TWO-STAGE ANAEROBIC DIGESTION OF HOG WASTES

BY

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ABSTRACT

The present trend towards concentrated land-use animal farming has given rise to a number of new animal waste disposal problems due to the very high strength of liquid wastes from such facilities.

One treatment alternative applicable to these wastes is anaerobic digestion. A study was undertaken to determine the anaerobic digestion characteristics of waste from a high-density hog-raising facility. Earlier work had provided treatment efficiency data for a single-stage, laboratory-scale anaerobic reactor, as well as giving certain design criteria for anaerobic lagoons.

The present study was intended to provide a measure of the increase in treatment efficiency obtained through use of a two-stage anaerobic reactor, again on a laboratory scale, and to give information regarding biodegradability of the settled sludge. The effect of variations in temperature and detention time was included in the study, as was an investigation of volatile acids, total organic carbon, and copper toxicity due to the use of brass fittings in test apparatus.

Conclusions reached on the basis of this study were that the two-stage system gives a slightly higher loading capacity, due to improved settling capability, but the effluent from the second cell is still of higher strength than is often desirable for discharge to receiving waters. The settled solids were found to be degradable to a limited extent only, and thus most of them will require physical removal from a lagoon. No significant correlation was found between BOD, COD, and TOC and copper levels were found to reach significant levels in the reactors.

This report was based on laboratory findings only. No correlation between laboratory-scale and field results was attempted in the study.

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This thesis is dedicated to the author's father, Dr. J.P. Duncan, without whose encouragement it might never have been written.

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CHAPTER 1. INTRODUCTION

1.1 General Discussion

During the last fifteen years or so there has been a marked trend among farmers involved in the breeding and raising of animals towards concentration of their stock on ever-decreasing areas of land. This process, while bringing considerable economic benefits to the farmer, has led to certain new agricultural problems, not the least of which is that of animal waste disposal. Previously, wastes could be spread on arable land as fertiliser, but clearly this concept is not applicable, except in special instances, in the case of concentrated land-use animal farms. Today it is generally accepted that some form of biological waste treatment system is a prerequisite in the design of such farms[1].

Biological treatment takes many forms, but basically there are two major classifications:

a) Aerobic treatment -- employs micro-organisms which require dissolved oxygen to obtain their energy. In this instance some indirect means must clearly be found of supplying and distributing sufficient oxygen throughout the system to keep the bacteria fully active.

b) Anaerobic treatment -- employs micro-organisms which do not require dissolved oxygen, but employ fermentation, or anaerobic respiration, to obtain their energy. In this case, there exists no oxygen supply problem, which greatly simplifies matters from a mechanical standpoint.

From these brief observations it becomes clear that anaerobic treatment does offer several advantages over aerobic treatment when considered for use in farming. For a typical treatment facility, such as a lagoon, the anaerobic system will give a lower initial cost, and usually a lower maintenance cost, as it does not require the aeration and mixing equipment essential to the aerobic process, and also requires no power to function. Maintenance time, also, will be minimal with the anaerobic system, as mechanical parts are reduced to the bare minimum, a few valves and pipes being all that are required. However, the anaerobic system, for all its simplicity, does have its drawbacks, among which may be counted the odor problem often associated with anaerobic treatment. This is due to the production of hydrogen sulphide gas which accompanies the digestion process. The anaerobic system also tends to give a somewhat inferior effluent quality compared to an aerobic system [2]. Thus it is not uncommon to find an aerobic pond following an anaerobic pond in situations where a very high effluent quality is a requirement. The effluent quality problem is offset, however, by the fact that anaerobic systems operate under a very high loading rate, which is important when one considers the high strength of the animal wastes with which farmers are concerned.

Thus it may be seen that both methods have their drawbacks, and careful thought must be given in any design project to the choice of system, having due regard to the type and strength of waste, the location and size of the facility, and the quality of effluent required. This study concerns itself with investigations into the anaerobic system only.

