from the other three digesters was utilized with a supplement of raw waste. The liquid temperature was gradually lowered from 20°C to 10°C over a one month period. Using the previously outlined feeding procedure a bacterial culture acclimated to 10°C was established. From then on the testing and feeding procedure used on this digester was the same as that for the other three. With this unit, however, sludge build-up was even more pronounced than in the heated digesters. By early Fall the build-up had interfered with the sampling and feeding procedure. At this point some sludge was drained and discarded. This was done only once with this digester.

3.4 Testing Procedure for the Influent and Effluent

As required during the study, eight-hour composite samples of raw waste were obtained from the outfall sewer at the hog farm. About 100 to 150 litres of raw waste were collected on each occasion. Sampling was done from the sewer line leading from the barns at the manhole closest to the point of discharge into the lagoons (Figure 1-1). The filled carboys were delivered to a refrigerated storage facility at UBC. Refrigeration was necessary in order to minimize bacterial growth and activity. The carboys of raw waste were then used individually for feeding and testing purposes. For the analysis of the raw waste samples, a grab sample of mixed raw waste was taken from each carboy being used.

The samples taken for testing of the settled liquid portion of the digesters were also grab samples. This sampling however, was done regularly during the middle of each week. In the event that testing was delayed for one or more days for either raw waste or effluent, the samples were immediately refrigerated until the analysis was performed.

Tests in triplicate were performed on both the mixed raw waste and digester supernatant. The experimental procedures followed are outlined in the twelfth edition of Standard Methods [15]. The tests performed were:

(1) Phosphate (page 231)

(2) Alkalinity (page 369)

(3) Total and Organic Kjeldahl Nitrogen (page 402 & 404)

(4) Biochemical Oxygen Demand (BOD) (page 415)

(5) pH Value (page 422)

(6) Total and Volatile Solids (TS & VS) (page 423)

(7) Chemical Oxygen Demand (COD) (page 510)

It was also necessary due to the high waste strength, to dilute the test samples. Through repeated trials the dilution factors for the raw waste and the effluent from each digester were determined. These values remained fairly constant throughout the subsequent testing period. For purposes of accurate control all dilutions were made using appropriate pipettes, volumetric flasks and distilled water.

3.5 Testing Procedure for the Evolved Gas

A properly functioning anaerobic digester evolves primarily CH_4 and CO_2, with traces of some other gases. In the case of a flow-through system with a uniform feed, the two primary gases would be evolved in a relatively constant ratio for the given operating conditions. Determination of this ratio during testing would possibly aid in showing

(1) any upset or inbalance in the digester by the variation in the gas ratio,

(2) the effect of temperature on the composition of the evolved gas.

Actual analysis of the constituents of the evolved gas was completed on a research gas chromatograph with a thermal conductivity detector unit. The detector was temperature programmed.

After some literature review, a series of columns and packings were tested with standard gas samples of CH_4, CO_2, H_2S and NH_3. The packing finally decided upon was chosen because it separated most effectively the gas constituents and also gave distinguishable peaks for these gas constituents. A typical gas chromatogram is shown in Figure 3-1.

The details of the model and columns are:

Model - Hewlett-Packard 5752B

Column - 16' × 1/8" ϕ SS

Packing in Column - 8' Poropack Q 50-80 Mesh +
8' Poropack R 50-80 Mesh

Gas for the purpose of analysis was collected in a glass chamber fitted with a gas sampling port. The samples were then extracted with a syringe and analyzed on the gas chromatograph. Testing at the start was done three times weekly but as the study progressed a weekly analysis was deemed sufficient.

Measurement of the rate of gas production and total production of gas during a 24 hour period was accomplished through a water-gas displace-

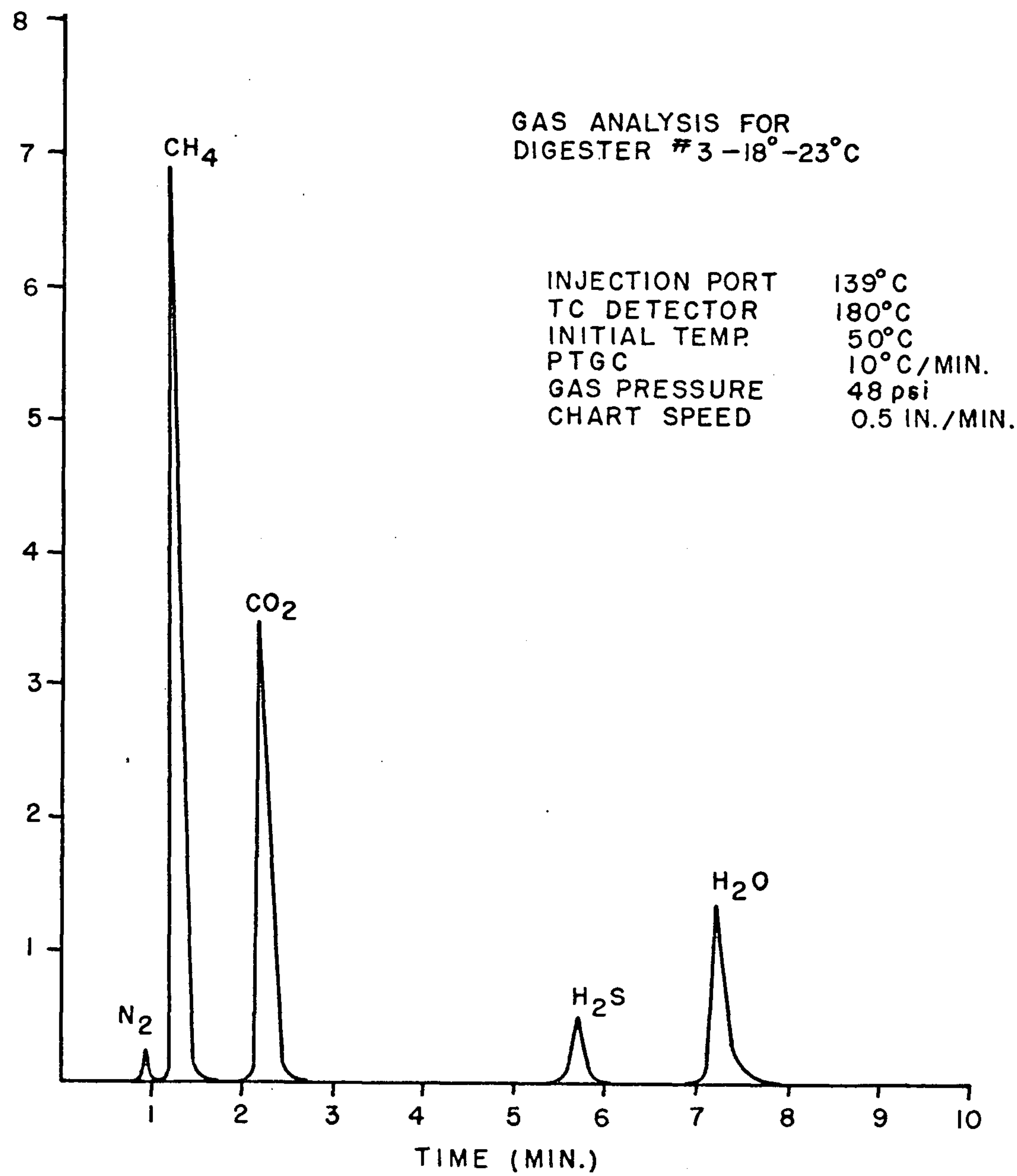


FIGURE 3-1

CHROMATOGRAM OF DIGESTER GAS

ment mechanism (see Figure 1-5). By this method, water which had previously been in contact with digester gas in order that the water be saturated with dissolved digester gas, was contained in a rigid plastic tube. As gas evolved, an equal volume of water was displaced. (The configuration of the plastic tube was designed so that a minimal back pressure acted on the digester system.) The displaced water was then collected in a graduated cylinder and the volume measured. A record was also kept of the time required to displace a specific volume of water, enabling periodic rate determinations for gas production.

During each 24 hour test period a record was kept of the average room temperature and local atmospheric pressure so that conversion to STP could be made.

Due to the crudeness of this equipment the results obtained were primarily valuable for comparison of digester operation rather than for absolute values of gas production.

3.6 Summary

Minor difficulties were encountered in all areas during the study but none of these adversely affected or changed the objectives of the program. The experimental data is shown in Appendix A. Discussion and conclusions with regard to these results are presented in the subsequent chapters.

CHAPTER IV

THE EFFECT OF DETENTION TIME

4.1 Introduction

The need for determining an optimum detention time for the raw waste is twofold. The required detention times must be sufficient to:

(i) provide adequate settling time for particulate matter;

(ii) provide intimate biological contact time in order that substantial bacterial degradation of organics can take place.

In this regard three areas were investigated: (1) influent and effluent concentrations of various waste parameters; (2) fluctuations or changes in effluent characteristics; (3) gas composition as affected by the loading rate.

4.2 General Discussion

In order to study the effects of different holding periods on swine wastes it was necessary to determine a broad yet practical range of detention times for these tests. As previously mentioned, an upper limit of 50 days was chosen to match the approximate field lagoon detention time and the lower limit was to be determined experimentally.

Solids were allowed to settle and accumulate in the digesters in order to simulate the field lagoons. Due to the constant daily accumulation of solids, the liquid detention time (LDT) was not constant (i.e.

the LDT calculated at the start of a specific feeding rate was reduced over a period of time because an increasing portion of the total volume was occupied by the accumulated solids, thereby reducing the liquid volume). No restriction however was placed on the detention time for the settled solids (solids detention time (SDT) >> LDT). As previously stated, attempts at measuring the gradual build-up of settled solids were unsuccessful. Thus no adjustment factor was determined to calculate the actual average LDT.

It should be noted that SDT is an important parameter to be considered with regard to anaerobic biological activity. However, any measurements of the sludge build-up and subsequent calculation of the average sludge age was impossible due to continuous gas lens formations in the sludge and overturning of the sludge. In this study therefore the possible effects on anaerobic digestion of sludge age was not further pursued.

In the following presentations the theoretical LDT (based on total digester volume and the volume of raw waste added daily) is tabled opposite the removal efficiencies rather than the true or actual LDT. This however, provided at the least a conservative estimate of removal efficiencies at the stated detention time (e.g. If the theoretical LDT is 50 days, the true average LDT because of solids build-up would be less than 50 days. The removal efficiencies tabled for a theoretical LDT of 50 days would probably be equal to or less than the removal at a true average LDT of 50 days.)

During the testing two primary characteristics of the raw waste and effluent were monitored:

(i) COD and BOD_5,

(ii) TS and VS

and two secondary characteristics:

(iii) total and organic nitrogen,

(iv) total phosphate.

Items (i) and (ii) are of primary importance in standard waste treatment policy (i.e. reducing particulate discharge into, and oxygen depletion in, receiving waters). Items (iii) and (iv) are important because of nutrient requirements for the anaerobic digestion process and because of nutrient addition to receiving waters. Nutrients will be further discussed in Chapter VII.

4.3 Average Raw Waste Characteristics

In calculating the average values presented in Tables II and III only those experimental results were considered which were recorded after the appropriate theoretical LDT had elapsed from the start of a given feed-rate phase. The final results of per cent removal based on theoretical LDT are presented in Table IV. These results are also graphically illustrated in Appendix B.

4.4 Discussion of Results

(a) Solids

From the results in Table IV the following comments can be made:

(i) excluding the results for LDT = 6 days,

TABLE II

AVERAGE RAW WASTE CHARACTERISTICS*

Theoretical LDT (Days)	BOD_5 (mg/ℓ)	COD (mg/ℓ)	TS (mg/ℓ)	VS (mg/ℓ)
50	9175	29550	-	-
25	9760	29900	28195	20800
12.5	9950	32770	27150	19020
6	9950	49100**	39700	31800

*Values for raw waste used in the calculations for the results in Table IV.

**The high COD value is due to the high volatile solids concentration in the final raw waste samples. It was also noted that the majority of the solids were feed chips and sawdust which rapidly settled out when a sample was left to stand. The BOD_5 value did not change to such an extent as did the other characteristics, indicating that a large portion of the volatile solids was essentially non-biodegradable.

TABLE III

AVERAGE EFFLUENT CHARACTERISTICS*

Temp. of Digester (°C)	Theoretical LDT (Days)	COD (mg/ℓ)	BOD_5 (mg/ℓ)	TS (mg/ℓ)	VS (mg/ℓ)
30	50	5025	1010	-	-
	25	5275	1170	7470	4265
	12.5	7540	1590	7060	3995
	6	6630	1095	6350	3660
25	50	5615	1100	-	-
	25	5390	1170	7470	4160
	12.5	7375	1690	7330	3995
	6	5645	1195	5560	3020
18-23	50	5760	1190	-	-
	25	5500	1465	7330	3950
	12.5	7210	1940	7060	3710
	6	5890	1790	5560	3020
10	50	-	-	-	-
	25	10665	5515	7610	4370
	12.5	15730	7265	8280	4850
	6	11295	5820	5560	3180

*The average values for the 6 day LDT were obtained from 2 samples.

TABLE IV

PER CENT REMOVAL OF COD, BOD_5, TS AND VS

Temp. of Digester (°C)	Theoretical LDT (Days)	Average Removal (%)*			
		COD	BOD_5	TS	VS
30	50	83.0	89.0	-	-
	25	82.5	88.0	73.5	79.5
	12.5	77.0	84.0	74.0	79.0
	6	86.5	89.0	84.0	88.5
25	50	81.0	88.0	-	-
	25	82.0	88.0	73.5	80.0
	12.5	77.5	83.0	73.0	79.0
	6	88.5	88.0	86.0	90.5
18-23	50	80.5	87.0	-	-
	25	81.5	85.0	74.0	81.0
	12.5	78.0	80.5	74.0	80.5
	6	88.0	82.0	86.0	90.5
10	50	-	-	-	-
	25	64.5	43.5	73.0	79.0
	12.5	52.0	27.0	69.5	74.5
	6	77.0	41.5	86.0	90.0

*The values for per cent removal for the 6 day LDT are questionable due to the unusually high solids contents in the last two raw waste samples used.

increasing the LDT from 12.5 to 25 days in the four digesters did not significantly improve solids removal;

(ii) for the 6 day LDT in the 30, 25 and 18-23°C digesters, the per cent removal for VS was 88.5-90.5% and for TS was 84-86%. Comparable removals of VS and TS occurred in the 10°C digester. As explained previously these unusual results for the 6 day LDT were probably due to the unusually high solids concentrations in the final raw waste samples.

(b) Oxygen Demand

Results similar to those obtained for solids removal were recorded for COD and BOD_5 removal (see Table IV). Observations to note were:

(i) increasing the LDT from 12.5 to 50 days in the 30, 25 and 18-23°C digesters only improved COD removal 3.5-6% and BOD_5 removal 5-6.5%;

(ii) over a range of 12.5-25 days LDT for the 10°C digester, COD and BOD_5 removal significantly improved;

(iii) for the 6 day LDT in the four digesters, the per cent removals are unusually high due probably to the high solids content in the final raw waste samples.

From these observations, it is apparent that the rapid settling characteristics of this waste is an important factor in treatment. With the high concentration of settleable VS in the waste, untreated discharges could have adverse effects upon receiving waters in the form of oxygen depletion and development of sludge banks. Consequently, for treatment of this type of waste, where 65-70% of the TS are organic, removal of VS by settling should be a prime design feature. The removal of solids would not only reduce the organic load in the effluent but the removed solids would also provide an adequate food source for further biological degradation. This degradation process could be accomplished by anaerobic means.

Two further points to note as shown by the experimental results are:

(i) for oxygen demand removal detention time is more critical at low temperatures (10°C) as compared to higher temperatures (20-30°C);

(ii) for the four digesters, the increase in per cent removal of solids as the LDT is extended may be attributed to longer settling time and improved settling conditions due to less vigorous gas agitation; and to further biological reduction of suspended VS because of increased contact time.

(c) pH and Alkalinity

Two quality parameters were monitored to help detect changes in the effluent characteristics. These parameters, pH and alkalinity, also aided in charting possible changes in bacterial activity.

Results for pH and alkalinity are shown in Table V and shown graphically in Appendix A.

As shown in Table V

(i) increasing the LDT for all digesters from 6 to 50 days, resulted in changes of pH only .2-.3 units. However, the variability in the daily pH readings were more noticeable as LDT decreased;

(ii) the increase in variability of the pH for the digester effluents during the 6 day LDT (see Appendix A) can be attributed to 16% of the total digester contents being displaced daily by raw waste. Random testing of the raw waste pH gave values ranging from 6.5-7.5;

(iii) with regard to alkalinity concentration of the effluent during the 6 day LDT, the results clearly show that displacing 16% by volume of the digester contents with raw waste (the alkalinity concentration of which was much lower) markedly affected the results for the four digesters.

From these observations for pH and alkalinity, the lower limit for detention time is primarily determined by the per cent by volume of the

TABLE V

EFFLUENT pH AND ALKALINITY

Temp. of Digester (°C)	Theoretical LDT (Days)	pH	Alkalinity (mg/ℓ)
30	50	7.4 - 7.5	-
	25	7.4 - 7.6	6800 - 8100
	12.5	7.5 - 7.6	7000 - 7600
	6	7.3 - 7.4	5700 - 6100
25	50	7.3 - 7.4	-
	25	7.4 - 7.5	6800 - 7900
	12.5	7.4 - 7.5	6900 - 7600
	6	7.3 - 7.4	5500 - 6000
18-23	50	7.3 - 7.4	-
	25	7.3 - 7.4	6800 - 7700
	12.5	7.3 - 7.5	6800 - 7400
	6	7.2 - 7.3	4900 - 5700
10	50	-	-
	25	6.8 - 6.9	5200 - 6100
	12.5	6.6 - 6.9	5000 - 5700
	6	6.6 - 6.8	3600 - 3800

digester contents that the raw waste displaces. Because of the variability of the raw waste characteristics and the quantity of raw waste added daily, the digester contents are significantly affected during the addition of raw waste (i.e. the pH and alkalinity of the digester contents becomes as variable as the raw waste pH and alkalinity). This in turn initiates a sequence of events. A greater portion of the anaerobic bacteria are washed out daily from the system; the optimum pH range for the bacteria is not consistently maintained; and, the buffering mechanism provided by the digester contents against low raw waste pH is reduced. As a result the biological balance of anaerobic bacteria is progressively destroyed, potentially causing upset conditions in the digestion process.

4.5 Gas Production and Composition

For each detention time, total gas volume produced and gas composition were recorded. The object here was to monitor changes in gas constituents and in gas volumes in order to indicate the level of biological activity.

(a) Volume

The total gas production per day from the 30, 25 and 18-23°C digesters increased as the raw waste loading rate was increased (see Table VI and Figure 4-1). Since the total gas produced is related to the bacterial population and to the quantity of substrate added per unit time, the result is then as expected.

During the 4 ℓ/day loading rate (6 days LDT), the daily gas production (based on linear extrapolations of the results from lower

TABLE VI

DAILY GAS PRODUCTION AS RELATED TO DETENTION TIME

Temp. of Digester (°C)	Theoretical LDT (Days)	Total Daily Gas Production (1) (mℓ/day @ STP)	Gas Production Prior to Raw Waste Addition (2) (mℓ/day @ STP)	Gas Produced from Raw Waste Added Daily (1-2) (mℓ/day @ STP)
30	50	6250	4430	1820
	25	12000	9260	2740
	12.5	24700	19500	5200
	6	28000	20900	7100
25	50	6600	4890	1710
	25	9800	7350	2450
	12.5	19500	15600	3900
	6	25000	18800	6200
18-23	50	5600	4100	1500
	25	9600	7700	1900
	12.5	17250	14300	2950
	6	22750	17750	5000
10	50	-	-	-
	25	500	250	250
	12.5	1250	600	650
	6	-	-	-

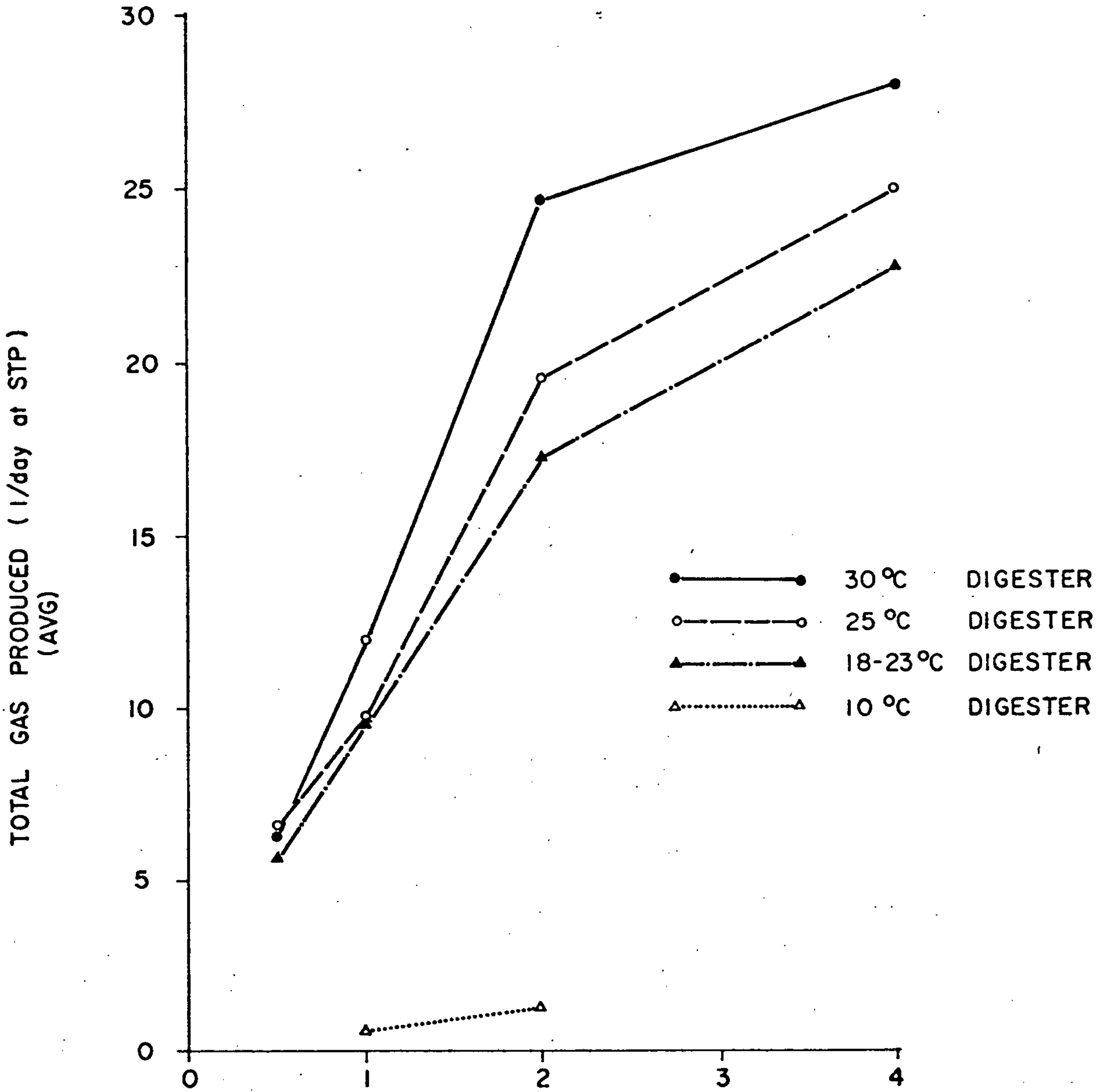


FIGURE 4-1

TOTAL DAILY GAS PRODUCTION AS RELATED TO RAW WASTE ADDITION feeding rates) was never achieved (see Figure 4-1). The falling off of the total volume of gas produced indicated that at this high loading rate:

(i) the biological system was unable to manage the increased load;

(ii) such a large portion of the digester contents was displaced daily that bacteria wash-out was occurring;

(iii) the increased variability in pH and alkalinity caused by the raw waste displacing 16% of the digester contents was adversely affecting the biological system.