Anaerobic lagooning is at first sight a very attractive proposition. All that is required is an area near the farm buildings sufficient to

accommodate a lagoon or group of lagoons large enough to handle the waste output of the farm and produce an effluent of quality acceptable to the appropriate regulatory agencies. No mixing or air-supply equipment is required. If the lagoon is initially well constructed, maintenance costs will be largely determined by the frequency at which accumulated sludge has to be removed from the bottom of the lagoons. The rate of sludge build-up is thus of great importance, and a primary objective of the research project under discussion was to learn something of the degree to which sludge is biologically degraded in such a lagoon. A knowledge of this would enable an estimate to be made regarding maintenance costs for many years ahead, as sludge which is not biologically degraded will eventually have to be physically removed.

Clearly the anaerobic lagoon is the simplest possible treatment facility for a high-concentration agricultural operation, and such lagoons have been widely used with success[3]. A good example of an operation of this kind, using the anaerobic lagoon system, is to be found at Abbotsford, B.C., in the Fraser Valley. Here the National Hog Center has a large indoor pig-raising facility. The treatment system on that farm provided the wastewater for this present study, as well as giving a check on performance under actual, as opposed to laboratory, operating conditions.

1.2 Fundamentals of Anaerobic Digestion

The mechanism of anaerobic sludge digestion is shown in Figure 1.1. There are two different groups of bacteria involved in the anaerobic chain. The first group are known as the "acid-forming bacteria". These take the organic materials in the waste, which are first liquified by extra-cellular

enzymes, and convert them to volatile acids, such as acetic, propionic and butyric. The second group of micro-organisms are known as the "methane-forming bacteria". They take the volatile acids already produced by the acid-forming bacteria and ferment them further to form gaseous products, the main constituents of which are methane and carbon dioxide. Some nitrogen and hydrogen sulphide are also produced at this stage, due to reduction of nitrates and sulphates, etc. However, these are present only as trace gases in a well-operating system that does not have to treat wastes high in nitrates or sulphates.

Obviously both links in the chain are equally important, as the acids formed in the first stage still exert BOD and COD on the receiving waters. The true reduction of the waste occurs only in the second stage. Thus it becomes important to understand the response of both acid-formers and gas-formers to changing conditions. It is generally assumed that the rate of reaction is controlled by the rate at which volatile acids are converted to methane and carbon dioxide[2]. Thus, system failure, which occurs when there is an imbalance in the process, results in a build-up of intermediate volatile acids. To check on this, the volatile acids and pH were carefully monitored in this study, as they are important indicators of how well the second phase is proceeding.

1.3 Need for Further Research

During the summer and fall of 1970, the Civil Engineering Department of The University of British Columbia undertook research intended to provide more detailed information regarding the design and operation of anaerobic lagoons than had previously been available[4]. The program employed a number of single-stage anaerobic digesters, each of twenty-five litres capacity,

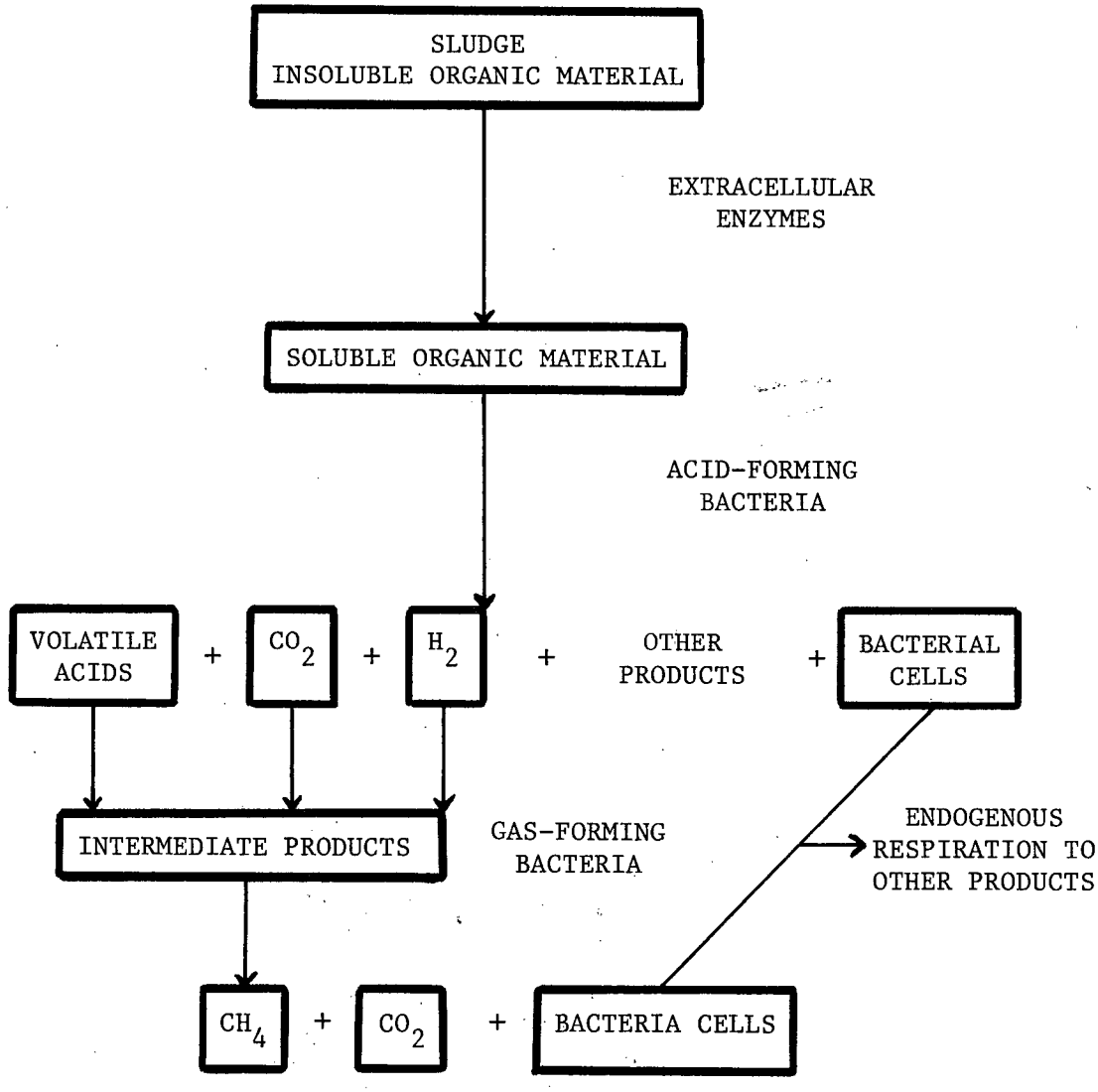

FIGURE 1.1 Mechanism of Anaerobic Sludge Digestion.

which were fed with samples of raw waste obtained from the previously-mentioned National Hog Center at Abbotsford, B.C. All the important operational and treatment-efficiency indices were monitored, and the effect on the system of changes in operating conditions was investigated. As a result of this work, certain recommendations for design of anaerobic lagoons were outlined, and a number of recommendations for future studies were made. The present study is based on three of those recommendations.

1.4 Separation of Settled Solids and Supernatant

The topic was recommended for further study in the previous report[4]. It was felt that much of the efficiency of treatment was due to settling out of the solids in the waste, and that biological degradation was of secondary importance in the production of a high-quality effluent. Thus any increase in settling efficiency should prove worthwhile. The problem encountered with the single-stage digesters used in the previous study[4] was that gas lenses would form in the sludge at the bottom, and would eventually uplift the solids, mixing them with the supernatant. These re-suspended solids would be flushed out with the effluent, contributing to lower overall efficiency. It was therefore decided to build, for the present work, a series of two-stage digesters, approximating on a laboratory scale the two-stage lagoon arrangement used in the Abbotsford operation. In the latter case, the main lagoon was followed by a smaller lagoon serving as a final settling and polishing chamber. The pairs of cells used in the laboratory were both of the same capacity, twelve and one-half litres each, giving an identical total volume to the single-stage units used in the previous research[4]. The first cell would trap the bulk of the solids by settling, and much of the biological activity would occur

here. The supernatant from this cell would be run into a second cell which would not exhibit as much biological activity, but which would serve as a settling chamber, as it would be less subjected to the self-mixing process already described. Thus it was expected that some idea of the effect of increased settling efficiency would be obtainable from the study.