The results to note for the 10°C digester were the lack of gas production and the insensitivity of gas production to all loading rates. At this temperature the methane bacteria barely function irrespective of the loading rate.

(b) Composition

The gas analysis for the 30, 25 and 18-23°C digesters during the test period did not vary appreciably even though the loading rate was increased four times (Appendix A). The results through the test period for these digesters are shown in Table VII.

The analysis for the constituents of the gas did not indicate any biological upset for the high loading rates even though the results for pH, alkalinity and gas production did point to this. The percentage of CH_4 and CO_2 gas to the total evolved gas is therefore characteristic of the substrate (i.e. specific species of bacteria once established in the

TABLE VII

GAS COMPOSITION FOR 30°, 25° AND 18-23°C DIGESTERS
(RAW WASTE ADDED DAILY)

Gas Composition*	% Extreme Limits	Average
CH_4	66-71	68
CO_2	28-32	30
N_2	0.4-1.0	0.8
H_2S	0.2-0.5	0.3
H_2O	0.4-1.5	0.9

TABLE VIII

GAS COMPOSITION FOR 30°, 25° AND 18-23°C DIGESTERS
(RAW WASTE ADDITION TERMINATED)

Gas Composition*	% Extreme Limits
CH_4	49-55
CO_2	42-49
N_2	0.5-1.5
H_2S	N/D
H_2O	0.5-1.5

*The combined percentage of CH_4 and CO_2 gas through this period was 97-99%.

digesters at these temperatures will continue to produce gas of this specific nature because of the type of raw waste being added) and does not necessarily indicate upset conditions (see Appendix A).

The results of the gas analyses for the 10°C digester, which was the least active of the digesters, were highly variable and the CO_2 percentage of the evolved gas had noticeably increased. It appears that under these circumstances the increase in the variability of the gas composition coupled with the increase in the per cent CO_2 of the gas are indicators of upset conditions within the digester.

After the raw waste loading was terminated, records were kept of the gas composition and production during the following five months. The gas composition changed markedly in the first twenty days but eventually stabilized. For the results during this period of the study see Table VIII.

These results substantiated the theory that the ratio of CH_4 and CO_2 is substrate specific and does not necessarily indicate biological upset. It appears from this that the characteristic substrate being utilized by the bacteria had changed (i.e. organics which were more difficult to degrade). The acid-formers produce different intermediate products and possibly because of this, the gas-formers produce CH_4 and CO_2 in different percentages. (In order to verify this theory, however, further analysis of intermediate products of digestion would have to be undertaken. This was not done in this study.)

(NOTE:- Taiginides [6] reporting on digestion of hog wastes at 35°C showed a gas analysis of 59% CH_4 and 40% CO_2 plus trace gases. Since vigorous anaerobic action was noted in Taiginides' study and similarly in this study, the different ratio of CH_4 to CO_2 can be attributed to the differences in the raw waste composition and is not an indicator of "poor" or "good" anaerobic digestion.)

CHAPTER V

THE EFFECT OF TEMPERATURE

5.1 Introduction

Another important parameter which must necessarily be considered in the anaerobic digestion process is temperature. The temperature affects the rate at which the waste is assimilated and reduced. Besides the temperature itself, temperature fluctuations are also critical to the anaerobic process [12]. Because methane bacteria are very sensitive to temperature changes, the range and frequency of temperature fluctuations determines whether anaerobic degradation can be maintained.

In this regard three items will be discussed, (1) influent and effluent concentrations of various waste parameters; (2) digester stability; and (3) gas production and composition.

5.2 General Discussion

The temperatures decided upon for the digesters were such that these temperatures covered the expected range of low and high temperature conditions for lagoons in the Fraser Valley. The specific temperatures chosen, as previously mentioned, were 10°, 25° and 30°C. The room temperature digester varied from 18-23°C. It was on the room temperature digester that the effects of small temperature fluctuations were to be studied.

The heating and cooling apparatus for the digesters, sampling techniques for the raw waste and digester effluent, and the chemical experiments and analytical techniques have previously been described in

Chapter III and IV.

The final results as related to temperature are presented in the following Table IX and are also graphically illustrated in Appendix C. The calculations for these results were carried out in the manner described in Chapter IV.

5.3 Discussion of Results

(a) Solids

From the results in Table IX, through the range of temperatures from 10°C to 30°C, the variation in per cent removal for TS was 1-4.5% and for VS was 2-5.5%. With this type of waste, where the majority of the solids readily settle out, varying the digester temperature does not significantly improve the supernatant quality with regards to solids removal.

(b) Oxygen Demand

For the results from 6 to 50 days LDT, the effect of temperature on the removal of both COD and BOD_5 was markedly similar. (See Table IX.) These observations were noted:

(i) as the LDT is increased from 12.5 days to 50 days, the effect of increased temperature becomes more significant;

(ii) the 18-23°C digester functioned nearly as well as the heated digesters and significantly better than the 10°C digester;

(iii) bacterial activity appears to be a step function of temperature:

(a) 10°C or less minimum activity

TABLE IX

PER CENT REMOVAL OF COD, BOD_5, TS AND VS

Theoretical LDT (Days)	Temp. of Digester (°C)	Average Removal (%)*			
		COD	BOD_5	TS	VS
50	30	83.0	89.0	-	-
	25	81.0	88.0	-	-
	18-23	80.5	87.0	-	-
	10	-	-	-	-
25	30	82.5	88.0	73.5	79.5
	25	82.0	88.0	73.5	80.0
	18-23	81.5	85.0	74.0	81.0
	10	64.5	43.5	73.0	79.0
12.5	30	77.0	84.0	74.0	79.0
	25	77.5	83.0	73.0	79.0
	18-23	78.0	80.5	74.0	80.5
	10	52.0	27.0	69.5	74.5
6	30	86.5	89.0	84.0	88.5
	25	88.5	88.0	86.0	90.5
	18-23	88.0	82.0	86.0	90.5
	10	77.0	41.5	86.0	90.0

*The values for per cent removal for the 6 day LDT are questionable due to the unusually high solids content in the last two raw waste samples used.

(b) 10-20°C transition range where the bacterial activity rapidly increases

(c) 20-30°C levelling off or plateau in the bacterial activity.

The extent to which the oxygen demand is reduced during the treatment of the waste depends on the nature of the organics and the activity of the bacteria. In the range of temperatures from 20-30°C the bacterial population appears to function actively with a balanced population of acid-forming and gas-producing bacteria which reduce organics to their respective end-products. However, it is apparent from the noticeable drop in the per cent removal of either BOD_5 or COD that between 20 and 10°C a change occurs. In the low temperature range (less than 10°C), it appears that the biological sequence of acid-formation to gas production is no longer carried through. For example, the total daily gas production for the 10°C digester was at the most one-tenth that produced from the other three digesters indicating that the methane bacteria which convert the intermediate-products to gaseous end-products no longer function to the same degree as in the other three digesters. It should also be noted that the alkalinity of the 10°C digester was consistently lower than the alkalinity of the effluent from the other digesters and of the raw waste samples, indicating incomplete anaerobic digestion with probable volatile acid build-up in the digester contents.

5.4 Stability of the Digesters

Considering the pH and alkalinity values of the effluent, along with the total daily gas production as being measures of the stability of the digesters (i.e. active anaerobic degradation), changes in temperature must be recognized as an important variable. In the 20-30°C range it was found that:

(i) the pH value of the effluent was consistently between 7.3-7.6;

(ii) the alkalinity concentration of the effluent was significantly greater than the alkalinity concentration of the incoming waste;

(iii) the daily gas production was always vigorous.

From the above mentioned data (see also Table V and Appendix A) it was concluded that the 30°C digester was operating under the most stable conditions of the three. It was found that throughout the test period the 30°C digester consistently had the highest daily gas production and maintained the highest effluent pH at 7.4-7.6.

For the 10°C digester the pH was never greater than 7, the gas production was minimal compared to the other three digesters, and the effluent alkalinity concentration was repeatedly lower than the incoming raw waste alkalinity due to the accumulation of excess organic acids. All of these conditions indicated that the 10°C digester was biologically unstable.

5.5 Gas Production and Composition

The metabolic activity of bacteria is a function of temperature [11,18]. Since the activity for methane bacteria governs the rate at which gas is produced in an anaerobic digester, the total daily gas production from each digester was anticipated to be a function of temperature.

For each temperature, total gas volume produced and gas composition were recorded. As mentioned in the previous chapter the object of this was to monitor the level of biological activity.

(a) Volume

From the experimental results recorded in Table X, temperature definitely affects the daily volume of gas produced. (See also Figure 4-1.)

(b) Composition

As previously mentioned in Chapter IV (also see Table VII and Appendix A), through the temperature range 20-30°C the gas composition was consistent. Through this temperature range the activity and specific types of bacteria are very similar.

The 10°C digester, however, was not as consistent with regards to the composition of evolved gas (Appendix A). The analysis of gas from this digester showed that CO_2 increased to 42-49% as compared to 28-32% CO_2 for the warmer digesters. This increase can be related to the drop in pH of the digester effluent, combined with the drop in the alkalinity concentration between the incoming raw waste and the effluent (Appendix A). Essentially all alkalinity measured in the digester was in the form of bicarbonate alkalinity. The chemical equilibria in the digester resulting from this bicarbonate alkalinity may be represented as

$$H^+ + HCO_3^- \rightleftarrows H_2CO_3 \rightleftarrows CO_2(aq.) + H_2O$$

$$CO_2(aq.) \rightleftarrows CO_2(gas)$$

As the pH dropped in the digester, a greater portion of the buffer capacity was utilized and consequently the chemical equilibria shifted to the right releasing additional CO_2 gas.

If this dynamic equilibrium applied to the 10°C digester, it provides an explanation for the increased percentage of CO_2 in the evolved gas. The variation in the gas composition (i.e. fluctuations in the per

TABLE X

DAILY GAS PRODUCTION AS RELATED TO TEMPERATURE

Theoretical LDT (Days)	Temp. (°C)	Total Daily Gas Production (ℓ/day @ STP) (1)	Gas Production Prior to Raw Waste Addition (mℓ/day @ STP) (2)	Gas Produced from Raw Waste Added Daily (1-2) (mℓ/day @ STP)
50	30	6250	4430	1820
	25	6600	4890	1710
	18-23	5600	4100	1500
	10	-	-	-
25	30	12000	9260	2740
	25	9800	7350	2450
	18-23	9600	7700	1900
	10	500	250	250
12.5	30	24700	19500	5200
	25	19500	15600	3900
	18-23	17250	14300	2950
	10	1250	600	650
6	30	28000	20900	7100
	25	25000	18800	6200
	18-23	22750	17750	5000
	10	-	-	-

cent of CO_2 gas) could conceivably have been caused by the variation in the alkalinity of the raw waste.

McCarty [11] states that the indicators of unbalanced treatment in a digester are:

(i) increased volatile acids concentration and CO_2 percentage in gas;

(ii) decreased pH, total gas production and waste stabilization.

These indicators were present in the 10°C digester but not in the other three.

CHAPTER VI

SETTLING - VS - BIOLOGICAL DEGRADATION

6.1 Introduction

Removal of organics from the raw waste added daily to the digesters was found to be due to two factors (1) settling and (2) biological degradation. Settling is strictly a physical phenomena and any removal of organics is achieved only by separation. Hence the organic load has not been disposed of, but merely concentrated.

Anaerobic degradation reduces the waste load by converting organics to gaseous end-products [11,18,19,20]. Biological reduction of waste depends to varying degrees on:

(i) temperature, which affects the biological activity;

(ii) characteristics of the waste (i.e. types of organics, toxic substances, etc.), which determine the ease with which bacteria can degrade or stabilize the waste;

(iii) contact time between the waste and bacteria, which determines the per cent of the total organics reduced.

The anaerobic treatment may be described as a three-step process involving

(i) hydrolysis of complex material

(ii) acid production

(iii) methane fermentation.

In the first step, complex organics are converted to less complex soluble organic compounds by enzymatic hydrolysis. In the second step, these hydrolysis products are fermented to simple organic compounds (predominanatly volatile fatty acids) by a group of facultative and anaerobic bacteria collectively called "acid-formers". In the third step, the simple organic compounds are fermented to methane and carbon dioxide by a group of substrate-specific strict anaerobes called "methane formers". Thus organic waste materials are converted effectively to bacterial protoplasm and gaseous end-products of CH_4, CO_2 and trace gases. The result is that for some organics an absolute removal is achieved through conversion to gaseous end-products. In actual waste treatment practice, not all organics can be taken through this chain of events, as some organics in the raw waste are resistant to biological breakdown. Hence for actual waste treatment, total removal of organics is not practically possible.

6.2 General Discussion

With regard then to the raw waste studied and its treatment, since build-up of settled solids from the daily addition of raw waste is inevitable, the solution is to control to some degree, depending on different circumstances, the rate of solids build-up and thereby receive maximum benefit from the anaerobic lagooning system. There are three possible alternatives in controlling the rate of solids build-up in lagoons for treatment of concentrated animal wastes. These are:

(i) an extended holding period where a large percentage of the organics are biologically reduced, and the remaining solids are held "indefinitely" in the lagoon. For a treatment system of this type, however the cost for the required land area and of construction of these lagoons could be prohibitive.

(ii) a very brief detention period where essentially only settleable waste materials are removed and only a small fraction of the degradable organics are reduced by bacteria. The sludge build-up in this case would be rapid and further treatment of the effluent would probably be required. Also, an additional method of disposal for the accumulated solids would be needed (e.g. land disposal by frequent trucking of the solids).

(iii) a compromise on the above two extremes (i.e. a lagooning system with active anaerobic digestion, and a limited sludge storage capacity with a program for the periodic disposal of the accumulated sludge). As an example, land disposal of the sludge produced could be co-ordinated to suit the requirements of surrounding farms.

In studying concentrated animal wastes and considering the above three alternatives, two questions were raised which required answers:

(1) What per cent of the total COD, BOD and VS of the raw waste was removed by settling and what per cent by biological activity?

(2) What temperatures and length of LDT would provide a balance between removal by settling and by biological degradation?

6.3 Methane Production Related to COD, BOD and VS Reduction

From previous work done on anaerobic treatment McCarty [11] has shown from theoretical considerations supported by experimental evidence that a maximum of 5.62 cu. ft. of methane gas will be produced per pound of COD or ultimate BOD reduced (0.35 ml. of methane/mg of COD or BOD_L). From the following formula the reduction of COD or BOD_L to methane can be calculated:

$$Cm = 5.62F \quad (1)$$

where

F = pounds of BOD_L or COD reduced per day

Cm = cubic feet of CH_4 produced per day

For VS reduction Eckenfelder [10] reports the following:

> "...The reported gas production for volatile solids (VS) reduction in a well operating anaerobic digestion tank is 17 to 20 ft^3/lb of VS destroyed with a methane content of about 65 percent. This is equivalent to 5 to 7 ft^3 of COD destroyed which is close to the value reported by Lawrence and McCarty. It is significant at this point that these values are a maximum, assuming complete conversion of the solids to methane. Volatile solids reduction can occur by liquefaction and conversion to volatile acids without any COD reduction. Under these conditions, the methane yield per unit of volatile solids reduction may be very low."

From the following formula the reduction of VS can be calculated:

$$C_t = KP \quad (2)$$

where

P = pounds of VS reduced per day

C_t = cubic feet of gas produced per day

k = 17-22 ft^3 gas/lb VS reduced

or 1.06-1.37 ml gas/mg VS reduced

In order to use formulae 1 and 2, the following information was necessary:

(i) weekly analysis of the evolved gas on a gas chromatograph in order to determine the CH_4 percentage;

(ii) measurement of the daily gas production for each of the specific LDT's. During the measurements a record was kept of the average room temperature and average local atmospheric pressure. This was done so as to enable conversion of the collected data to STP;

(iii) measurement of the rate at which gas was produced during a test run. Readings were taken every 15 minutes. With this data the daily volume of gas produced could then be separated into components - that produced from the accumulated sludge, and that produced from the daily addition of raw waste;

(iv) measurement of the average daily addition of VS for each LDT.

From the above data and assuming that measured chemical and biochemical oxygen demand are equivalent and interchangeable, experimental values of

F and P could be determined. The final results would then make possible a comparison between the per cent reduction of COD, BOD_L and VS to gaseous end-products and the per cent removed by settling.

Experimental results are given in Tables XI, XII, and XIII and Figures 6-1, 6-2 and 6-3. For the calculations using equations 1 and 2, see Appendix E.

In order to explain the rationale for Figures 6-1, 6-2 and 6-3, an example for each will be given.

Case I - COD

For the results obtained for given conditions of

(1) Temperature = 25°C

(2) LDT = 25 days (in this case a loading of 1ℓ/day of raw waste)

the maximum amount of the measured raw waste COD load that was biologically reduced to gaseous end-products was approximately 18.5% and 63.5% of the measured COD load of the raw waste was removed by settling.

Case II - BOD_5

For the same given conditions as Case I, the maximum amount of the measured raw waste BOD_5 load that was biologically reduced to gaseous end-products was approximately 51% and 27% of the measured BOD_5 load was removed by settling.

Case III - VS

For the same given conditions as Case I, assuming the constant k to be correct, approximately 15% of the measured raw waste VS load was biologically reduced and 65% of the measured VS load was removed by settling. For all of the above cases, the sum of the two percentages totals the

TABLE XI

PER CENT COD REDUCED BY BIOLOGICAL ACTION

Temp. (°C)	Loading Rate (ℓ/day)	Average Raw Waste COD* Conc. (mg/ℓ)	Average Raw Waste COD* Loading (mg/day)	Average Vol. of Gas Produced from Raw Waste Added** (mℓ/day)	% CH_4	Cm (mℓ/day)	F_{max}*** (=k_1Cm) (mg/day)	% of Raw Waste COD Loading
30	1/2	29350	14675	1850	66.5	1225	3490	24
	1	25450	25450	2750	68	1870	5330	21
	2	32400	64800	5200	66.5	3445	9815	15
	4	50000	200000	7100	68	4830	13765	7
25	1/2	29350	14675	1700	67.5	1145	3265	22
	1	25450	25450	2450	68	1665	4745	18.5
	2	32400	64800	3900	67.5	2620	7475	11.5
	4	50000	200000	6200	68	4215	12015	6
18-23	1/2	29350	14675	1500	71	1060	3015	20.5
	1	25450	25450	1900	69.5	1315	3750	14.5
	2	32400	64800	2950	68	2005	5715	9
	4	50000	200000	5000	69	3450	9835	5
10	1	25450	25450	250	51	125	355	1.5
	2	32400	64800	650	43	270	760	1

* Average Raw Waste COD added during this part of the testing.

** This is the adjusted value which takes into consideration the gas produced from the accumulated digester sludge (see Table VI)

*** $k_1 = 2.85$ mg COD/mℓ CH_4

TABLE XII

PER CENT BOD_5 REDUCED BY BIOLOGICAL ACTION

Temp. (°C)	Loading Rate (ℓ/day)	Average Raw Waste BOD_5* Conc. (mg/ℓ)	Average Raw Waste BOD_5* Loading (mg/day)	Average Vol. of Gas Produced from Raw Waste Added** (mℓ/day)	% CH_4	Cm (mℓ/day)	F_{max}*** (=k_1Cm) (mg/day)	% of Raw Waste BOD_5 Loading
30	1/2	9200	4600	1850	66.5	1225	3490	76
	1	9300	9300	2750	68	1870	5330	57
	2	10850	21700	5200	66.5	3445	9815	45
	4	10700	42800	7100	68	4830	13765	32
25	1/2	9200	4600	1700	67.5	1145	3265	71
	1	9300	9300	2450	68	1665	4745	51
	2	10850	21700	3900	67.5	2620	7475	34.5
	4	10700	42800	6200	68	4215	12015	28
18-23	1/2	9200	4600	1500	71	1060	3015	65.5
	1	9300	9300	1900	69.5	1315	3750	40.5
	2	10850	21700	2950	68	2005	5715	26.5
	4	10700	42800	5000	69	3450	9835	23
10	1	9300	9300	250	51	125	355	4
	2	10850	21700	650	43	270	760	3.5

* Average Raw Waste BOD_5 added during this part of the testing.

** This is the adjusted value which takes into consideration the gas produced from the accumulated digester sludge (see Table VI)

*** k_1 = 2.85 mg BOD/mℓ CH_4

TABLE XIII

PER CENT VS REDUCED BY BIOLOGICAL ACTION

Temp. (°C)	Loading Rate (ℓ/day)	Average Raw Waste VS*		C_t** (Average Vol. of Gas Produced from Raw Waste added) (mℓ/day)	P*** ($=k_2C_t$) (mg/day)	% of Raw Waste VS Reduced	
		Conc. (mg/ℓ)	Loading (mg/day)			Range	Avg.
30	1/2	-	-	1850	1350 - 1740	-	-
	1	15300	15300	2750	2010 - 2600	13.2 - 17	15
	2	22500	45000	5200	3800 - 4900	8.5 - 11	10
	4	35000	140000	7100	4900 - 6700	3.5 - 5	4
25	1/2	-	-	1700	1240 - 1600	-	-
	1	15300	15300	2450	1790 - 2310	11.5 - 15	13
	2	22500	45000	3900	2850 - 3680	6.5 - 8	7
	4	35000	140000	6200	4530 - 5850	3 - 4	3.5
18-23	1/2	-	-	1500	1100 - 1415	-	-
	1	15300	15300	1900	1390 - 1790	9 - 11.5	10
	2	22500	45000	2950	2150 - 2780	5 - 6	5.5
	4	35000	140000	5000	3650 - 4710	2.5 - 3.5	3
10	1	15300	15300	250	185 - 235	1 - 1.5	≃1
	2	22500	45000	650	475 - 615	1 - 1.5	≃1

* Average Raw Waste VS added during this part of testing.