1.5 Sludge Build-up and Gas Production

These topics were recommended for further investigations in recommendations B and D of the previous study[4]. There were a number of reasons for undertaking such an investigation. The first of these was to determine what percentage of the settled solids were "fixed", that is, would not respond to biological treatment, but would accumulate on the bottom of the lagoon, eventually having to be removed mechanically. The second, as outlined above, was that a major objective of the present work was to gain some idea of the relative importance of settling as opposed to biological activity in the degradation process. The only measure of biological activity readily available was gas production and analysis; thus gas production had to be linked to COD, BOD and volatile solids removal. Figures existed for these values for domestic wastes, but they would not necessarily apply to concentrated animal wastes.

To obtain this information, it was recommended [4] that a series of batch tests be undertaken, with the various parameters such as BOD, COD, etc., measured in a fully mixed condition. The temporal reduction in solids and oxygen demand could then be graphically linked to the amount of gas formed, and unit production figures obtained from these. Also, the proportion of solids remaining in the cells after biological degradation was

essentially complete would give the desired information regarding the proportion of "fixed" solids. This recommendation formed the basis for the remainder of the present study.

CHAPTER 2. EXPERIMENTAL PROCEDURE

2.1 General Discussion

Initially, much time was saved by the use of material and equipment from the former experiments[4]. The single-stage digesters previously used were still in operation, and hence still contained viable organisms. These organisms were used as seed for the ongoing research program. Two of the single-stage acrylic digesters were used as the containers for the batch experiments. The new two-stage units had to be constructed. Three of these two-stage units were built.

For the batch tests, it was decided for several reasons to run two concurrent experiments. Firstly, a comparison could be made on the results of one test against those of the other, giving a greater degree of certainty about the results. Secondly, the National Hog Center had for some months been using Acti-Zyme*, an enzyme additive intended to stimulate biological activity and prevent sludge build-ups at the inlets to the lagoons. This material had not been present in the samples taken for the previous tests[4], but it would be present in the samples used for the new series of tests. Thus, some idea of its effect, if any, on the anaerobic activity would be useful. The batch tests were accordingly filled with waste obtained, by special arrangement, free from Actizyme. One of the batch tests was treated with Acti-Zyme according to the manufacturers instructions, and the other was left untreated. Each batch test unit was filled to the twenty-four and one-half litre level initially. As samples were taken weekly, the volume decreased. Allowance was made for this in all calculations. The batch tests were both

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*Manufactured by Actizyme Co., Box 188, Three Rivers, California, U.S.A.

run at room temperature, which held fairly constant at around 22° Celsius.

The two-stage systems were specially designed to prevent carry-over of suspended solids from the first cell to the second cell, or from the second cell to the effluent. The old cells had inlet and outlet valves at the same level. Thus short circuiting of some of the influent waste to the effluent valve was very possible (Figure 2.1). The new digesters had baffles in front of the transfer pipe in both first and second-stage cells. This effectively prevented any short-circuiting of this kind (Figures 2.2 and 2.3).

The three two-stage units were run at 30° Celsius, room temperature, and 10° Celsius respectively. Thermostatically controlled heating tapes were used to heat the high-temperature system, while the low-temperature system was equipped with a set of cooling coils in each cell. Thermostats similar to those used in the high-temperature unit controlled the pumping of cold water through these coils. An immersion refrigeration unit kept the cooling water reservoir at around 4° Celsius, and submersible electric pumps were used for water circulation. Thermometers in the digester lids enabled a check on temperature to be kept at all times.

The objective of the study was to use this and other laboratory equipment to obtain the necessary data for all objectives of the investigation. The experimental procedure may be broken down conveniently as follows.

2.2 Establishment and Operation of the Batch Systems

As previously mentioned, the cells from the previous single-stage

FIG. 2 - 1
SINGLE - STAGE DIGESTER, SHOWING POSSIBILITY OF SHORT-CIRCUITING DURING FEEDING.

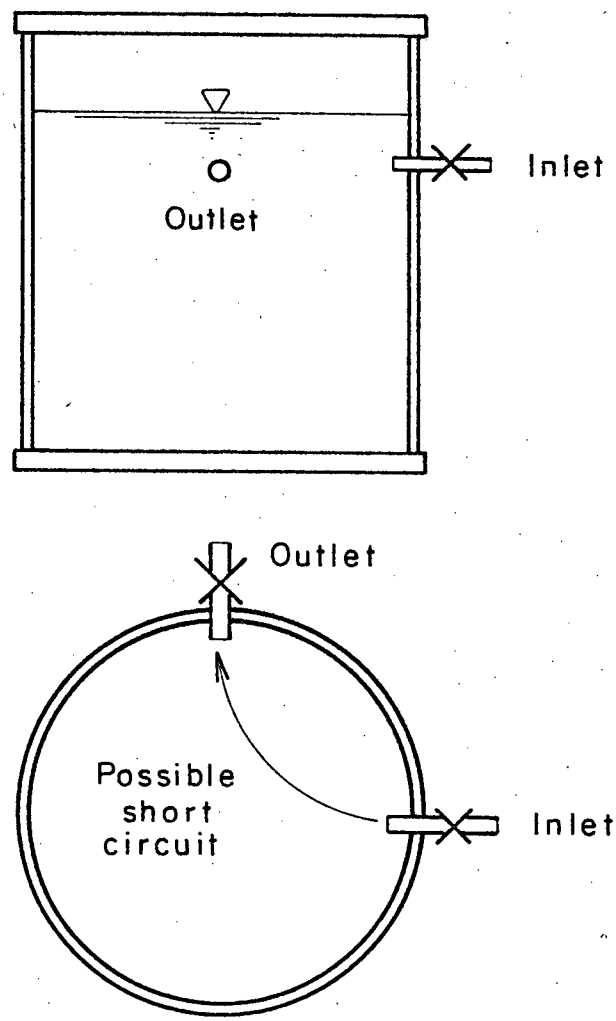


FIG. 2-2
TWO-STAGE DIGESTER, SHOWING FLOW PATTERN DURING FEEDING.

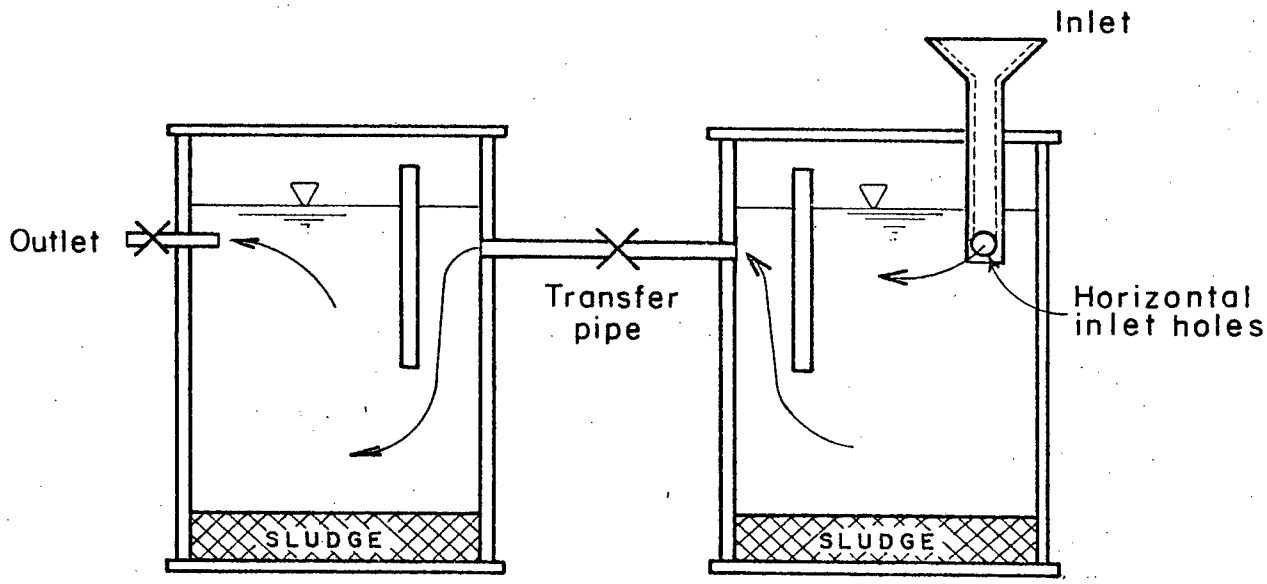
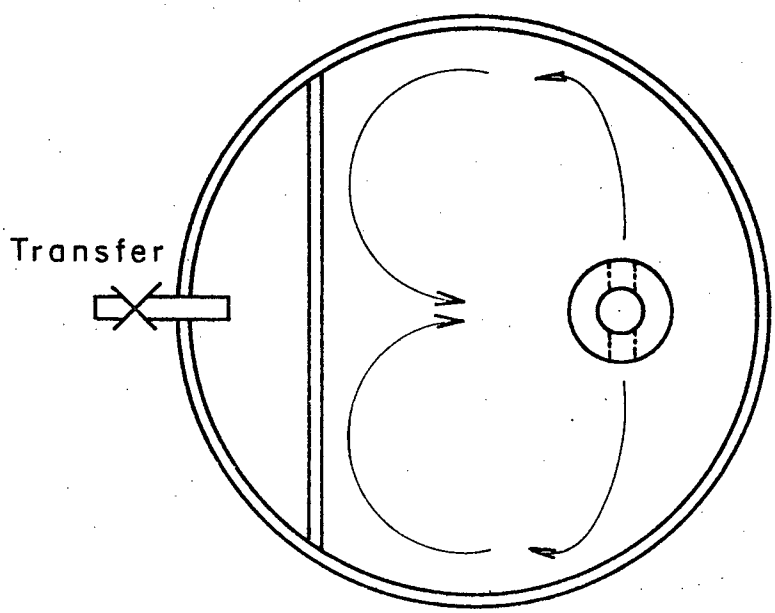