** This is the adjusted value which takes into consideration the gas produced from the accumulated digester sludge (see Table VI)

*** k_2 = 0.73 - 0.94 mg VS/mℓ gas produced (65 - 70% CH_4)

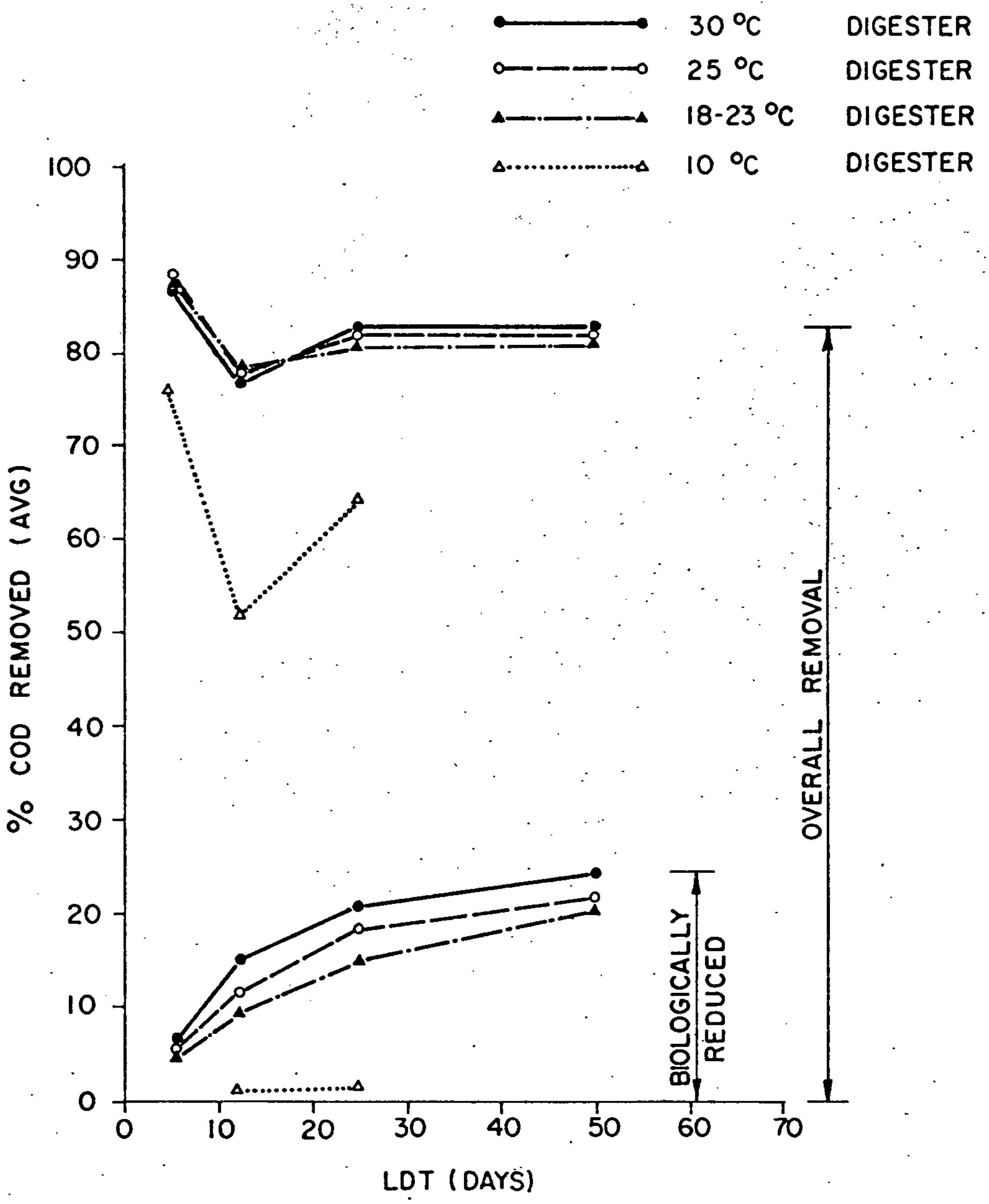


FIGURE 6—1

PERCENT OF COD REMOVED BY BIOLOGICAL REDUCTION AS COMPARED TO THE OVERALL COD REMOVAL OVER A RANGE OF LDTs.

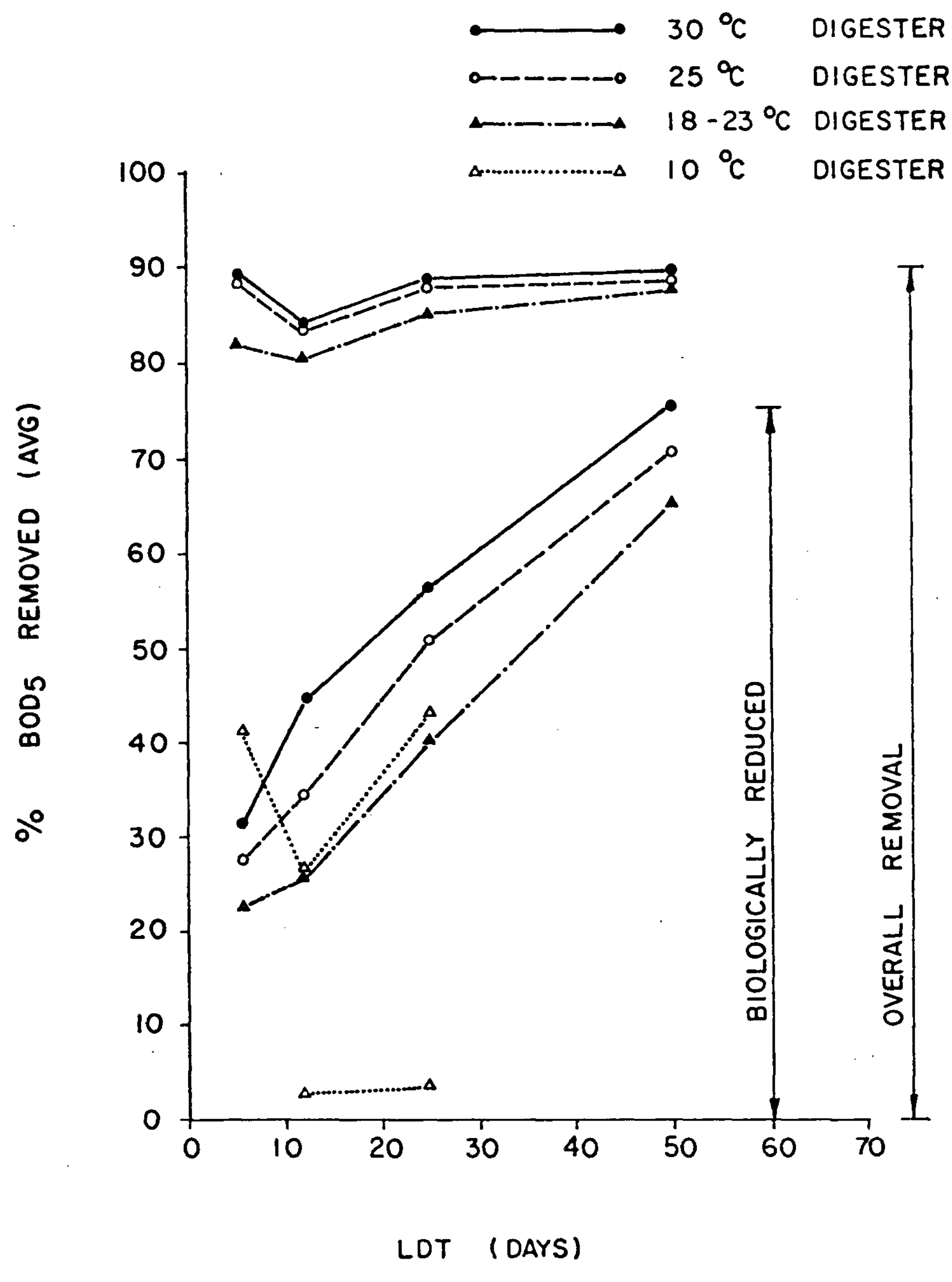


FIGURE 6-2

PERCENT OF BOD_5 REMOVED BY BIOLOGICAL REDUCTION AS COMPARED TO THE OVERALL BOD_5 REMOVAL OVER A RANGE OF LDTs.

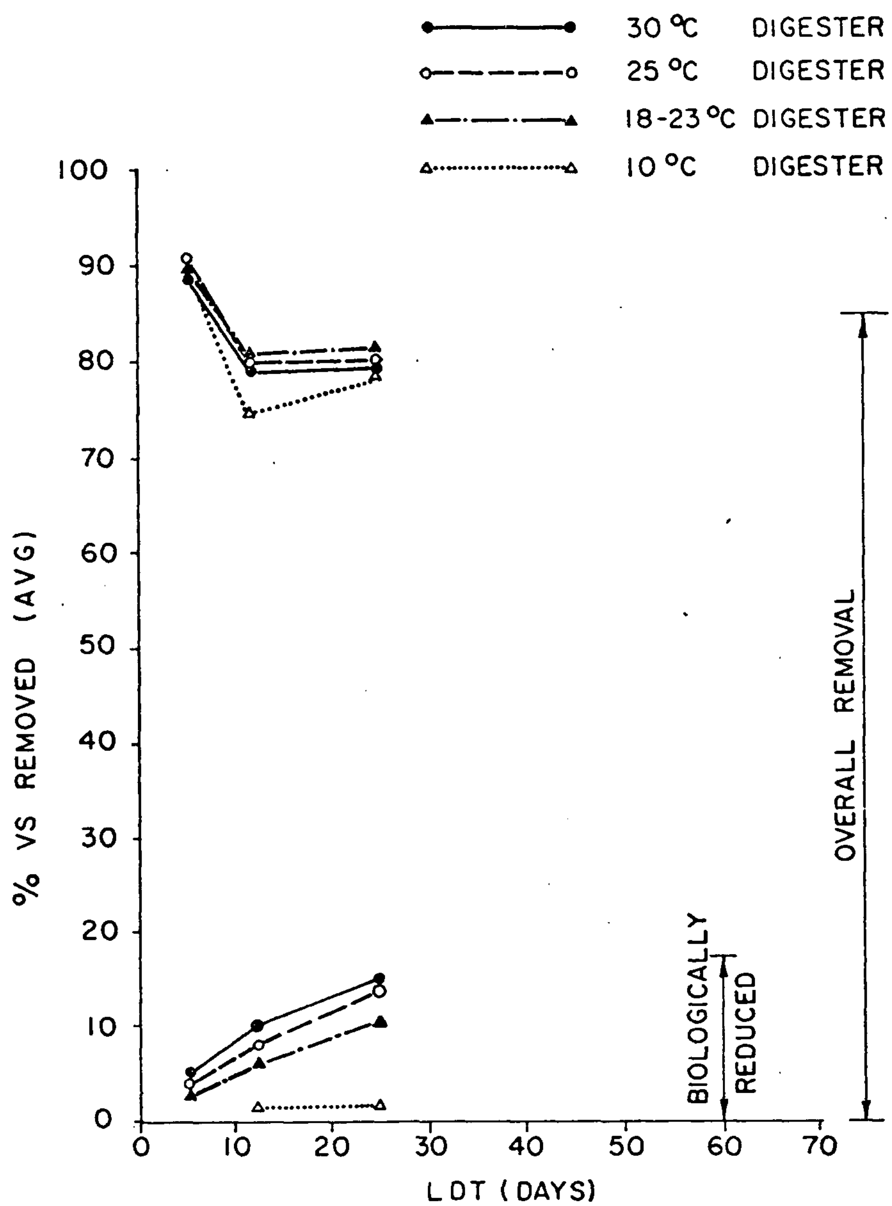


FIGURE 6-3

PERCENT OF VS REMOVED BY BIOLOGICAL REDUCTION AS COMPARED TO THE OVERALL VS REMOVED OVER A RANGE OF LDTs.

measured overall removal.

6.4 Discussion of Results

These results were noted:

(a) Temperature

(i) For the range of temperatures studied, sequential drops in removal efficiency resulted as the temperature decreased. This was as expected, since the level of biological activity is more intense at elevated temperatures and a greater portion of the organic matter is therefore metabolized during a specified time period.

(ii) The rapid drop in the activity of the bacteria between 20°C to 10°C is of significance. It appears that even at the moderate temperatures of 10°C methane fermentation is severely retarded. However, complete anaerobic activity does not necessarily cease. The hydrolysis process and organic acid production still continues, altering the digester contents. Thus when the temperature finally does increase, methane fermentation can continue. This observation was noted with the 10°C digester. Gas production increased markedly within 2-3 days after the refrigeration unit was disconnected and the digester temperature increased to the lab temperature of approximately 20°C.

(iii) Allowing the temperature to fluctuate from 18°-23°C did not adversely affect biological activity. A smaller per cent of the organics were metabolized as compared to the 25°C and 30°C digester but this was expected because of the lower average temperature. The per cent removal was much above the results obtained for the 10°C digester.

(b) Detention Time

(i) From the results for biological reduction of VS and COD, it is apparent that a large portion of the VS and COD load of the raw waste is not amenable to biological action. For COD reduction, a levelling off occurs after 25 days LDT and any further increase in the detention time is of little benefit. This would also appear to be the case for VS reduction.

(ii) Extending the biological contact time markedly affects the biological reduction of the BOD_5 load at temperatures above 20°C.

(iii) There appears to be little benefit for extended biological contact time at temperatures 10°C or less.

(c) Organics Removal

(i) Included in the waste composition are aggregated complex organics such as feed chips, wood fibres, swine hairs, seeds and grain hulls which are essentially non-biodegradable. These are readily separable from the digester supernatant and are concentrated in the sludge and scum layers. From the data for VS removal the indication is that a significant portion of the organics in the digesters are of this nature and hence will accumulate in the digester.

(ii) Reduction of organics by bacteria is temperature sensitive and is significantly reduced at temperatures below 20°C.

(iii) The rapid increase in the biological reduction of the BOD_5 load by extending the contact time indicates that the measured

BOD_5 load of the raw waste provides a readily available food source for the bacteria.

CHAPTER VII

NUTRIENTS

7.1 Introduction

It is generally agreed today that phosphates and nitrogen compounds are primary contributors to eutrophication in natural bodies of water and at the same time are necessary in any biological treatment schemes. During this study the possible effects of those two nutrients were considered in light of the above two points. The "in" and "out" concentrations of ammonia-nitrogen and phosphate were monitored in an attempt to answer a number of questions.

(1) Will the ammonia-nitrogen concentration in the digester contents and raw waste affect anaerobic treatment?

(2) What effects do detention time and temperature have on the effluent concentrations of phosphate are ammonia-nitrogen?

(3) What per cent of the total biological oxygen demand will be due to nitrogeneous oxygen demand?

In order to measure the concentrations and effects of the above two nutrients, chemical and gas analyses were carried out. The chemical tests are outlined in Standard Methods [15] and were:

(i) total Kjeldahl-N

(ii) organic Kjeldahl-N

(iii) total phosphate

(NOTE - the arithmetic difference between total and organic Kjeldahl-N concentrations determines the ammonia Kjeldahl-N concentration.)

7.2 Average Raw Waste and Effluent Characteristics

The data presented in Tables XIV and XV are average values and as mentioned previously, in calculating these average values only those results were considered in the calculation of average values which were recorded after the appropriate theoretical LDT had elapsed.

7.3 Ammonia-N Toxicity

McCarty in his paper entitled Anaerobic Waste Treatment Fundamentals [11] states:

> "Ammonia may be present during treatment either in the form of the ammonium ion (NH_4^+) or as dissolved ammonia gas (NH_3). These two forms are in equilibrium with each other, the relative concentration of each depending upon the pH or hydrogen ion concentration as indicated by the following equilibrium equation:
>
> $$NH_4^+ \rightleftarrows NH_3 + H^+$$
>
> When the hydrogen ion concentration is sufficiently high (pH of 7.2 or lower), the equilibrium is shifted to the left so that inhibition is related to ammonium ion concentration. At higher pH levels, the equilibrium shifts to the right and the ammonia gas concentration may become inhibitory. The ammonia gas is inhibitory at a much lower concentration than the ammonium ion."

This summary is given by McCarty on ammonia toxicity:

Ammonia Nitrogen Concentration (mg/ℓ)	Effect on Anaerobic Treatment
50-200	Beneficial
200-1000	No Adverse Effect
1500-3000	Inhibitory at Higher pH Levels
Above 3000	Toxic

TABLE XIV

AVERAGE RAW WASTE CHARACTERISTICS*

Theoretical LDT (Days)	Total Phosphate (mg/ℓ)	Organic Kjeldahl-N (mg/ℓ)	Total Kjeldahl-N (mg/ℓ)	Ammonia Kjeldahl-N (mg/ℓ)
50	2195	660	2435	1775
25	2040	750	2740	1990
12.5	2060	705	2285	1580
6**	3000	920	2310	1390

*Values for raw waste used in calculations for the results in Table XVI.

**The unusually high values for the 6 day LDT appeared to be due to the high solids concentration in the final raw waste samples.

TABLE XV

AVERAGE EFFLUENT CHARACTERISTICS

Temp. of Digester (°C)	Theoretical LDT (Days)	Total Phosphate (mg/ℓ)	Organic K-N (mg/ℓ)	Total K-N (mg/ℓ)	Ammonia K-N (mg/ℓ)
30	50	800	200	1810	1610
	25	730	255	2190	1935
	12.5	670	265	2130	1865
	6	680	240	1740	1500
25	50	740	210	1850	1640
	25	810	265	2155	1890
	12.5	690	255	2095	1840
	6	550	220	1600	1380
18-23	50	660	220	1850	1630
	25	700	260	2100	1840
	12.5	620	255	2070	1815
	6	530	210	1500	1310
10	50	-	-	-	-
	25	670	265	2030	1765
	12.5	790	315	2070	1755
	6	750	195	1360	1165

For all four digesters over the entire duration of the lab study, the concentration of ammonia nitrogen in the raw waste and effluent fluctuated between 1300-2000 mg/ℓ (with the pH always less than 7.6). The effect of ammonia in this case according to the above chart would be to cause little adverse effects. From all indications during the study no complications were encountered in terms of ammonia toxicity upsetting normal anaerobic digestion.

7.4 Effect of Temperature on Total Phosphate and Ammonia-N Removal

From the results in Table XVI, (see also Appendix D) the following observations were noted:

(i) Total phosphate removal - the average percent removal of phosphate appears not to be affected by temperature. Through the range of temperatures from 10-30°C, the average per cent removal of phosphate varied 6-7% and did not indicate any dependency on temperature as was the case for COD and BOD_5 removal.

(ii) Ammonia-N removal - data obtained is insufficient to determine if temperature does affect the average per cent removal of ammonia-N. However the point to note is that the maximum per cent removal was approximately 15% which indicates that the ammonia-N is primarily dissolved and not removable by settling.

TABLE XVI

PER CENT REMOVAL OF TOTAL PHOSPHATE AND AMMONIA-N AS AFFECTED BY TEMPERATURE

Theoretical LDT (Days)	Temperature (°C)	Average Removal (%)	
		Total Phosphate	Ammonia-N
50	30	63.5	9.5
	25	66.5	7.5
	18-23	70	8
	10	-	
25	30	64	3
	25	60.5	5
	18-23	65.5	7.5
	10	67	11.5
12.5	30	67.5	0
	25	66.5	0
	18-23	70	0
	10	61.5	0
6	30	77.5	0
	25	81.5	0.5
	18-23	82.5	5.5
	10	75	16

Therefore the 15% of ammonia-N that is removed is probably removed through two mechanisms:

(i) biological uptake

(ii) adsorption of ammonia-N in the collected sludge

7.5 Effect of Detention Time on Total Phosphate and Ammonia-N Removal

From the results in Table XVII (see also Appendix D), the following observations were noted:

(i) Phosphate removal - two-thirds of the phosphate concentration is rapidly removed by settling. The remaining phosphate is present in dissolved form and further removal would likely require chemical treatment.

(ii) Ammonia-N removal - the ammonia nitrogen in both the incoming raw waste and the effluent is present in the form of ammonium ion (NH_4^+) or as dissolved ammonia gas (NH_3), and cannot therefore be removed by settling. Based on this then extending the detention period is not the solution to ammonia-N removal.

As previously mentioned, the small degree of removal of ammonia-N can be attributed to (1) biological uptake and (2) adsorption in the digester sludge.

TABLE XVII

PER CENT REMOVAL OF TOTAL PHOSPHATE AND AMMONIA-N AS AFFECTED BY DETENTION TIME

Temp. of Digester (°C)	Theoretical LDT (Days)	Average Removal (%)*	
		Total Phosphate	Ammonia-N
30	50	63.5	9.5
	25	64	3
	12.5	67.5	0
	6	77.5	0
25	50	66.5	7.5
	25	60.5	5
	12.5	66.5	0
	6	81.5	0.5
18-23	50	70	8
	25	65.5	7.5
	12.5	70	0
	6	82.5	5.5
10	50	-	-
	25	67	11.5
	12.5	61.5	0
	6	75	6

*These results of per cent removal for the 6 day LDT are questionable due to the unusually high VS content of the raw waste samples used. The results are based on only two test samples.

7.6 Nitrogenous Oxygen Demand

The results from the single long term BOD test completed on the raw waste Figure 7-1 indicated that:

(i) carbonaceous BOD of the raw waste was between 10,000-10,500 mg/ℓ. This accounted for 70-75% of the total measured BOD;

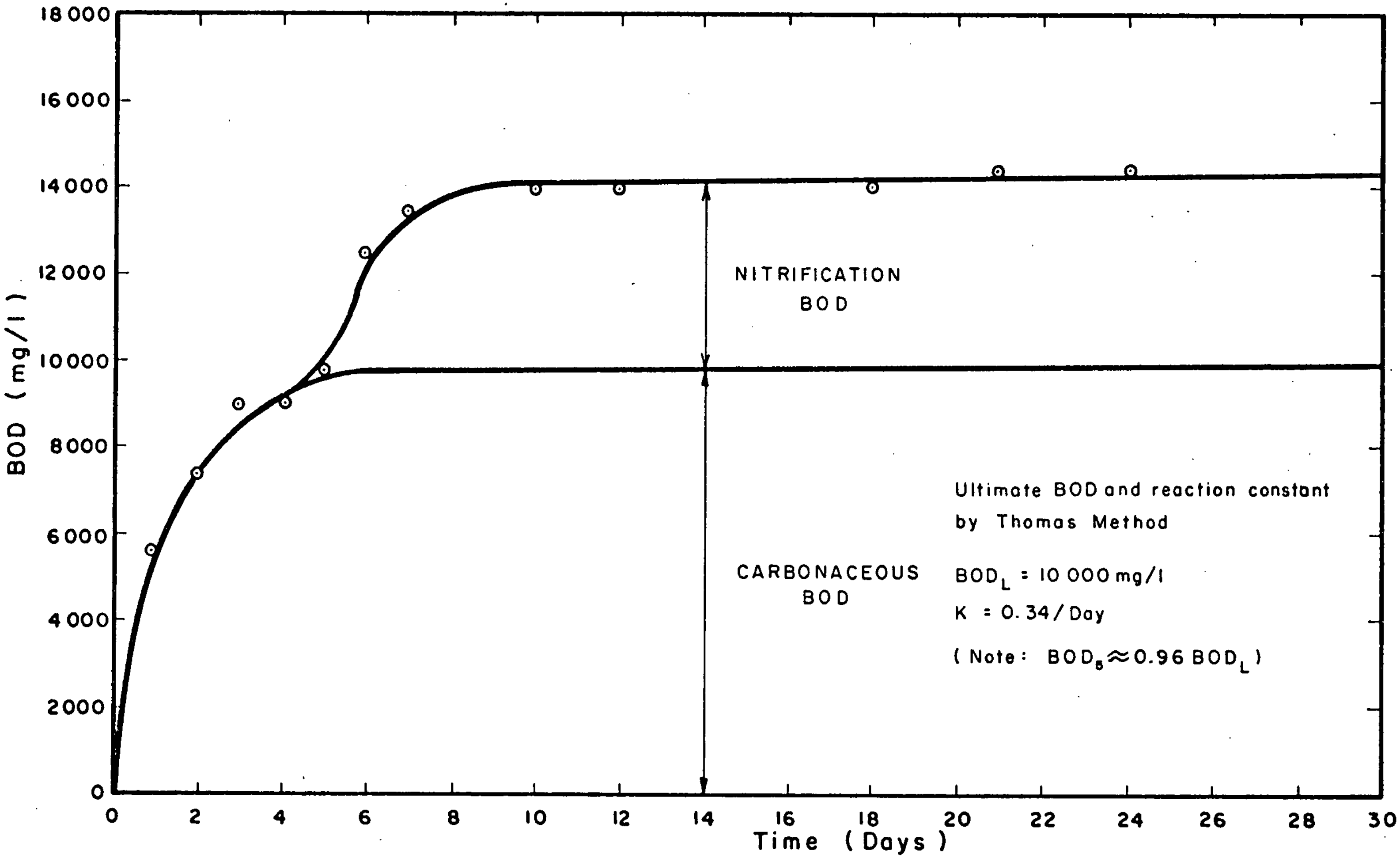
(ii) nitrogenous oxygen demand of the raw waste was between 4000-4500 mg/ℓ making up the other 25-30% of the total measured BOD.

During the treatment in the digesters the carbonaceous BOD was measurably reduced but maximum reduction for ammonia-N concentration was 15% (i.e. little reduction of the nitrogenous BOD). Consequently, if a similar long term BOD test was carried out on the digester effluent these results could be expected:

(i) carbonaceous BOD of the effluent would be reduced to 1000-1500 mg/ℓ. This would account for approximately 20-30%;

(ii) nitrogenous BOD reduced only to approximately 3500-4000 mg/ℓ would now account for 70-80% of the total measurable BOD.

This is a significant result in terms of the potential added oxygen demand the effluent will exert on any receiving water.



LONG TERM BOD CURVE FOR RAW PIG WASTE.

FIGURE 7-1

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

The anaerobic decomposition of concentrated animal wastes is affected by various parameters such as:

(i) reaction temperature,

(ii) detention time,

(iii) waste characteristics.

The laboratory program assessed the effects on hog waste treatment of these parameters by measurements of the following:

(i) inlet and outlet concentrations of nutrients, oxygen demand and solids;

(ii) gas production and composition.

This lab study has provided some valuable insight into the mechanics of anaerobic digestion of concentrated animal wastes. It is hoped therefore that it will provide design engineers with additional information to be used in the optimal design of waste treatment facilities.

The following conclusions and recommendations stem from the results obtained through this lab study.

8.2 Conclusions

(A) Temperature - the temperature of the digester contents with regard to the waste studied is the primary factor in determining the operating efficiency of anaerobic digestion. The fermentation kinetics will continue to operate satisfactorily as long as the temperature is maintained above 20°C. However in decreasing the temperature from 20°C to 10°C, the activity of the methane organisms is markedly reduced and for temperatures 10°C and below, the methane fermentation process and consequent gas production will drop to zero. When this occurs, the digester does little else than act as a settling basin.

(B) Detention Time - detention time, or biological contact time, is significant when related with temperature. With increasing contact time for temperatures from 20° to 30°C, an increasing portion of the reduceable organic matter is converted to stable end-products. For temperatures less than 20°C, detention time is even more critical in terms of providing sufficient time for maximum solids removal by settling and achieving significant reductions in oxygen demand. (As mentioned above, reduction of reduceable organics virtually ceases at temperatures less than 10°C.)

(C) Settling vs Biological Degradation - with this particular waste, in addition to the inorganic matter, a large protion of organic matter is inert to biological reduction. It is thus obvious that the non-reduceable organic solids add to the solids accumulation problem. In this regard adequate solids storage in the cell design and periodic dredging of the anaerobic cells will be necessary.

(D) Nutrient Concentration - a large percentage of the nutrient load of ammonia-N and total phosphate is dissolved and therefore cannot be further removed by settling. The digestion process also does not achieve further nutrient reduction. In this regard therefore, to achieve further improvement in the effluent quality an addition to the anaerobic process will be required (i.e. chemical treatment and/or nitrification and denitrification).

(E) Gas Production and Composition - with regard to this waste, gas production is a function of temperature (this follows from the known fact that the biological activity is a function of temperature); the gas constituents during active anaerobic digestion should test 97-99% methane and carbon dioxide. The ratio of methane and carbon dioxide gas is characteristic of the substrate being added and does not necessarily indicate upset conditions.

(F) Organic Loading - with regard to this specific waste treatment, organic loads of 10.4 to 82.4 lb BOD_5/1000 ft^3/day did not induce digester upset. However the per cent of the total load reduced decreased with the increasing organic load. Conventional recommended values range from 10-20 lb BOD_5/1000 ft^3/day, and comparing this with the experimental data, conventional design practise is at least conservative.

8.3 Recommendations for Design

These recommendations based on the laboratory study without any correlation to full-scale results, which to date have not been carried out, are presented for treatment of concentrated hog waste by anaerobic digestion:

(i) in designing an anaerobic cell system for a given area, a factor to consider is climatic conditions; (e.g. For cold climates where the mean maximum temperature frequently does not exceed 20°C, a larger lagoon volume will be required as compared to warm climates because less solids will be reduced and more accumulated.);

(ii) in order to maintain continuous active anaerobic digestion the temperature of the digester contents should not drop below 20°C, unless a higher effluent oxygen demand can be tolerated during the colder operating period;

(iii) the required pH range should preferably be between 7.2-7.6;

(iv) due to the nature of the waste, two cells in series would probably provide a better treatment system than one cell of the same total volume. The initial cell would provide primary settling and vigorous digestion of the solids, and the second cell with less vigorous overturning of the sludge would provide quiescent conditions for further removal of solids by settling plus additional anaerobic treatment;

(v) enough volume should be provided for sludge accumulation to ensure that the LDT does not become so short that required bacteria are washed out (i.e. because of the relative growth rate of methane organisms some methane bacteria will be washed out if LDT drops below 7 days).

8.4 Recommendations for Future Studies

(A) Separation of Settled Solids and Supernatant

This study would determine if separation of the supernatant and the settled solids during the digestion process will improve the quality of the effluent. This would entail having two cells in series with a total volume equivalent to the volume of the single cell used in this study. The primary cell would contain the accumulated solids and sludge; the secondary cell the supernatant. By providing quiescent conditions for the supernatant, improved effluent quality through solids settling could be achieved.

(B) Determination of the Rate and Degree of Biological Reduction of the Concentrated Animal Waste Oxygen Demand and Volatile Solids

This study would consist of a series of batch anaerobic vessels regulated at various temperatures. An initial measurement of the COD, BOD and VS of the completely mixed digester contents would be required.

Following this, weekly analysis of the digester contents and evolved gas plus measurement of gas production would be carried out. From this a determination of the degree of reduction that can be expected with such a waste and the biological rate of reduction as related to such a waste could be accomplished.

(C) Ammonia-N Removal

In this respect, a study related specifically to nitrogenous oxygen demand removal from the digester supernatant would be worthwhile. This study would include a two cell system as mentioned previously. The second cell would incorporate mechanical aeration or chemical treatment in order to achieve ammonia-N removal.

(D) Sludge Characteristics

Because accumulation of sludge poses a problem in terms of eventual disposal, a study related to the chemical and physical characteristics of sludge, the extent to which the sludge can be biologically reduced and the effect of detention on reducing the sludge volume would be worthwhile in more fully understanding the overall picture for treatment of concentrated animal wastes.

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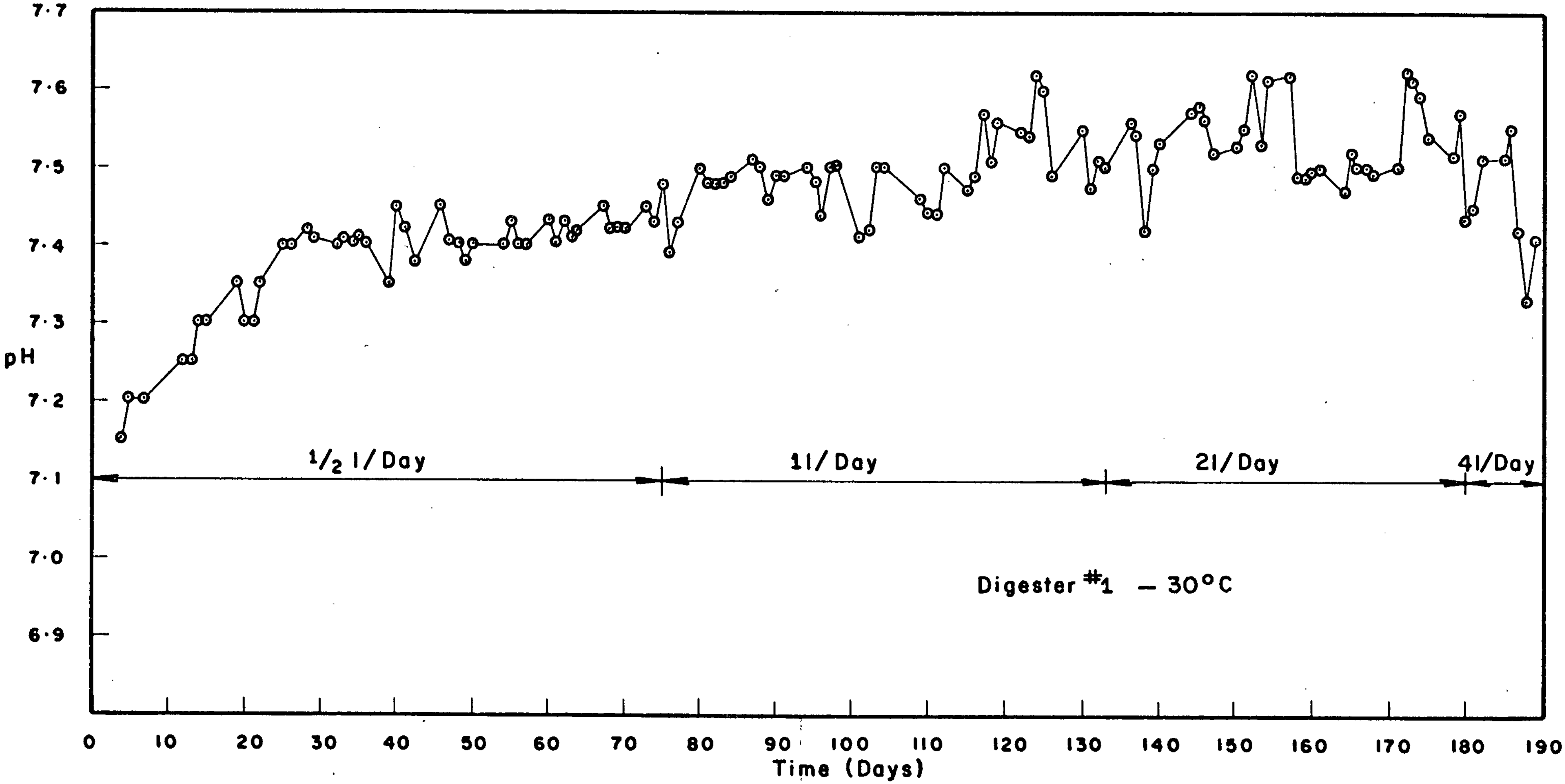
APPENDICES

APPENDIX A

LABORATORY RESULTS



pH OF THE EFFLUENT AS RELATED
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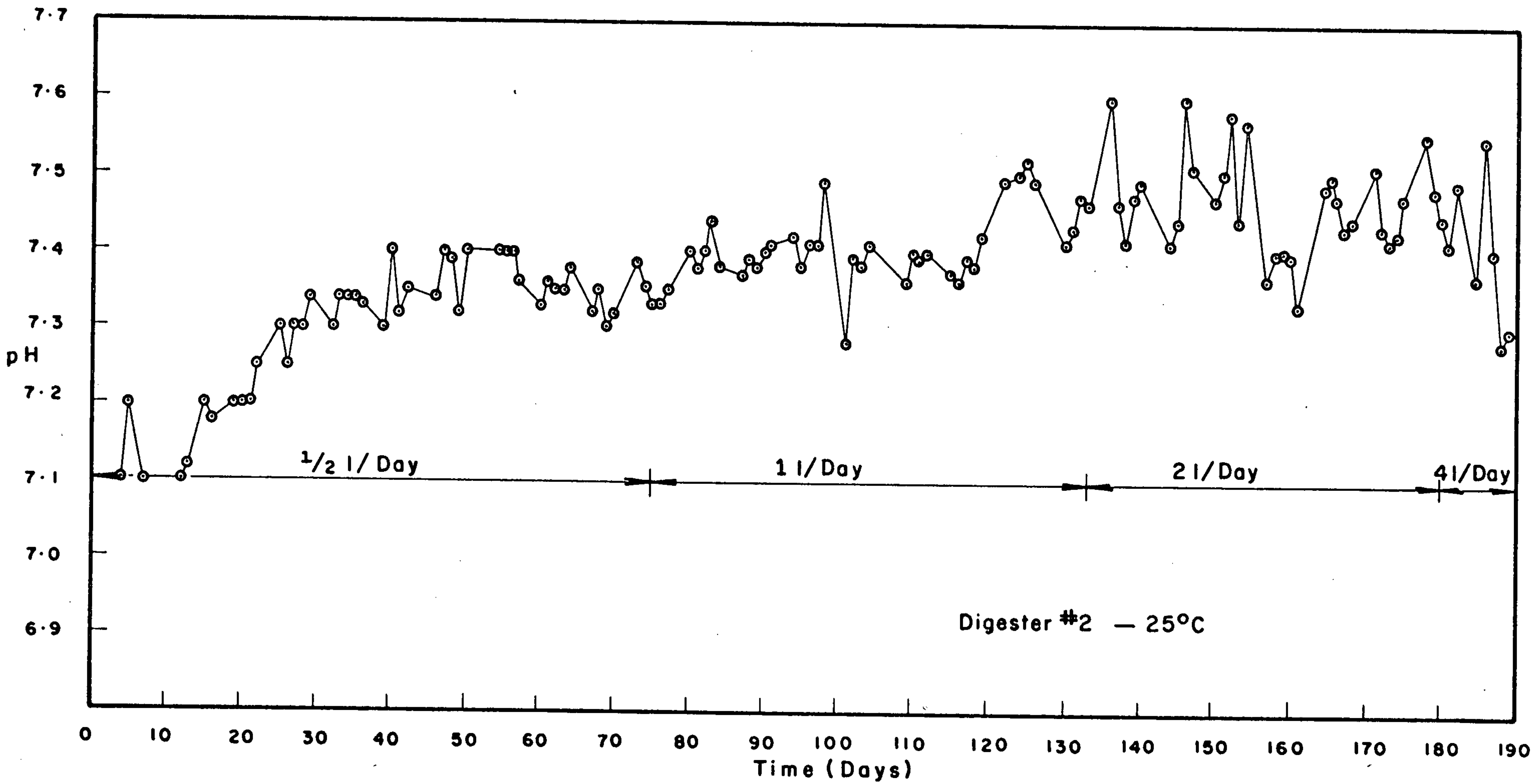

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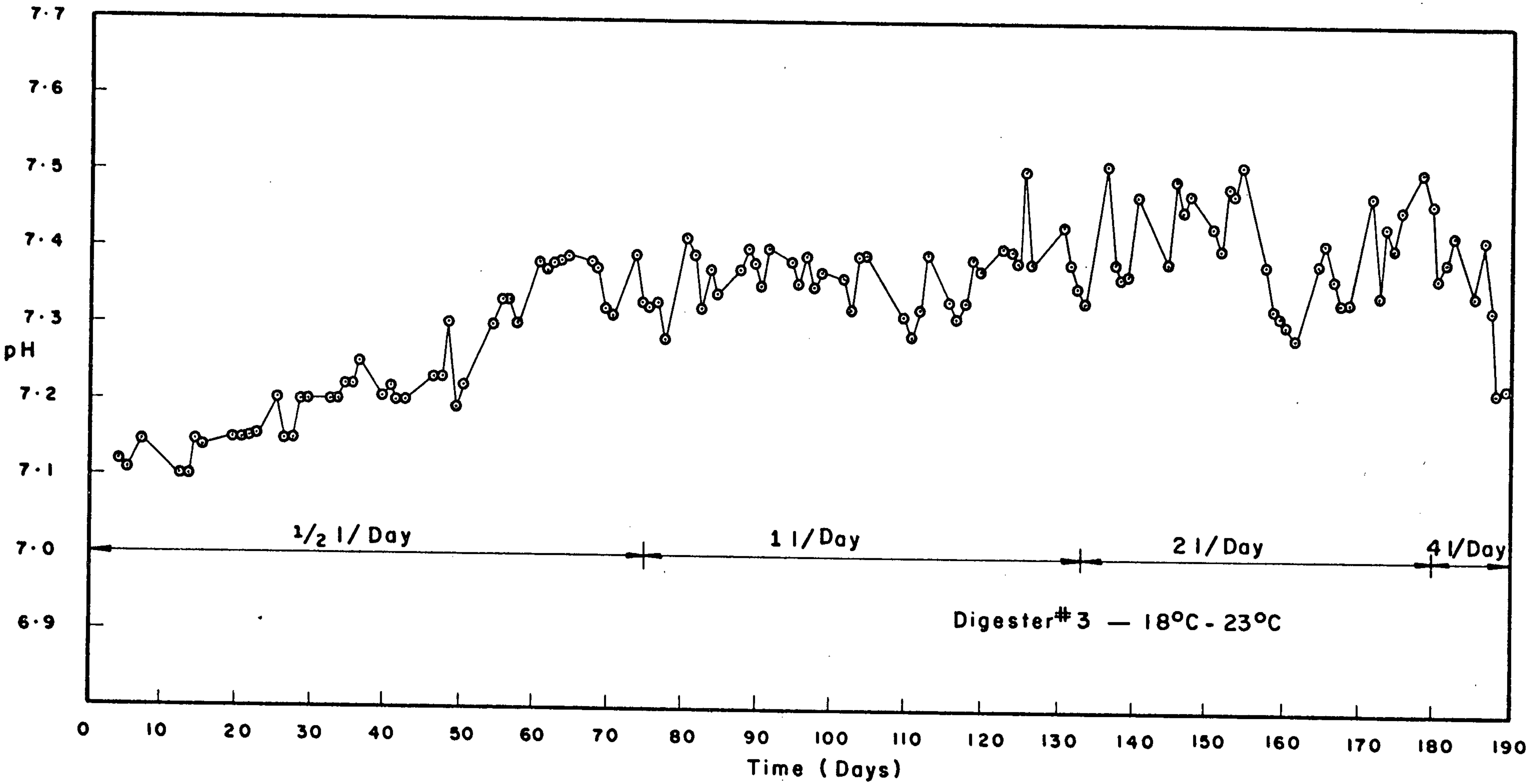

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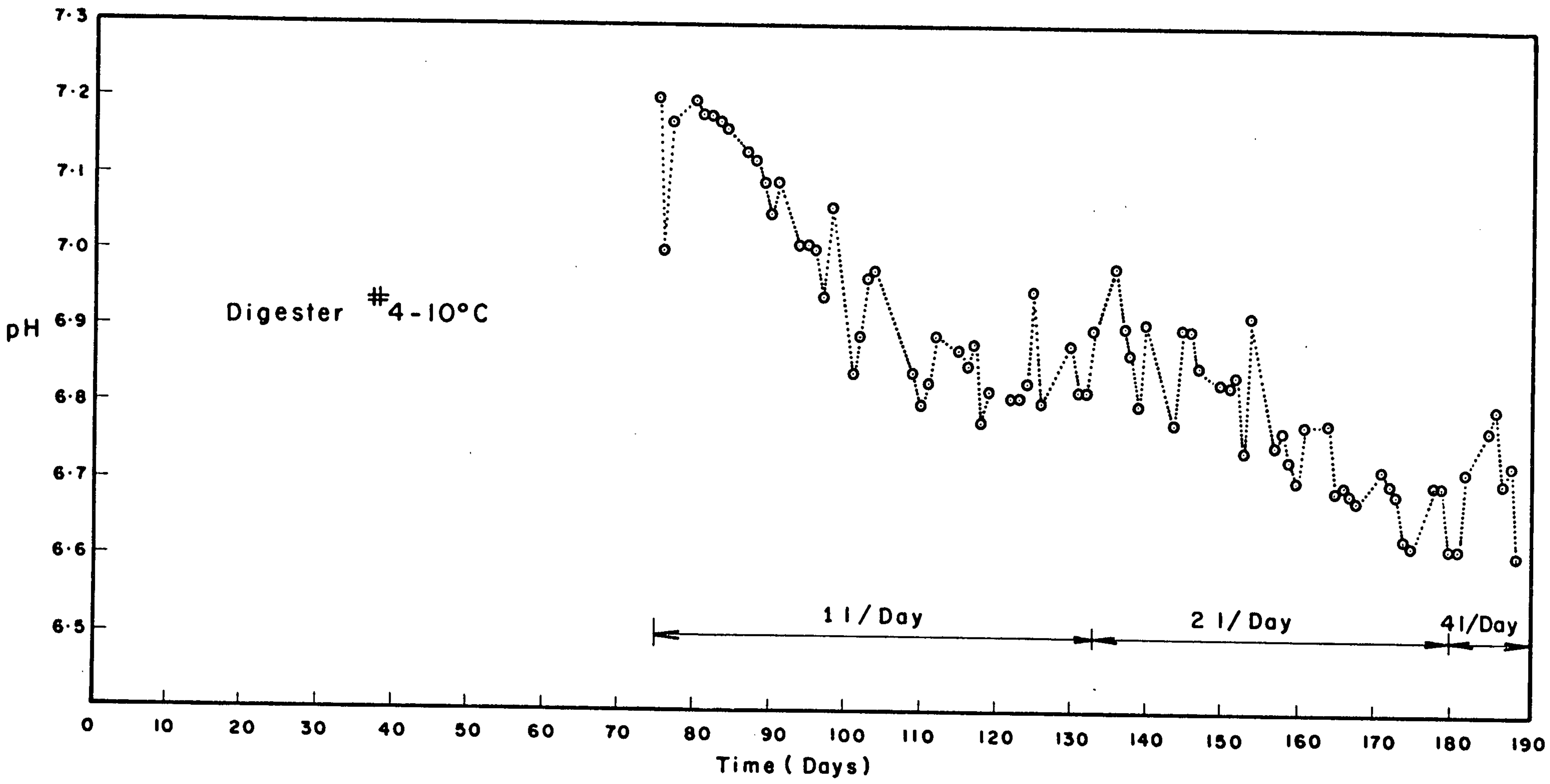