FIG. 2-3
PLAN OF FLOW DURING FEEDING.



tests were still set up in the laboratory, and still contained sludge. Although gas production had fallen off to practically nil, it was fairly safe to assume that a viable culture of bacteria still existed in this sludge. The two digesters to be used for the batch tests were therefore drained until only an inch or so of sludge remained. Fresh raw waste from the Abbotsford farm was then used to re-fill the digesters up to the twenty-four and one-half litre level. Digester number 1 was filled with wastewater which was specially collected to be free of Acti-Zyme, while digester number 2 was treated with an Acti-Zyme concentration of 0.00625% as recommended by the manufacturer.

It may be stated that the use of Acti-Zyme on the farm had proved effective in keeping pipe blockages and sludge build-ups on the lagoons to a minimum. It was interesting to note in view of this, that, while unit number 1 took twenty-five days to become biologically active, number 2 started immediately. Also, as may be seen from the gas production rate curve (Figure 3.1), number 2 had, throughout the test, a higher gas production rate. This will be further discussed in the next chapter, but certainly on the basis of these indications, the use of Acti-Zyme in systems of this type would seem to be beneficial.

2.3 Establishment and Operation of the Two-Stage Systems

In the case of the two-stage units, little or no activity could be obtained at first, despite the addition of seed material from the still active single-cell units. The problem was that the acid-forming bacteria began to work at once, and produced enough acid to send the pH of the system down to the region of 6.6 to 6.8 in the primary cells. The pH of the

secondary cells held in the 7.1 - 7.2 range. Previous studies have found that, for a balanced system to be achieved, the optimum pH is in the order of 6.8 to 7.2, depending on system operating conditions. In the case under discussion, the acid-formers were far outperforming the gas-formers in the primary cells and in doing so were giving rise to a pH range which made it extremely unlikely that a balanced state could be achieved. Thus, after four weeks, it was decided to raise the pH of the digester contents with lime. Just after this decision was taken, however, the 30°C digester suddenly exhibited a rise in pH on its own, and began to function well. The other two, both of which were at room temperature for starting purposes, remained at their former unfavourable pH levels, so after another two weeks they were treated with lime ($Ca(OH)_2$) to artificially raise the pH. Lime was added 0.1 gm. at a time and thoroughly mixed: this process was continued until the pH was raised to about 7.2. This process was spread over several days to avoid shock to the system. At the new pH, both digesters began to function well. The 10°C digester was given a further month to become established, during which time it was cooled down to 10°C in a series of 1°C increments of temperature, in order to give the organisms ample time to acclimatise.

Feeding was done once a day and was accomplished by means of a funnel and spigot mounted in the lid. No air could pass into the digester gas space through this, and the outlet into the digester was a two-opening one which gave horizontal flow in opposite directions, thus minimising swirl in the chamber and disturbance of the bottom deposits (Figure 2.3). It was anticipated that this would tend to reduce solids transfer from the primary to the secondary cell. Effluent was drawn off from the secondary cell at the time of feeding the primary cell to maintain a constant level in the digesters and effect a uniform transfer of supernatant from the

primary to the secondary cells. To ensure complete independence of operation of the two cells, the transfer valve between the two was kept closed except during feed addition.

Initially, it had been intended to use a rotary wire screen in the primary cells to disturb the sludge just sufficiently to prevent lensing and self-mixing as encountered in the previous tests. However, it was found impossible with the equipment available to run this screen slowly enough to prevent lensing without itself causing re-suspension of solids by mixing. This idea was therefore dropped, and the systems were operated entirely undisturbed except by self-action in the sludge.

2.4 Testing Procedure for the Influents and Effluents

The raw waste used in the tests was obtained in exactly the same manner as in the previous series of tests [4], with eight-hour composite samples being taken from the manhole closest to the lagoons in the main outfall sewer. Polyethylene carboys were used as sample containers, and these were stored in a refrigeration unit until needed for feeding the experimental units. Unfortunately, during the tests, the farm at Abbotsford was closed down and evacuated due to an outbreak of virus disease among the hog population, and so enough waste to supply the second half of the tests had to be gathered and stored at once, while there was still a waste-producing population in the farm. The raw waste samples varied in strength throughout the tests, but there were no marked abnormalities among the characteristics of the long-term storage samples, as opposed to the previous short-term storage ones. The only problem was a shortage of feed during the final stages of the experiment, which limited the scope of the work

somewhat.

Grab samples were used to test the digester effluent. Effluent from both primary and secondary cells of the two-stage systems was tested. Tests were performed weekly for most parameters, and under equilibrium conditions only for the remainder. The object of the experiment was to achieve an equilibrium state at each of several feeding rates, and to run all relevant tests to measure digester performance at these feeding rates. Feeding rates used were 0.5 ℓ/day, 1.0 ℓ/day, and 1.5 ℓ/day, giving a similar range of detention times to that used in the previous research[4].

Both mixed raw waste and digester supernatant were tested. In the case of the batch tests, the contents of the digester were fully mixed before testing, as actual quantities, not concentrations, were required in this case. Initially, some irregularity was found in the batch test results, but extension and standardisation of the pre-sampling mixing time solved this problem.

All tests were carried out according to the procedures given in Standard Methods[5], and further explained in Chemistry for Sanitary Engineers[6]. In the case of both the batch tests and the two-stage digesters, tests run routinely on the effluents were:

1) pH
2) Biochemical Oxygen Demand (BOD)
3) Chemical Oxygen Demand (COD)
4) Total and Volatile Solids (TS and VS)
5) Kjeldahl Nitrogen, both Total and Organic.

Dilution of the samples was necessary, due to the high strength of

the waste. These were arrived at using the previous work as a basis and modifying the figures through repeated trials.

In the case of the two-stage digesters, tests run routinely on the influent and effluent in addition to the above were:

6) Volatile Acids

7) Total Organic Carbon.

The volatile acids data were expected to be of great interest as indicators of micro-biological conditions in the test units. Volatile Acids analysis was accomplished using a Hewlett-Packard Model 5752 B gas chromatograph with a six-foot by 1/8 inch diameter stainless steel column packed with Porapack Q 50 - 80 Mesh packing, containing 2 percent phosphoric acid.

Total Organic Carbon was determined using a Beckman Model 915 Total Organic Carbon Analyser. The data generated was intended to provide a correlation between BOD, COD and TOC. It is felt by some that TOC may, at some time, become a standard test, perhaps even supplanting the comparatively lengthy and involved BOD and COD tests[7]. Hence this test was also included to assist a link-up to possible future results.