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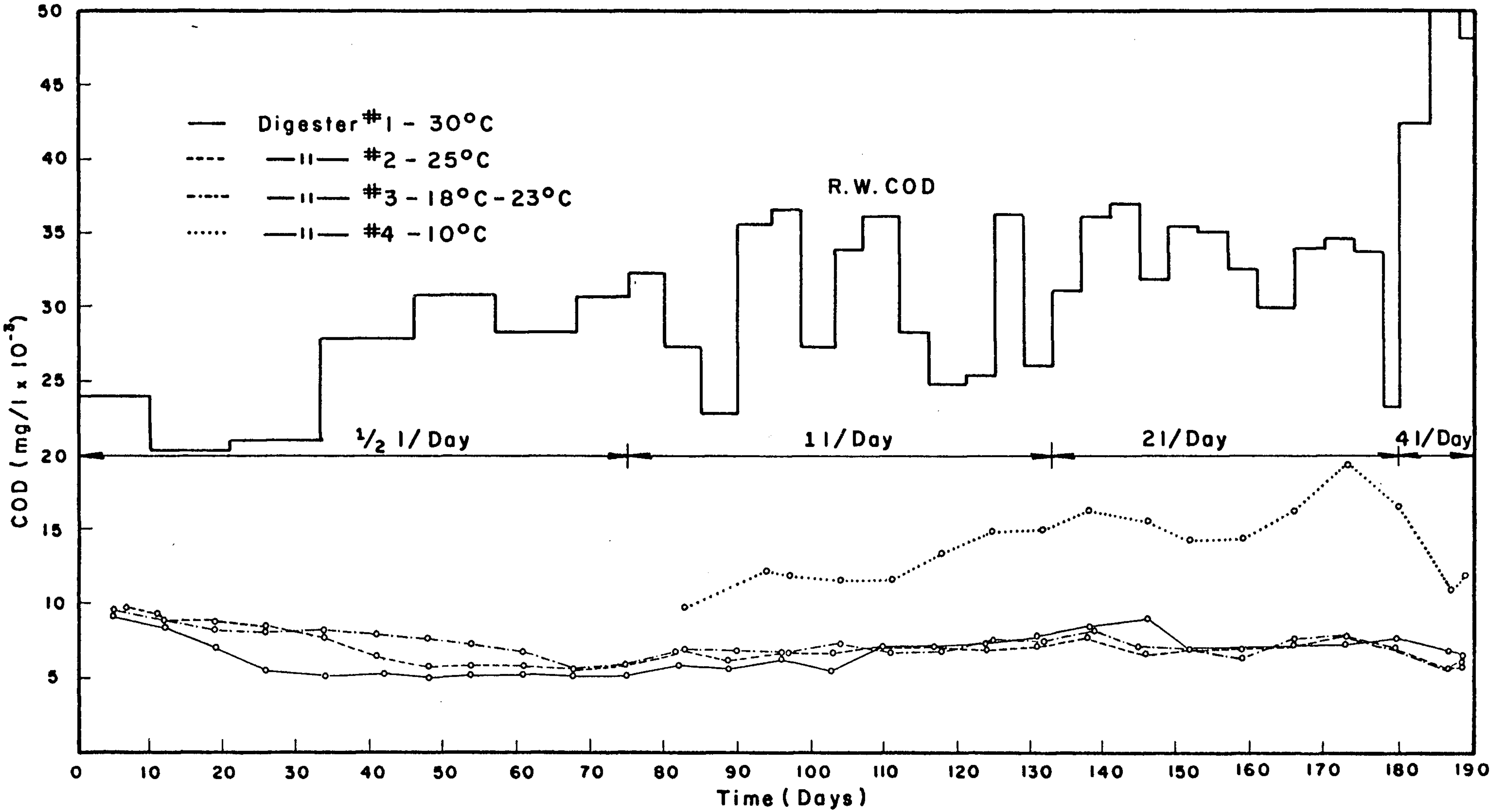
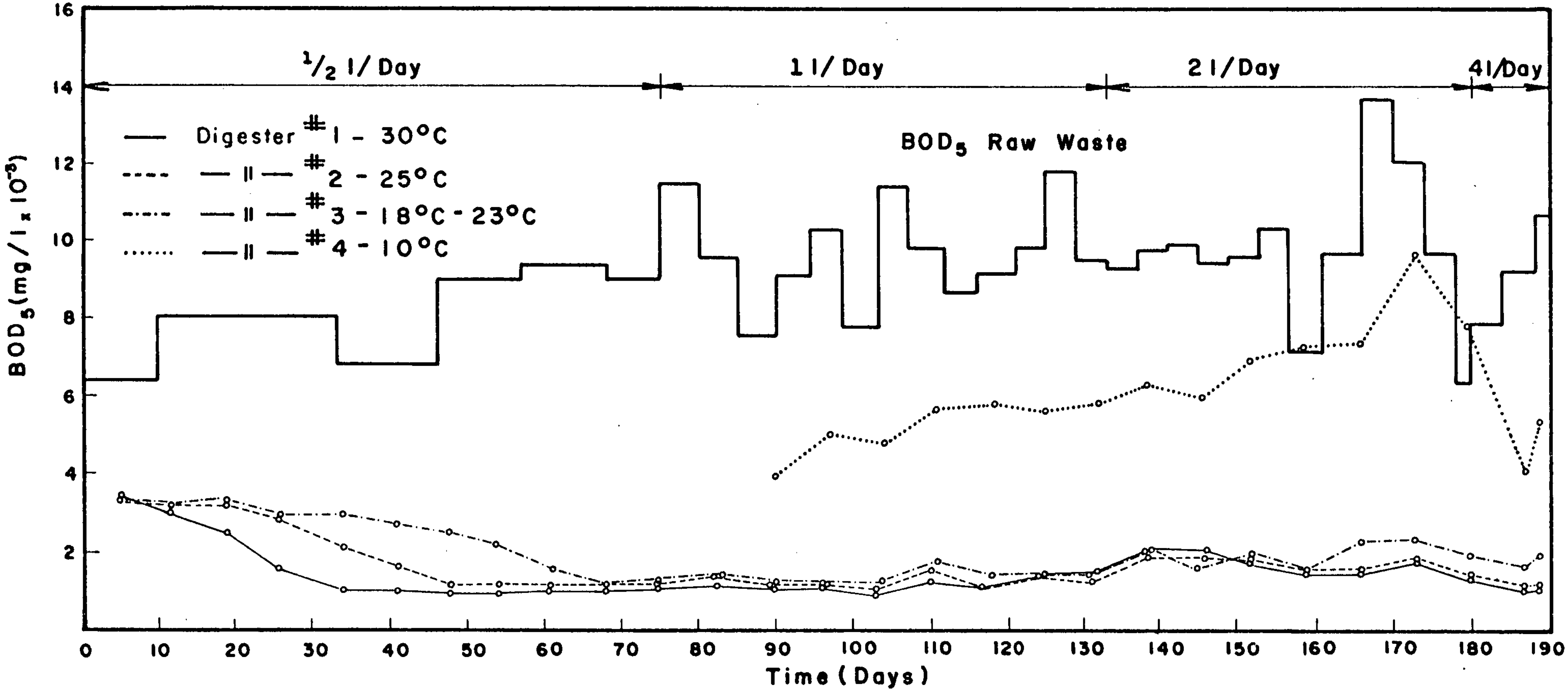
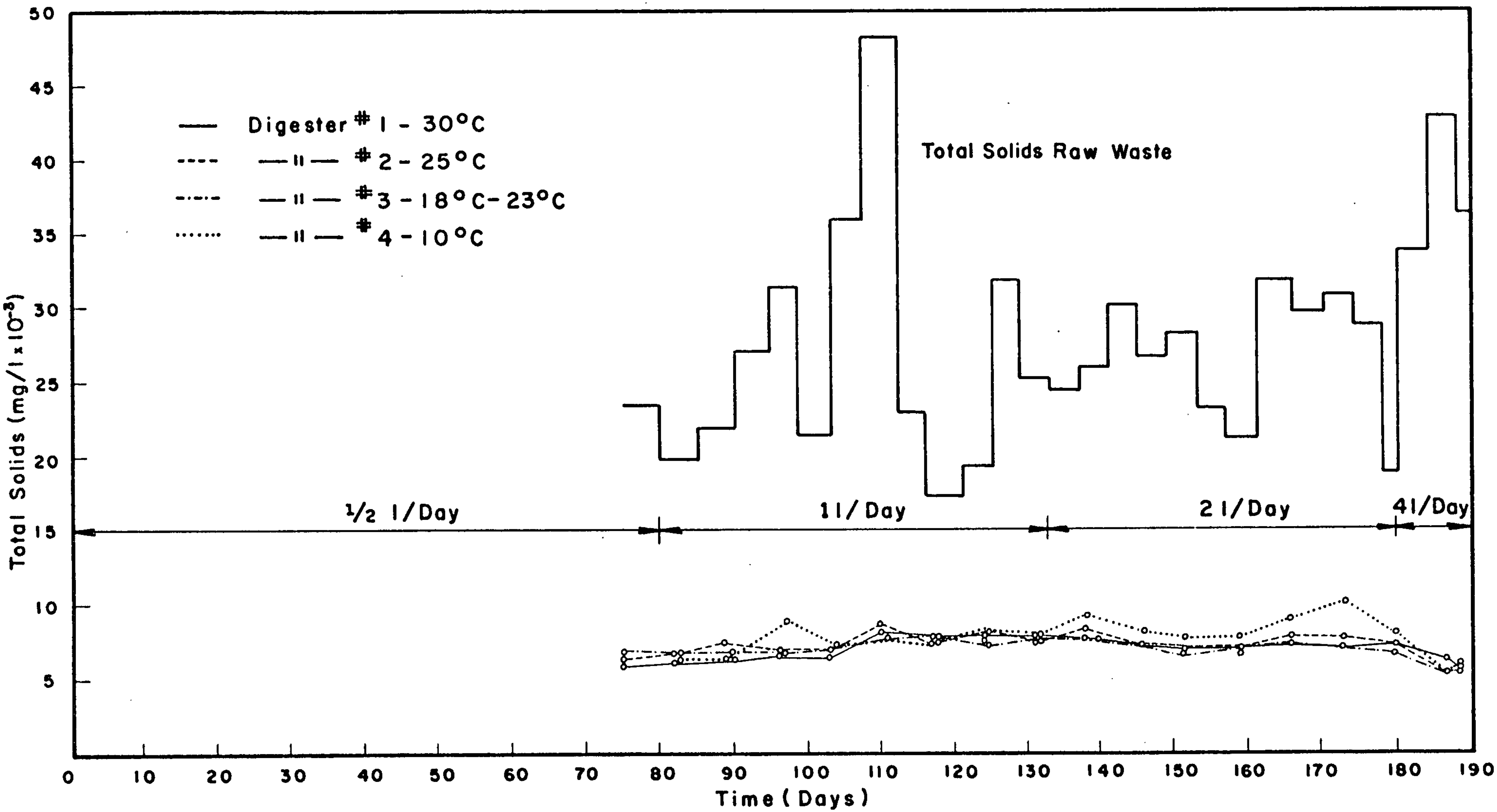


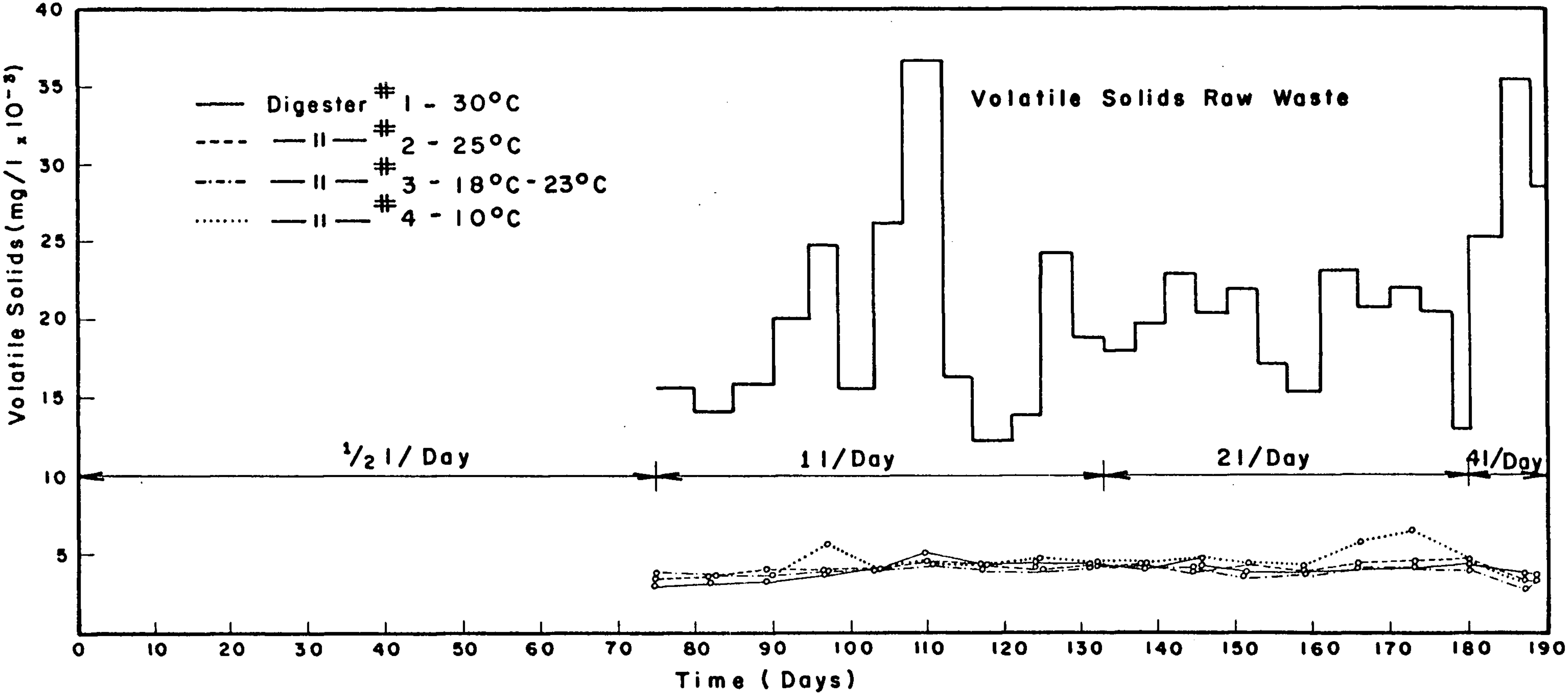
COD OF RAW WASTE & EFFLUENT AS RELATED TO THE FEEDING RATE.



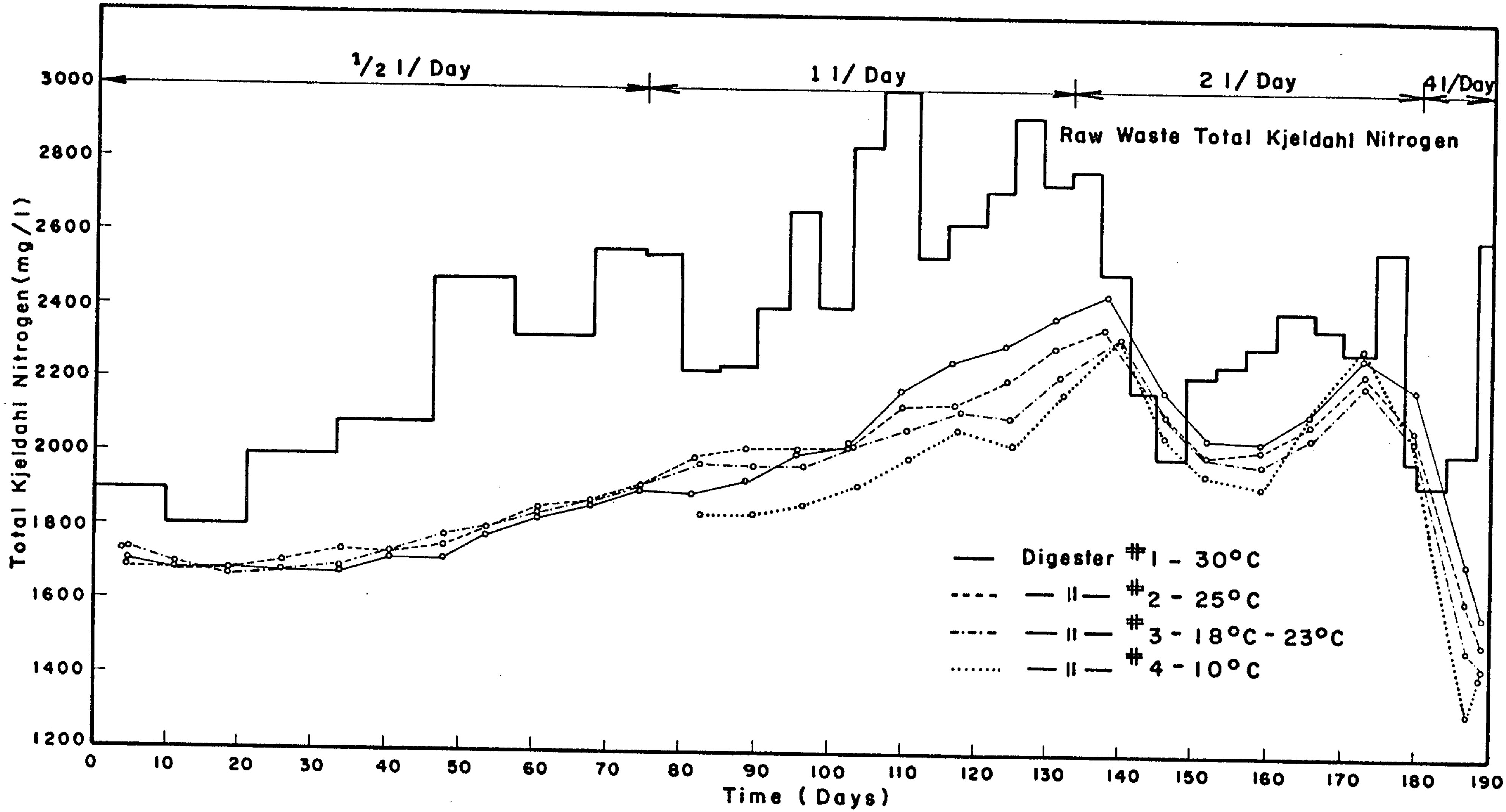
BOD$_5$ OF RAW WASTE & EFFLUENT AS RELATED TO THE FEEDING RATE.



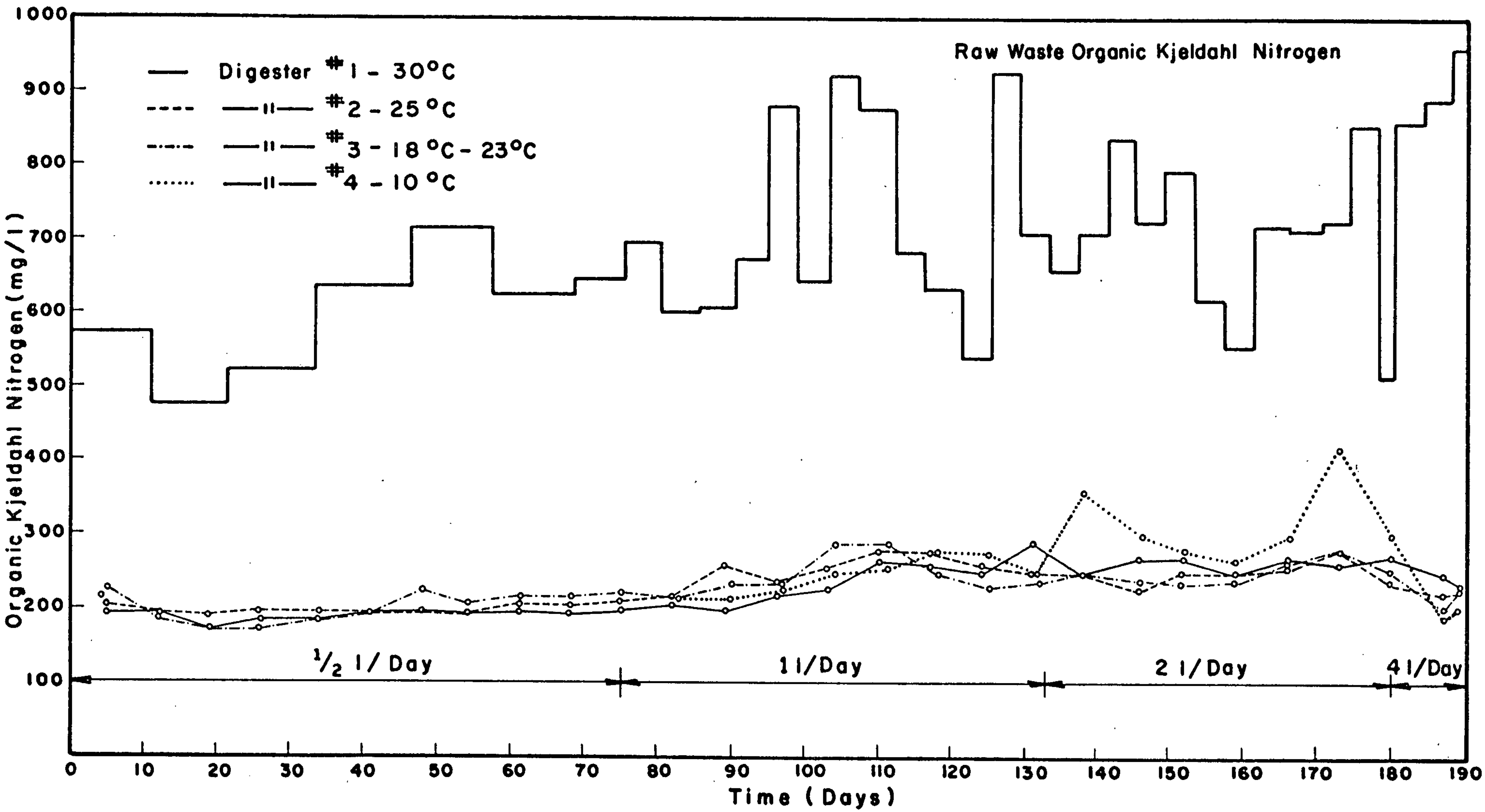
TS OF RAW WASTE & EFFLUENT AS RELATED TO THE FEEDING RATE.



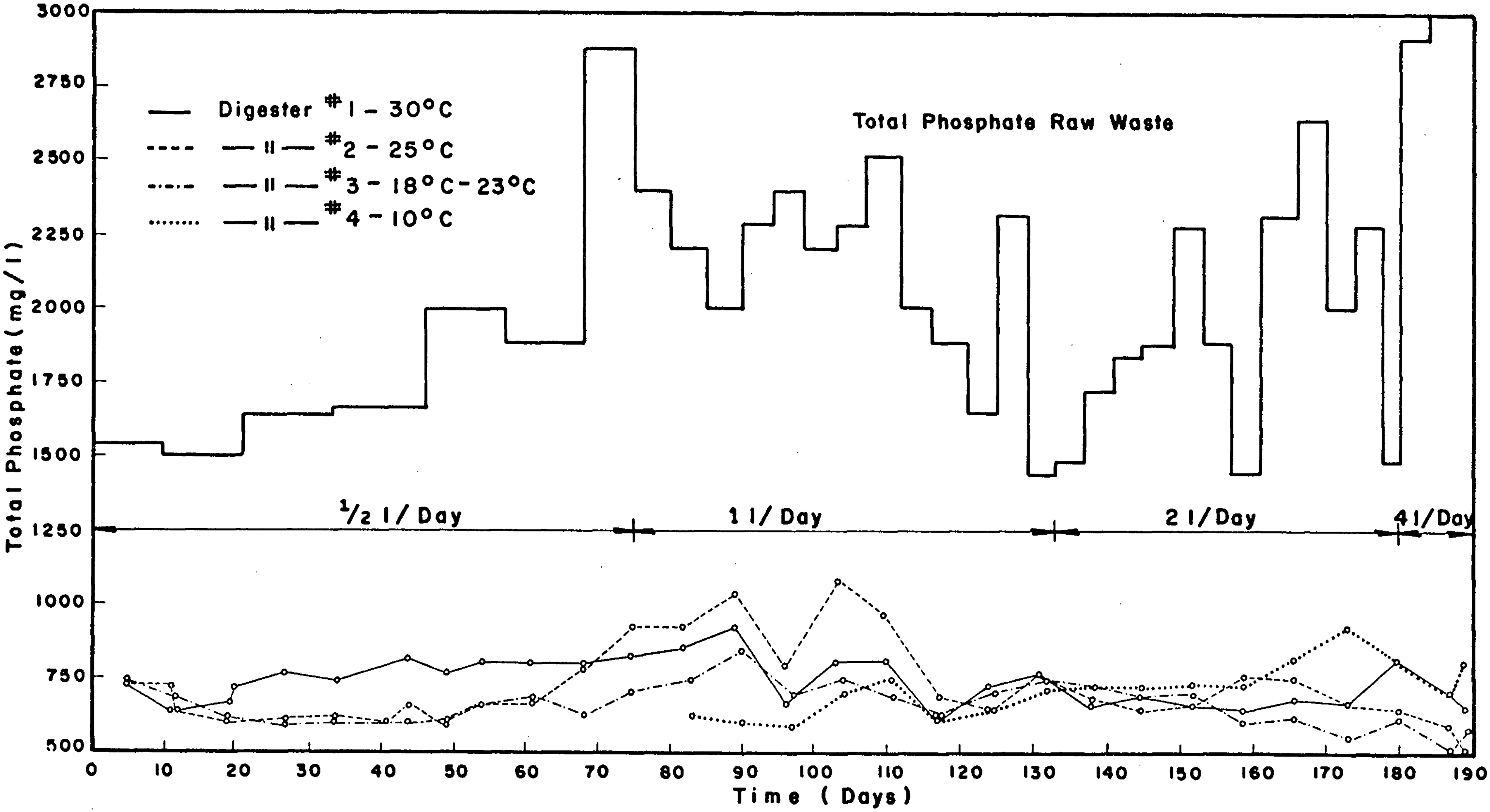
VS OF RAW WASTE & EFFLUENT AS RELATED TO THE FEEDING RATE.



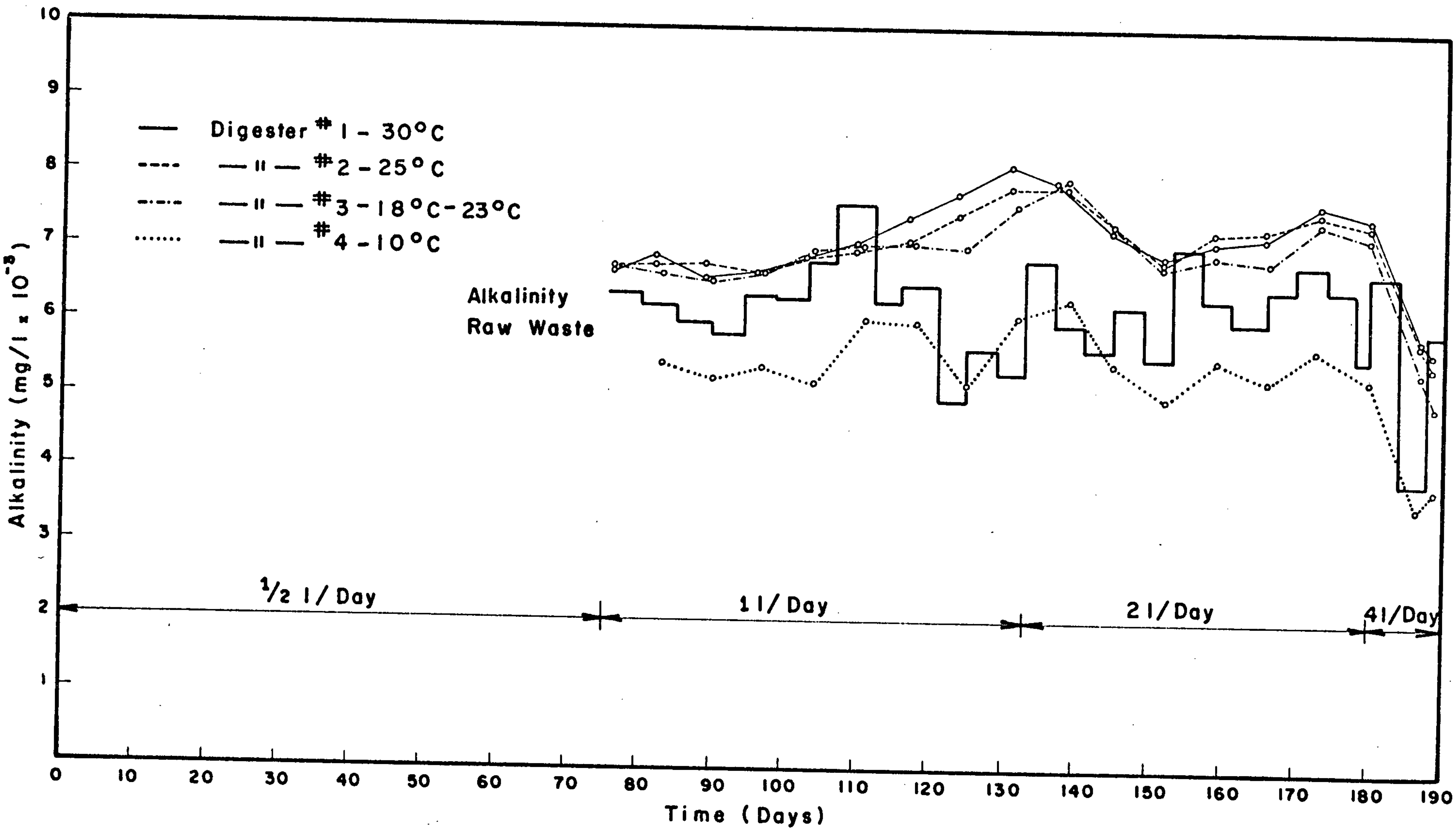
TOTAL KJELDAHL N OF RAW WASTE & EFFLUENT AS RELATED TO THE FEEDING RATE.



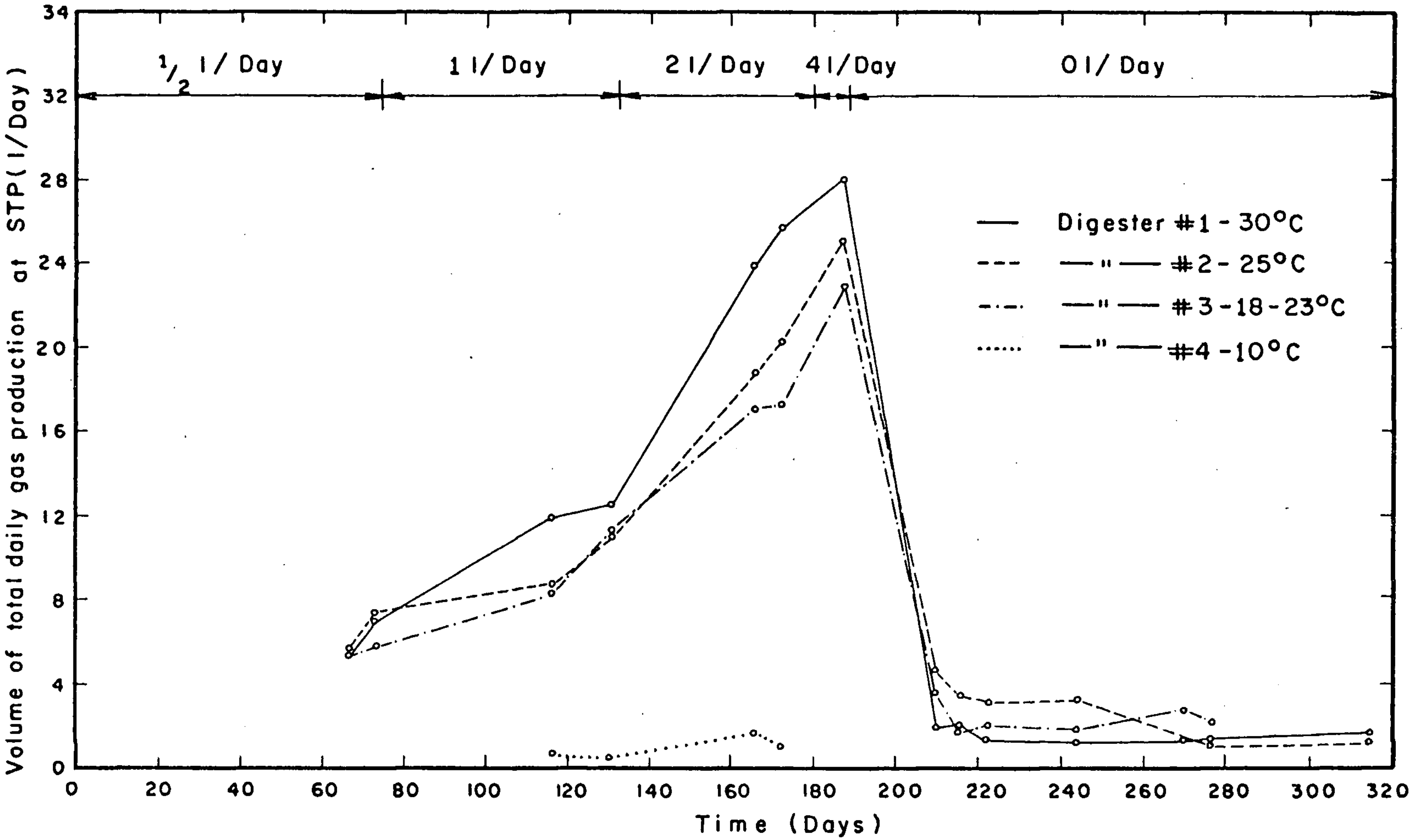
ORGANIC K.N OF RAW WASTE & EFFLUENT AS RELATED TO THE FEEDING RATE.



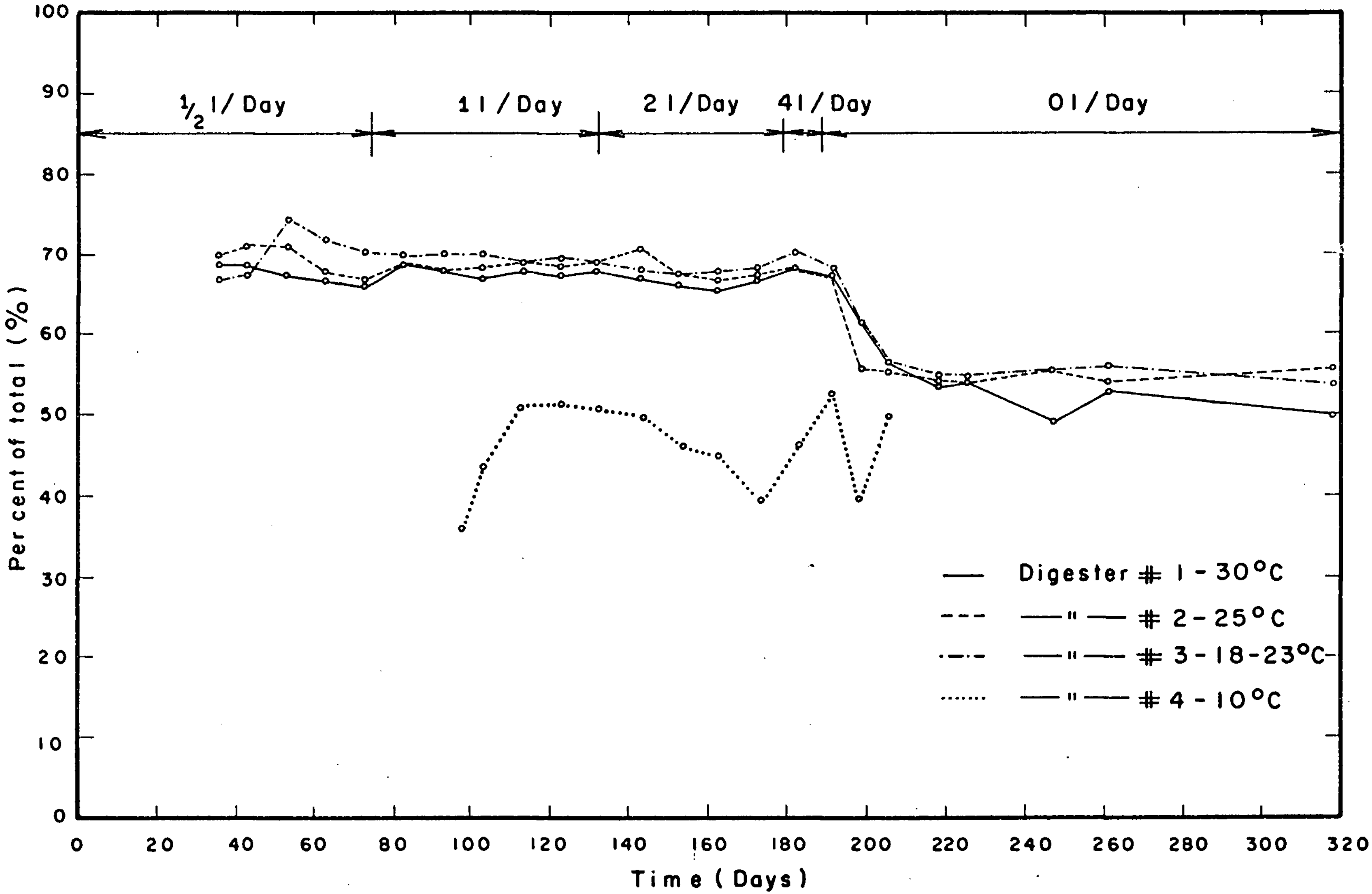
TOTAL PHOSPHATE OF RAW WASTE & EFFLUENT AS RELATED TO THE FEEDING RATE.



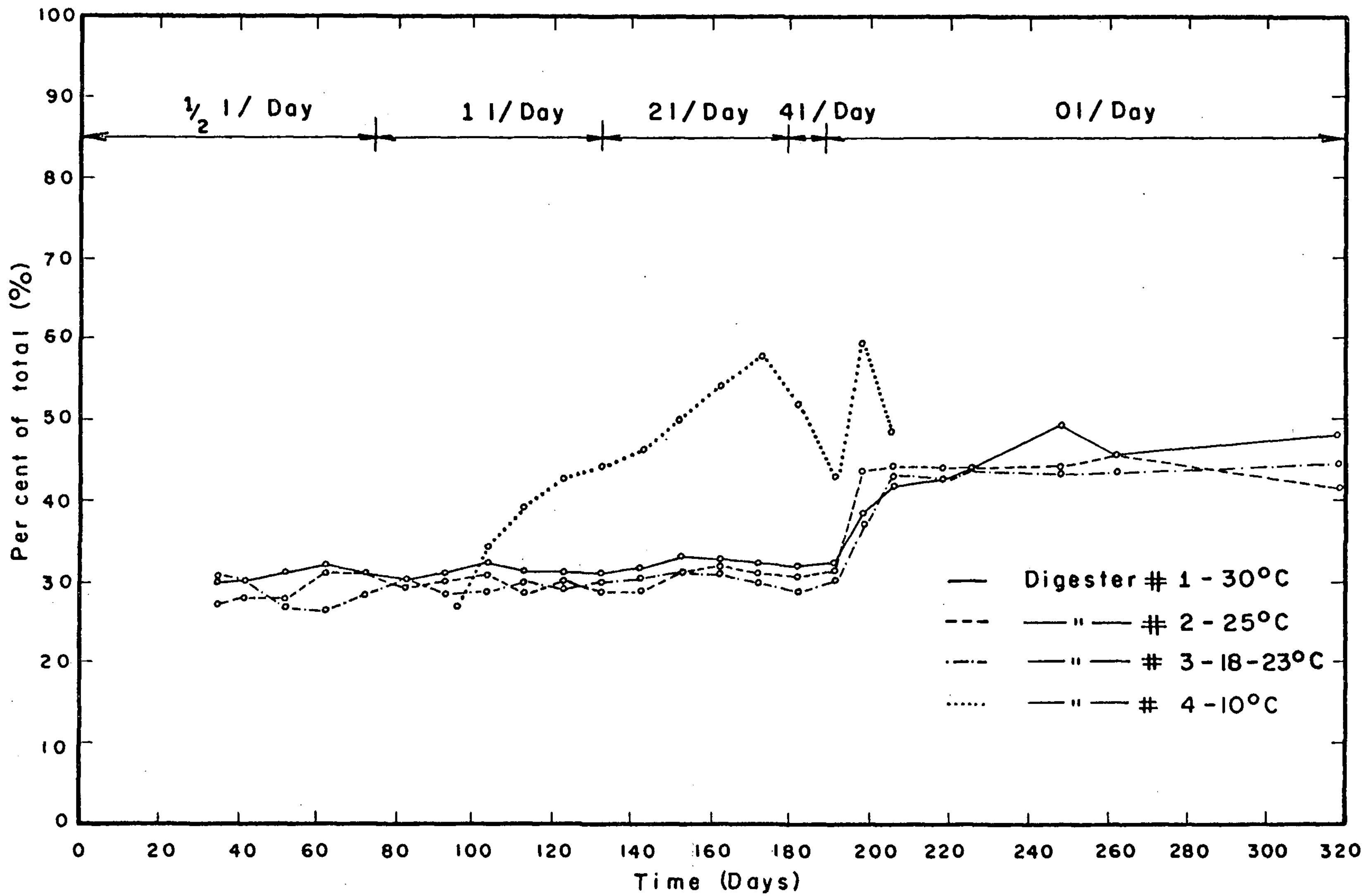
ALKALINITY OF RAW WASTE & EFFLUENT AS RELATED TO THE FEEDING RATE.



TOTAL GAS PRODUCED FOR SPECIFIC FEEDING RATE.



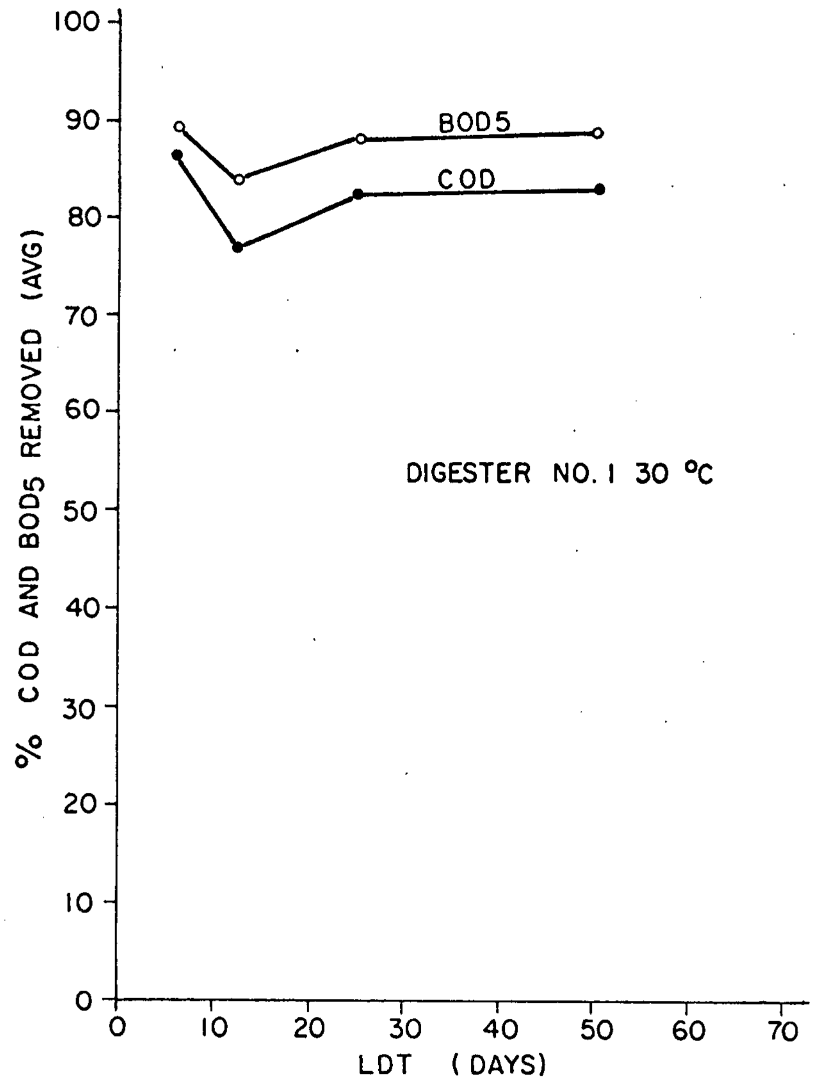
% METHANE GAS OF TOTAL GAS COMPOSITION.

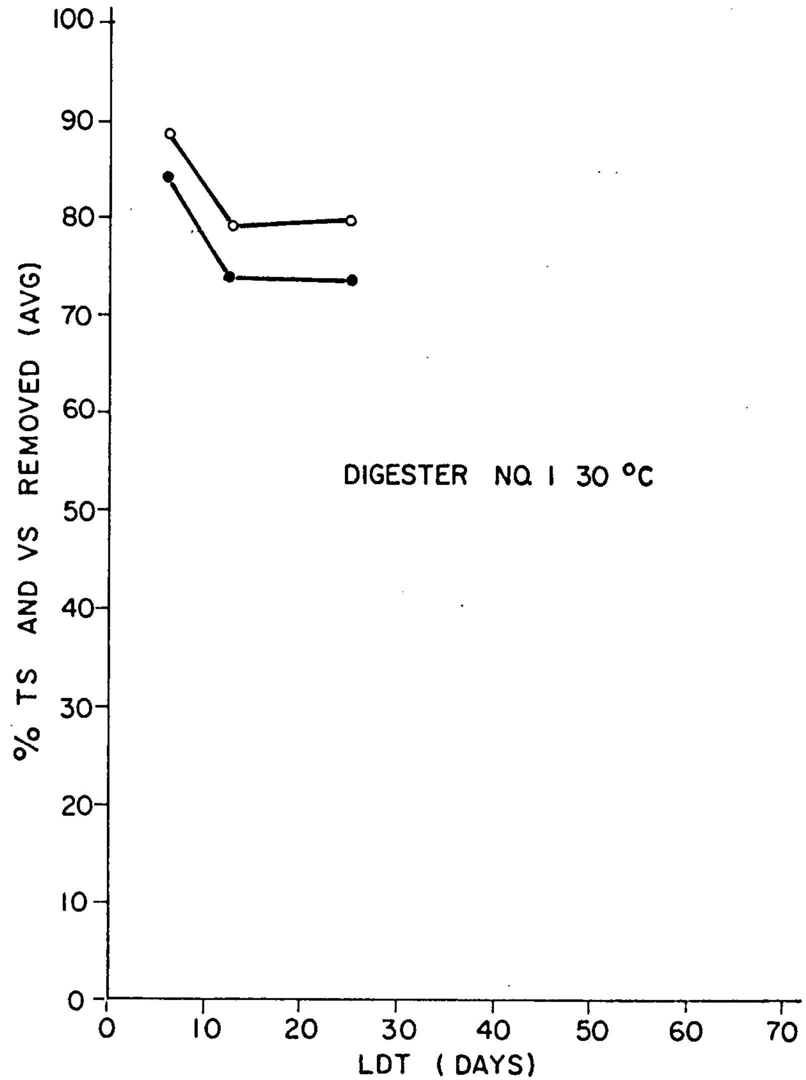


% CARBON DIOXIDE OF TOTAL GAS COMPOSITION.

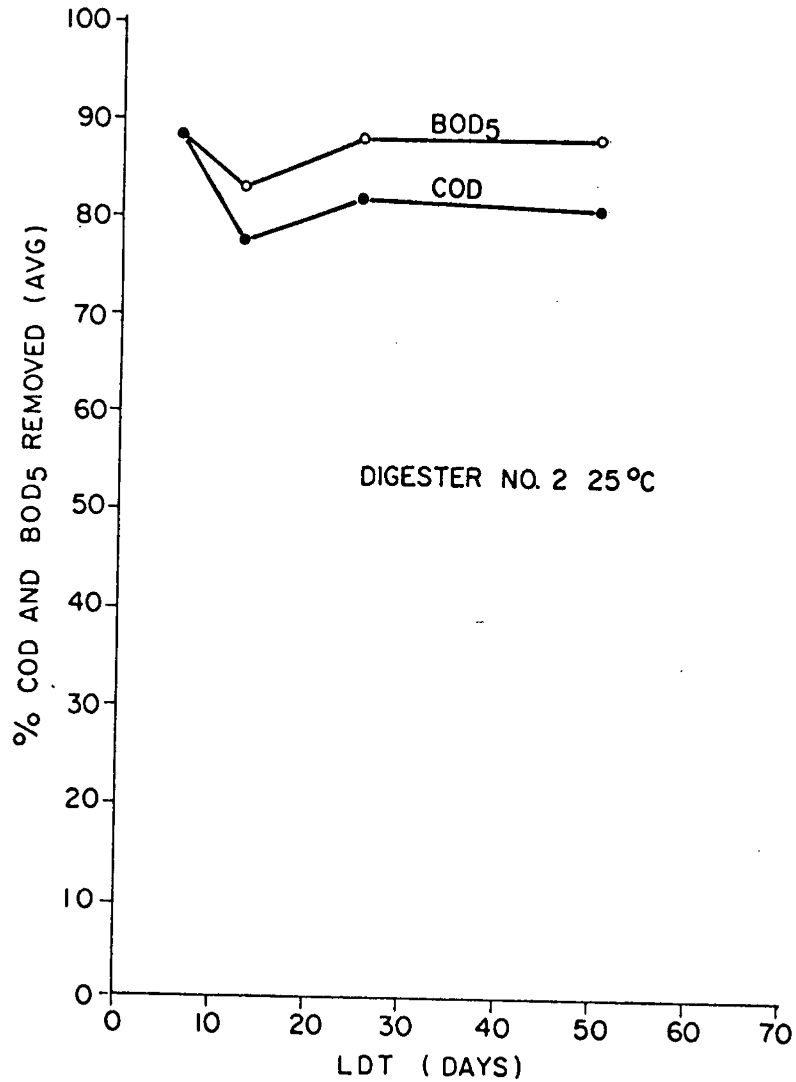
APPENDIX B

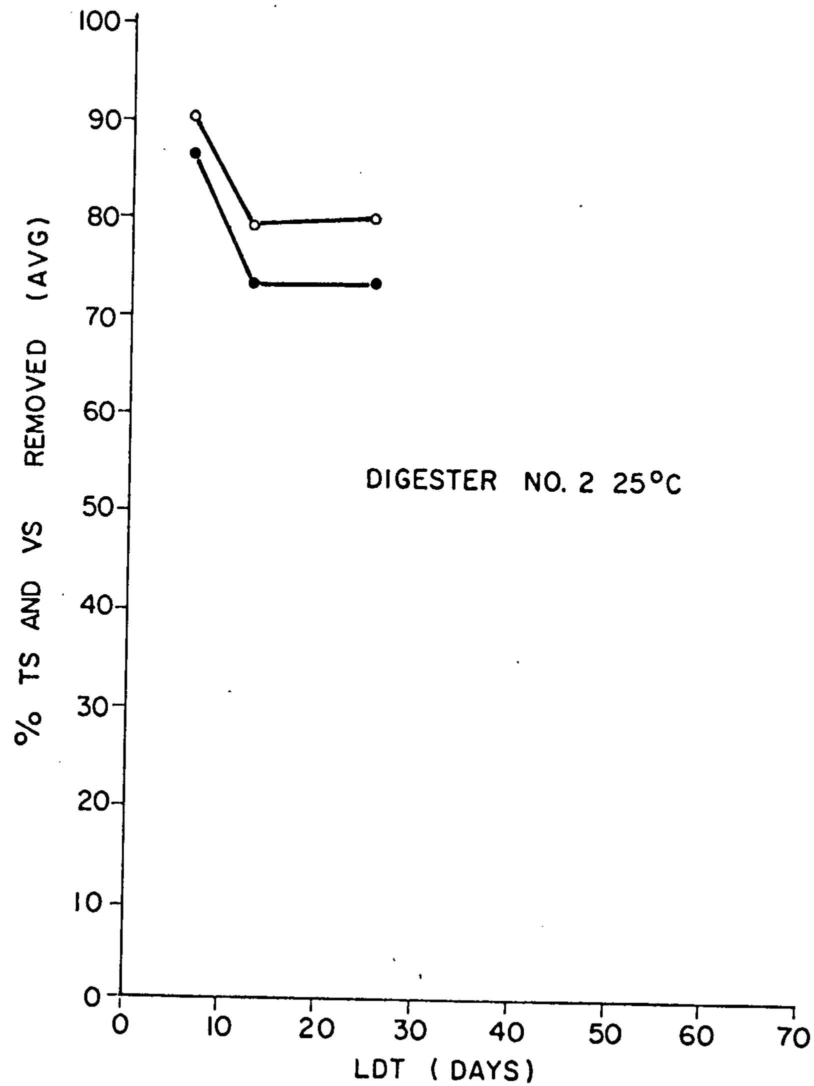
EFFECT OF DETENTION TIME ON COD, BOD_5 AND SOLIDS REMOVAL



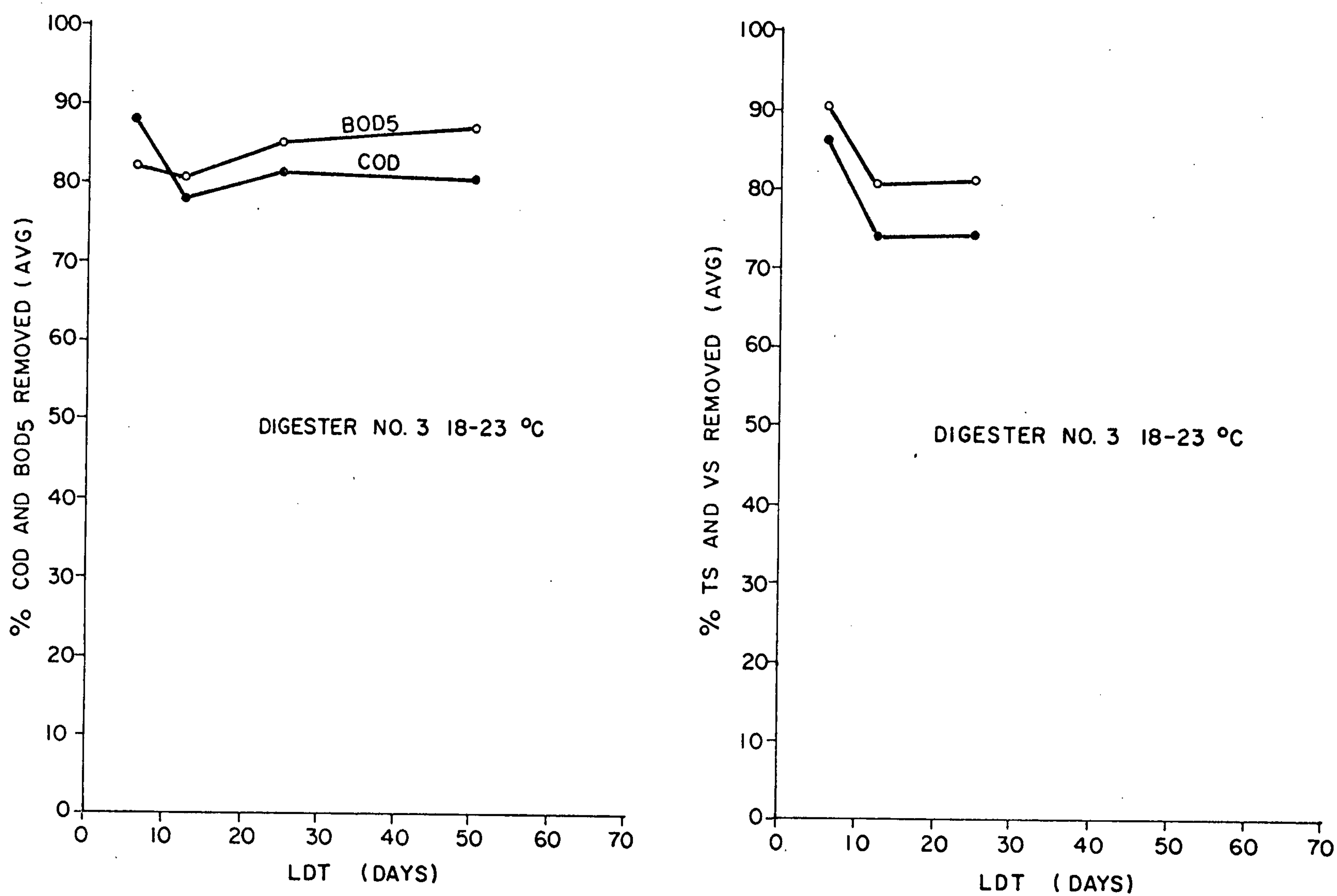


THE EFFECT OF DETENTION TIME ON COD, BOD5 & SOLIDS REMOVAL

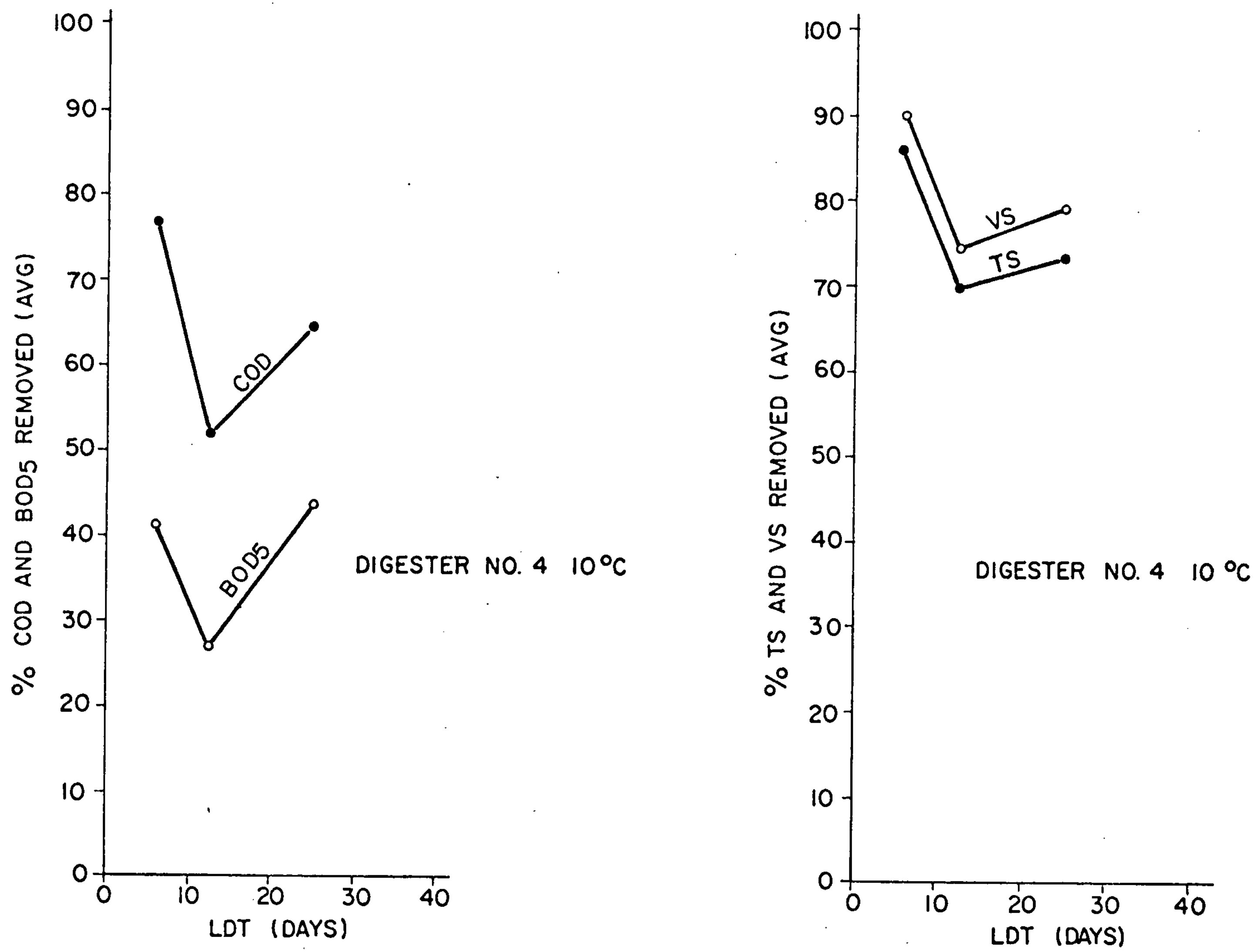




THE EFFECT OF DETENTION TIME ON COD, BOD_5 & SOLIDS REMOVAL



THE EFFECT OF DETENTION TIME ON COD, BOD_5 & SOLIDS REMOVAL

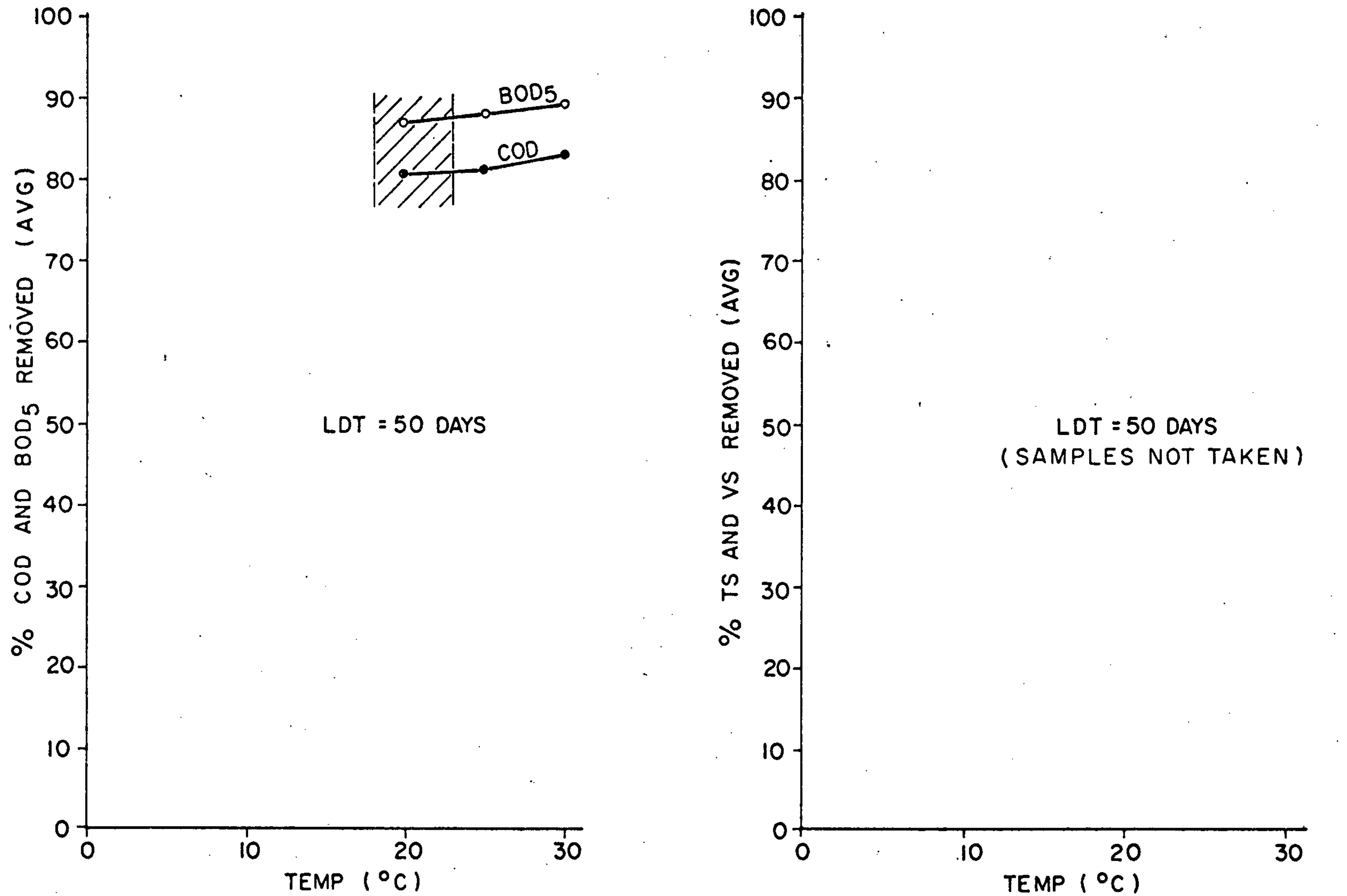


THE EFFECT OF DETENTION TIME ON COD, BOD_5 & SOLIDS REMOVAL

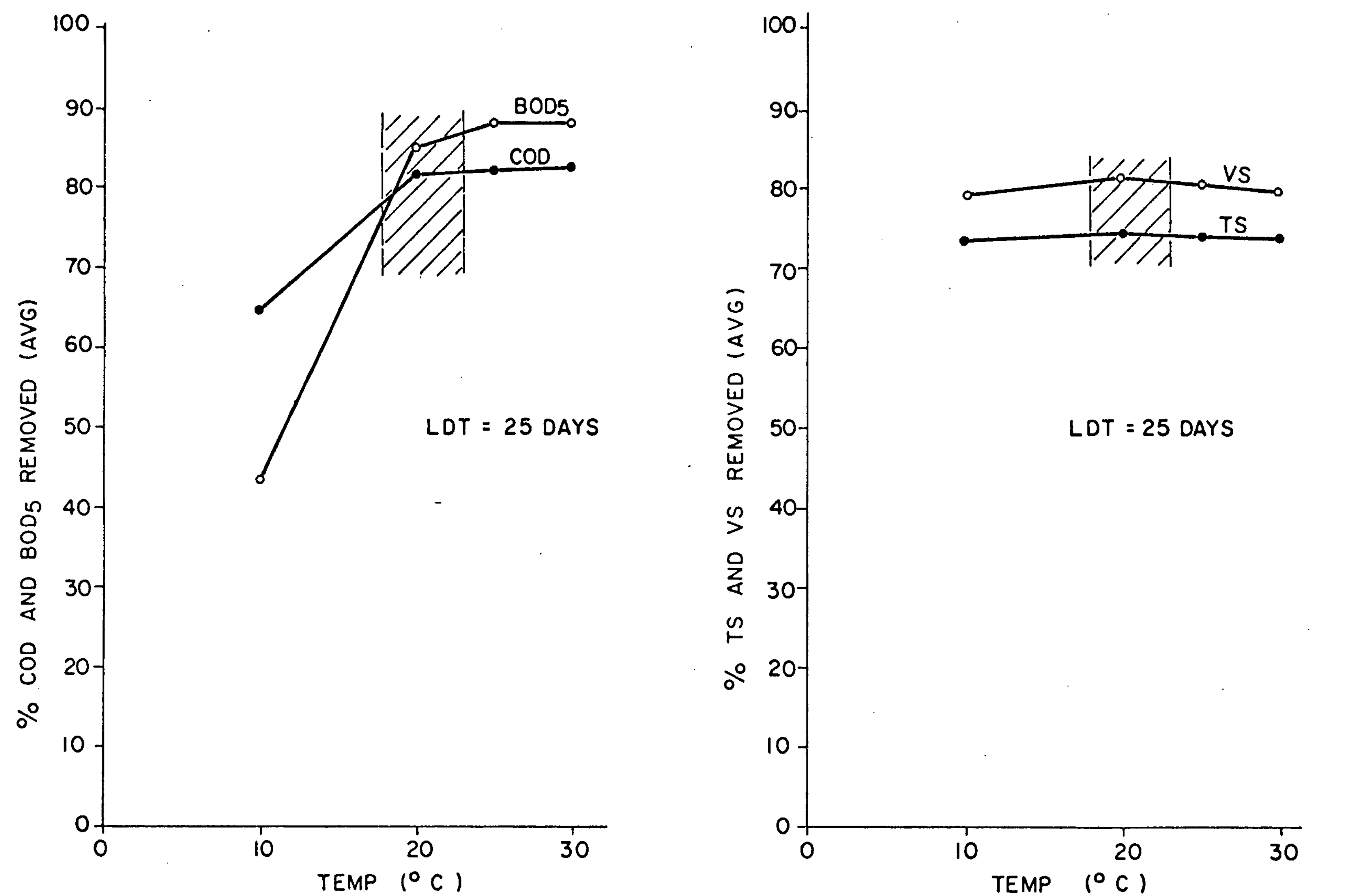
APPENDIX C

EFFECT OF TEMPERATURE ON COD,

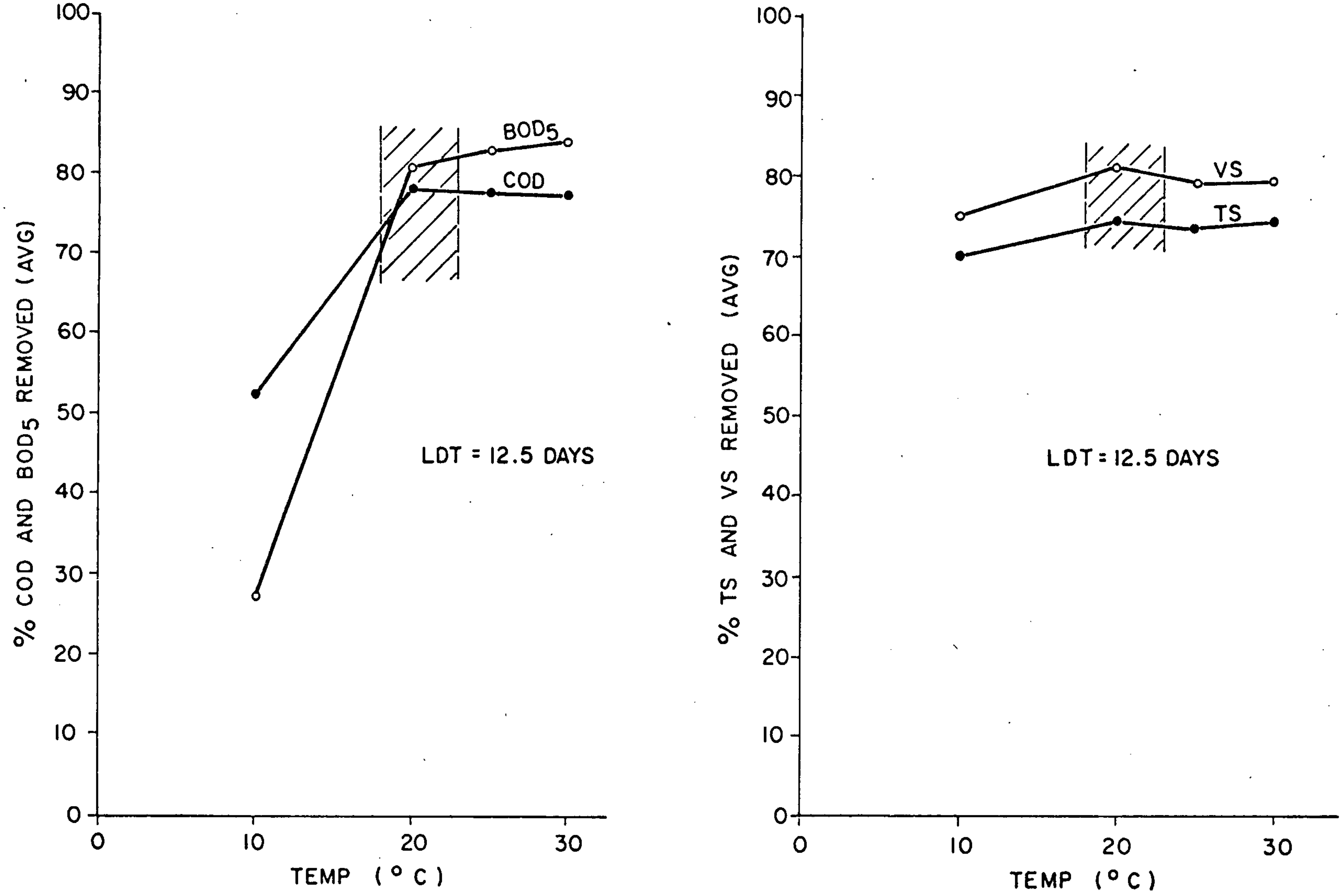
BOD_5 AND SOLIDS REMOVAL



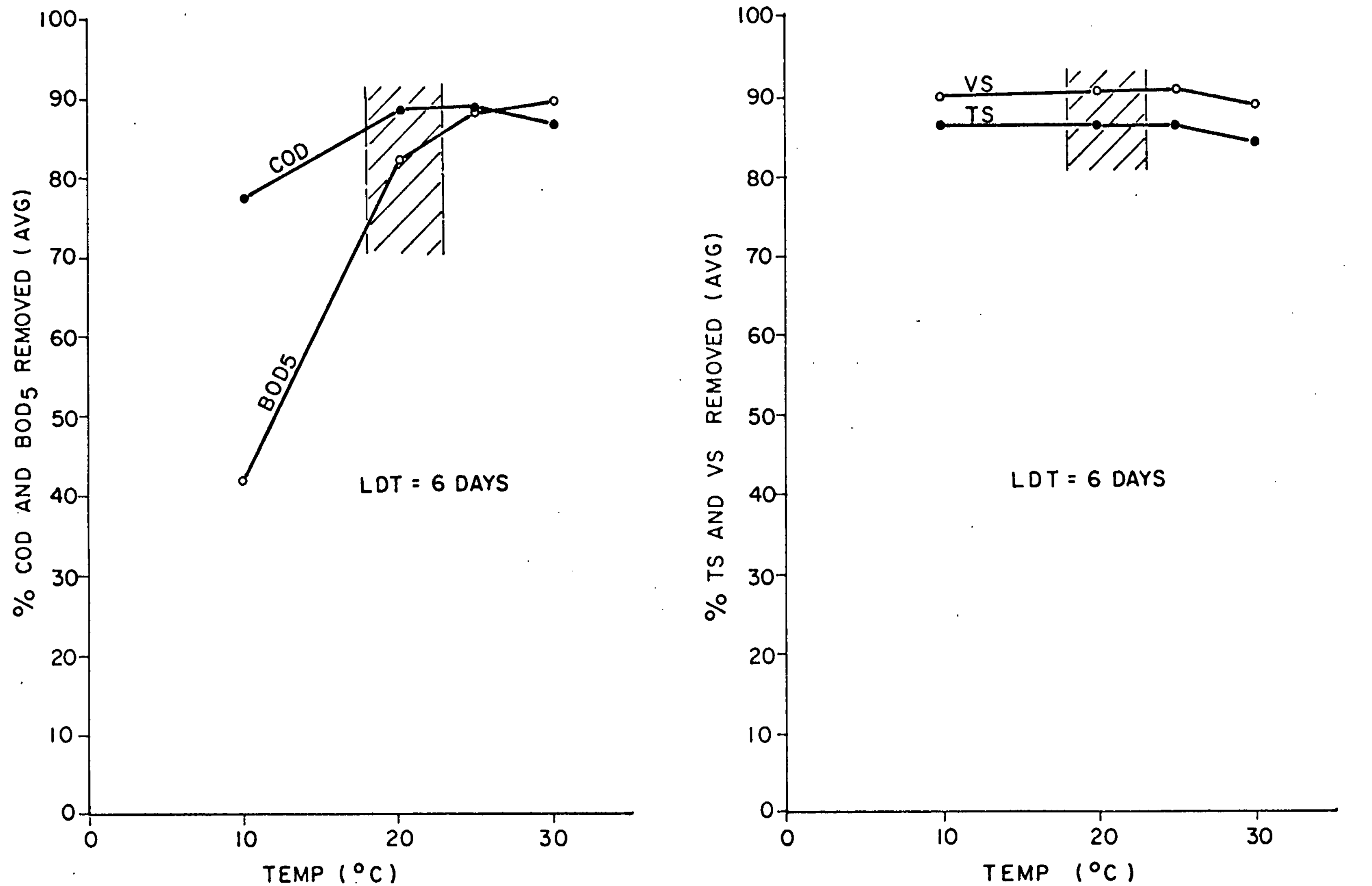
THE EFFECT OF TEMPERATURE ON COD, BOD_5 AND SOLIDS REMOVAL



THE EFFECT OF TEMPERATURE ON COD, BOD_5 AND SOLIDS REMOVAL



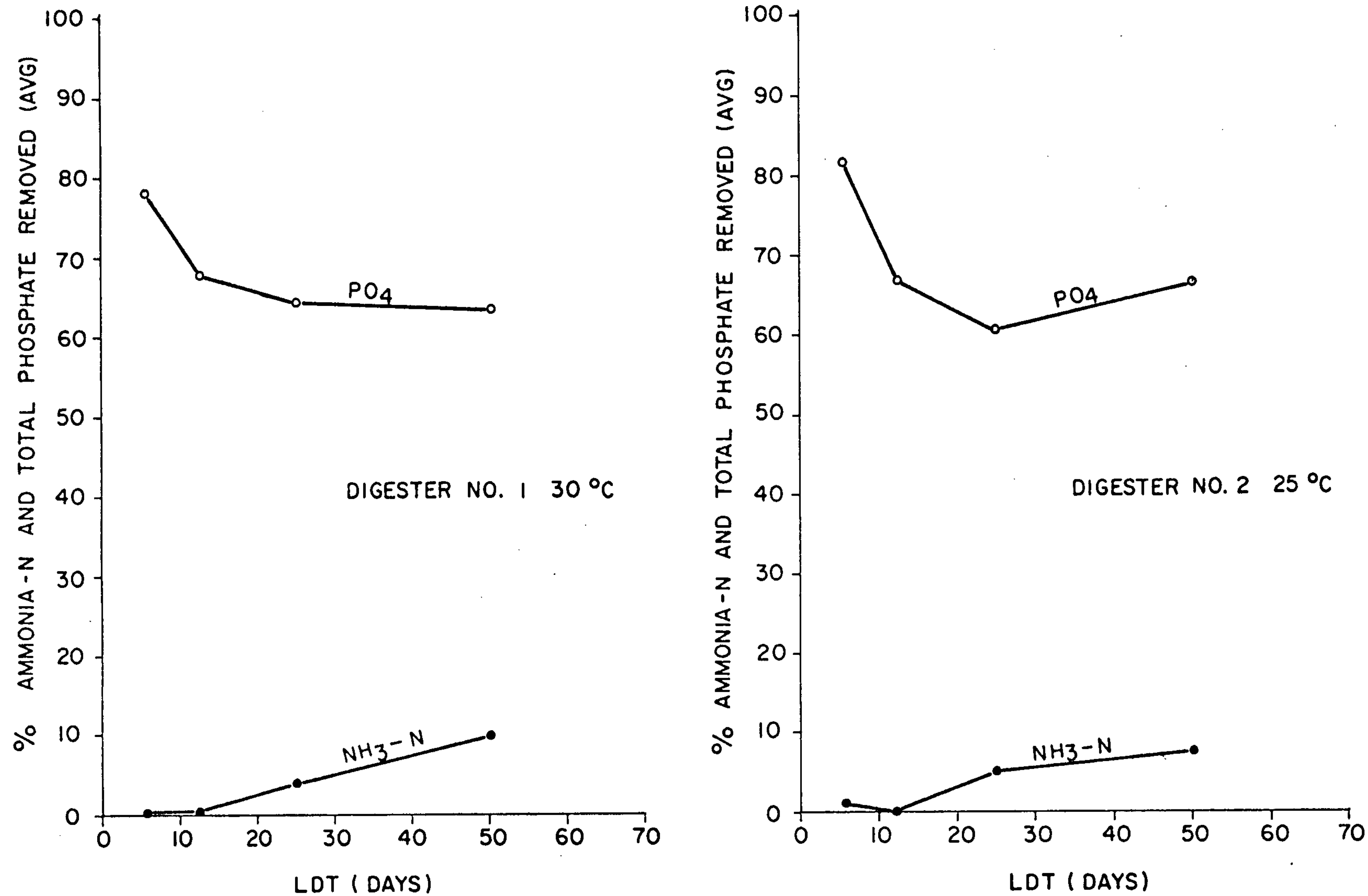
THE EFFECT OF TEMPERATURE ON COD, BOD_5 AND SOLIDS REMOVAL



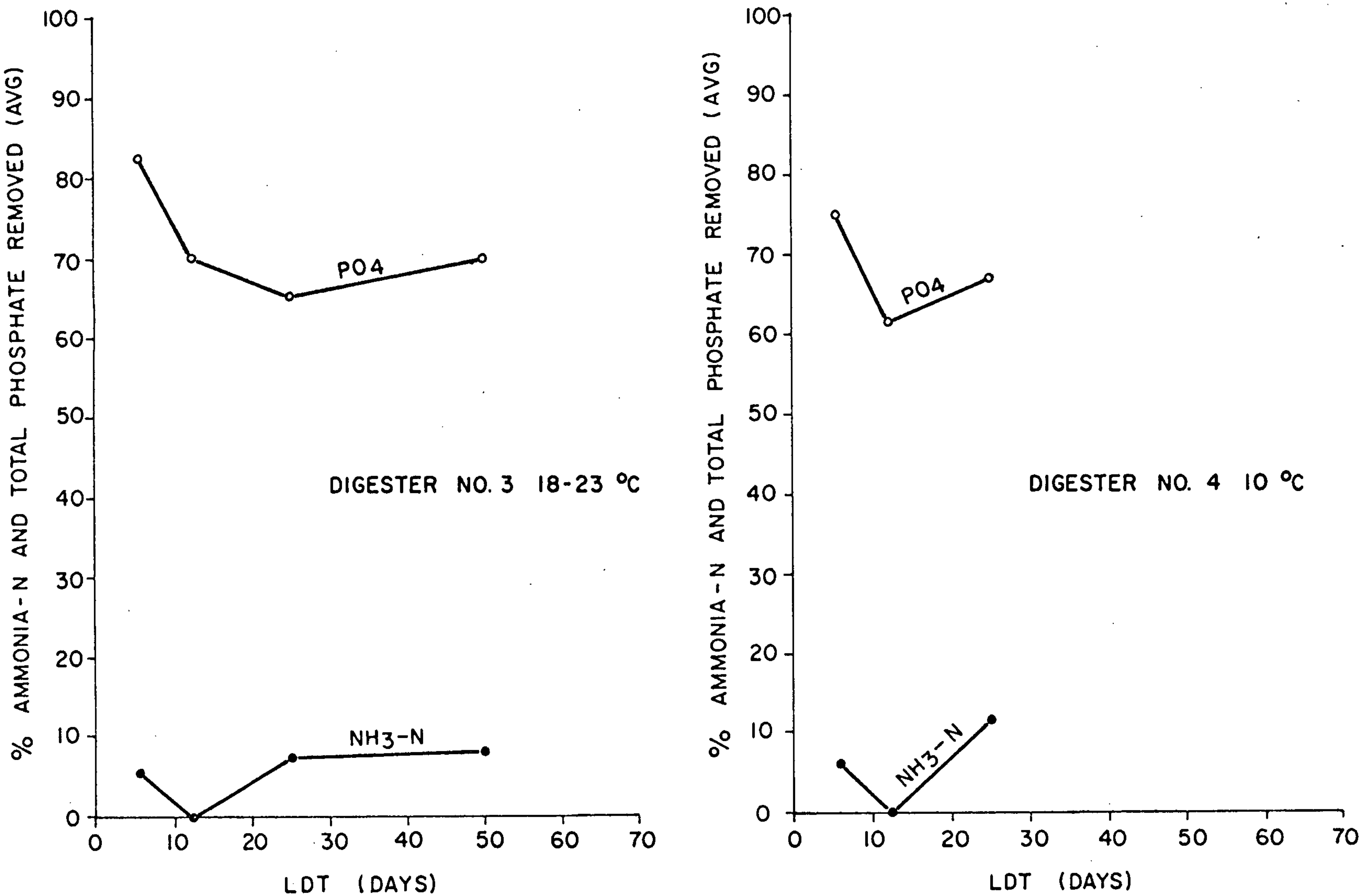
THE EFFECT OF TEMPERATURE ON COD, BOD_5 AND SOLIDS REMOVAL

APPENDIX D

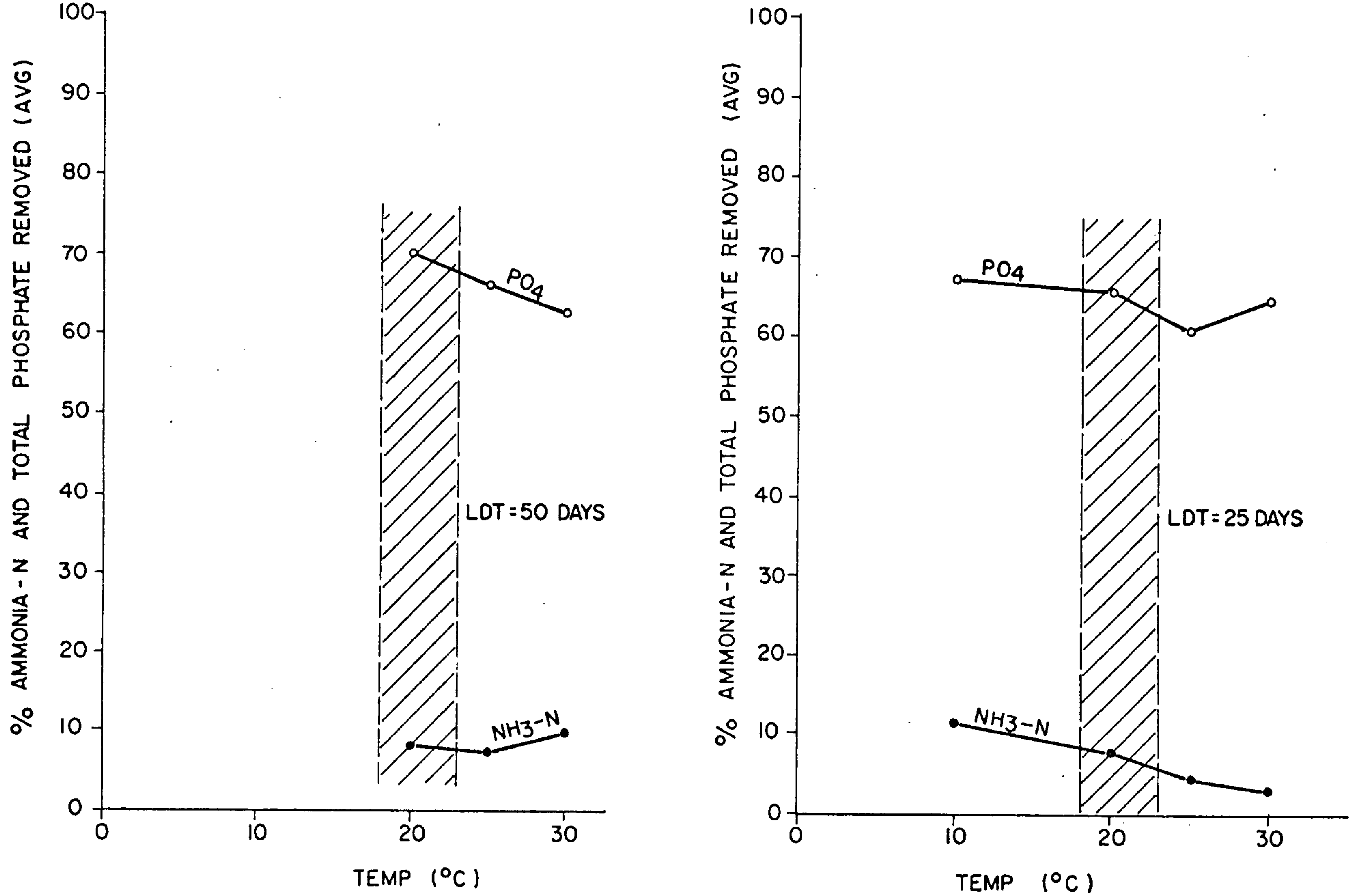
EFFECT OF DETENTION TIME AND TEMPERATURE ON AMMONIA-N AND TOTAL PHOSPHATE REMOVAL



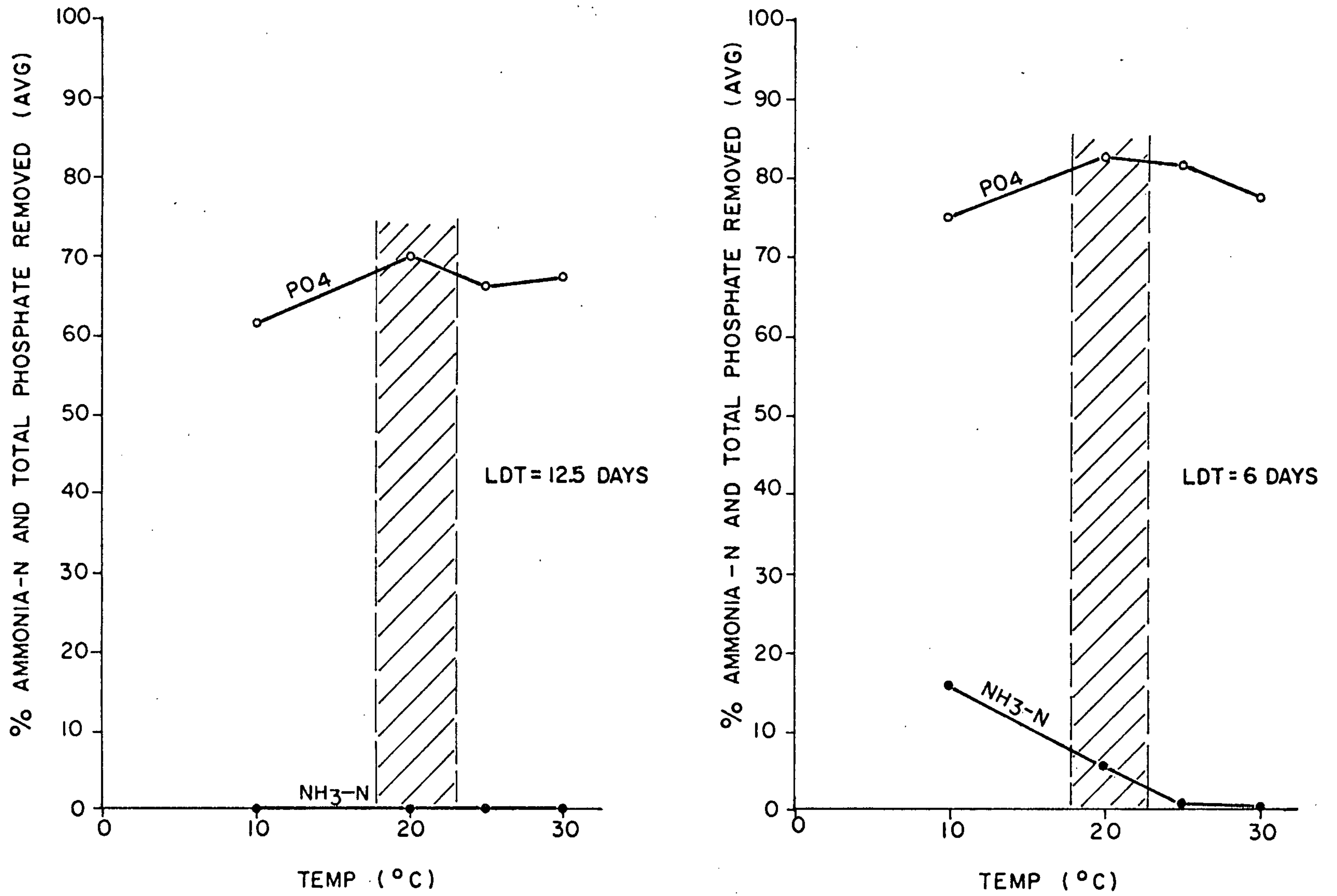
THE EFFECT OF DETENTION TIME ON AMMONIA-N AND TOTAL PHOSPHATE REMOVAL



THE EFFECT OF DETENTION TIME ON AMMONIA-N AND TOTAL PHOSPHATE REMOVAL



THE EFFECT OF TEMPERATURE ON AMMONIA-N AND TOTAL PHOSPHATE REMOVAL



THE EFFECT OF TEMPERATURE ON AMMONIA - N AND TOTAL PHOSPHATE REMOVAL

APPENDIX E

SAMPLE CALCULATIONS

CASE I - COD

Cm = $m\ell$ of CH_4 produced per day

k_1 = 2.85 mg COD/$m\ell$ CH_4

F = mg of COD reduced per day

for Temp. = 30°C

LDT = 50 days

COD reduced:

$$F = k_1 \, Cm$$

$$= 2.85(1225)$$

$$= 3490 \text{ mg/day}$$

Loading of COD = 14675 mg/day

% COD biologically reduced:

$$\frac{3490}{14675} \times 100 = 24\%$$

CASE II - BOD_5

$$Cm = m\ell \text{ of } CH_4 \text{ produced per day}$$

$$k_1 = 2.85 \text{ mg } BOD_5/m\ell \; CH_4$$

$$F = \text{mg of } BOD_5 \text{ reduced per day}$$

$$\text{for Temp.} = 30^\circ C$$

$$LDT = 50 \text{ days}$$

BOD_5 reduced:

$$F = k_1 \; Cm$$

$$= 2.85(1225)$$

$$= 3490 \text{ mg/day}$$

Loading of BOD_5 = 4600 mg/day

% BOD_5 biologically reduced:

$$\frac{3490}{4600} \times 100 = 76\%$$

CASE III - VS

C_t = mℓ of gas produced per day

k_2 = 0.73-0.94 mg VS/mℓ gas produced (65-70% CH_4)

P = mg of VS reduced per day

for Temp. = 30°C

LDT = 25 day

VS reduced:

$P = k_2 C_t$

(i) for $k_2 = 0.73$

$P = 0.73(2750)$

$= 2010$

(ii) for $k_2 = 0.94$

$P = 0.94(2750)$

$= 2600$

Loading of VS = 15300 mg/day

% VS biologically reduced:

$\frac{2010}{15300} \times 100 = 13.2\%$ (for $k_2 = 0.73$)

$\frac{2600}{15300} \times 100 = 17\%$ (for $k_2 = 0.94$)