In addition to the tests previously mentioned, tests run occasionally or at equilibrium only were:

8) Total Phosphate

9) Copper Concentration

10) Nitrate

11) Alkalinity.

For the purposes of this study, nutrient values were of little importance, as they were studied in some detail in the previous experiments. A check was kept on them in the present case, but no more. The copper concentration was of interest, because it was felt that dissolved copper from the brass fittings in the digesters, and also from the copper coils in the cold digester, might reach concentrations sufficient to have a harmful effect on the operation of the digesters.

2.5 Testing Procedure for the Evolved Gases

The evolved gases were analyzed both qualitatively and quantitatively. The Hewlett-Packard gas chromatograph was used to obtain gas composition figures. These results would enable methane production to be calculated and this was to be related to solids and BOD removal. Also they gave some indication as to the stability of the system.

To obtain volumes of evolved gas, the same water-displacement tubes used in the previous work[4] were employed. Later, a pair of Alexander Wright and Co., Model M 809 LT Hyde Pattern wet-meters were obtained and used for this purpose. Gas production for the two-stage units was measured only after equilibrium had been achieved. Continuous use of the wet-meters was not considered advisable from a corrosion standpoint.

Samples for gas composition analysis were taken by means of syringes from sampling ports installed in the gas outlet line which connected the treatment unit to the gas meter.

2.6 Summary

No great difficulties, other than the shortage of feed near the

end of the test, were encountered during the course of the experiment. All equipment worked well, and sufficient data was obtained. The analysis of this data and discussion of results is presented in the following chapters.

CHAPTER 3. RESULTS OF BATCH TESTS

3.1 Introduction

The first objective in the case of the batch tests was to quantitatively relate the rate of methane production to the rates of reduction of solids, BOD and COD. The second objective was to study the rate and degree of biological degradation of the accumulated solids. Such understanding would enable a good estimate to the made both of the relative importance of bio-degradation as opposed to settling, and of the proportion of solids which would eventually have to be removed from the lagoon by physical means. Eckenfelder[2], among others, gives figures for the relationship between gas production and reduction of solids, BOD and COD, but a check on these for the particular waste was felt to be necessary.

3.2 General Discussion of Procedure

Gas production was measured on a cumulative basis by taking the twenty-four hour production, converting to STP (having regard to laboratory temperature and pressure) and adding to the previous day's cumulative total. Hence the total amount of gas produced was known at any time. Composition of the gas was checked also at weekly intervals. Thus methane production was at all times monitored.

To check the reduction of solids, BOD, COD, etc., the fully mixed contents were sampled and analysed weekly. Knowing the concentrations, and the volume remaining in the digester, the actual quantity of solids, BOD, and COD remaining could easily be calculated. From the data thus obtained, it was easy to check the published figures for methane production,

versus BOD, COD and solids removal.

3.3 Gas Production and Analysis

Some difficulty was experienced in obtaining consistent readings on the gas chromatograph at first, but practise in technique improved this situation after a time. The results showed considerable variation, so an average value was used in calculations. Values obtained were as follows:

Methane:	56 - 65%	-- avg. 60%
Carbon Dioxide:	33 - 42%	-- avg. 38%
Nitrogen:	0.5 - 1.5%	-- avg. 1%
Water:	0.5 - 1.5%	-- avg. 1%
Hydrogen Sulphide:	trace	

Due to the difficulties mentioned previously, results were not obtained with any certainty near the beginning of the tests, but the above figures are good for the time at which production was at a peak and was consistent. Hence the use of the 60% figure for methane content seems justified, and accords with accepted figures [8].

With regard to volumetric production, Figure 3.1 shows the rate of methane production against time, and Figure 3.2 shows the cumulative methane production. As previously mentioned, the enzyme-treated digester number 2 produced more gas at all times than number 1, which was not so treated. However, it may be mentioned that the solids content initially present in number 2 was appreciably higher than that in number 1 due to differences in the solids content of the raw waste used and this may have some bearing on the higher gas production.

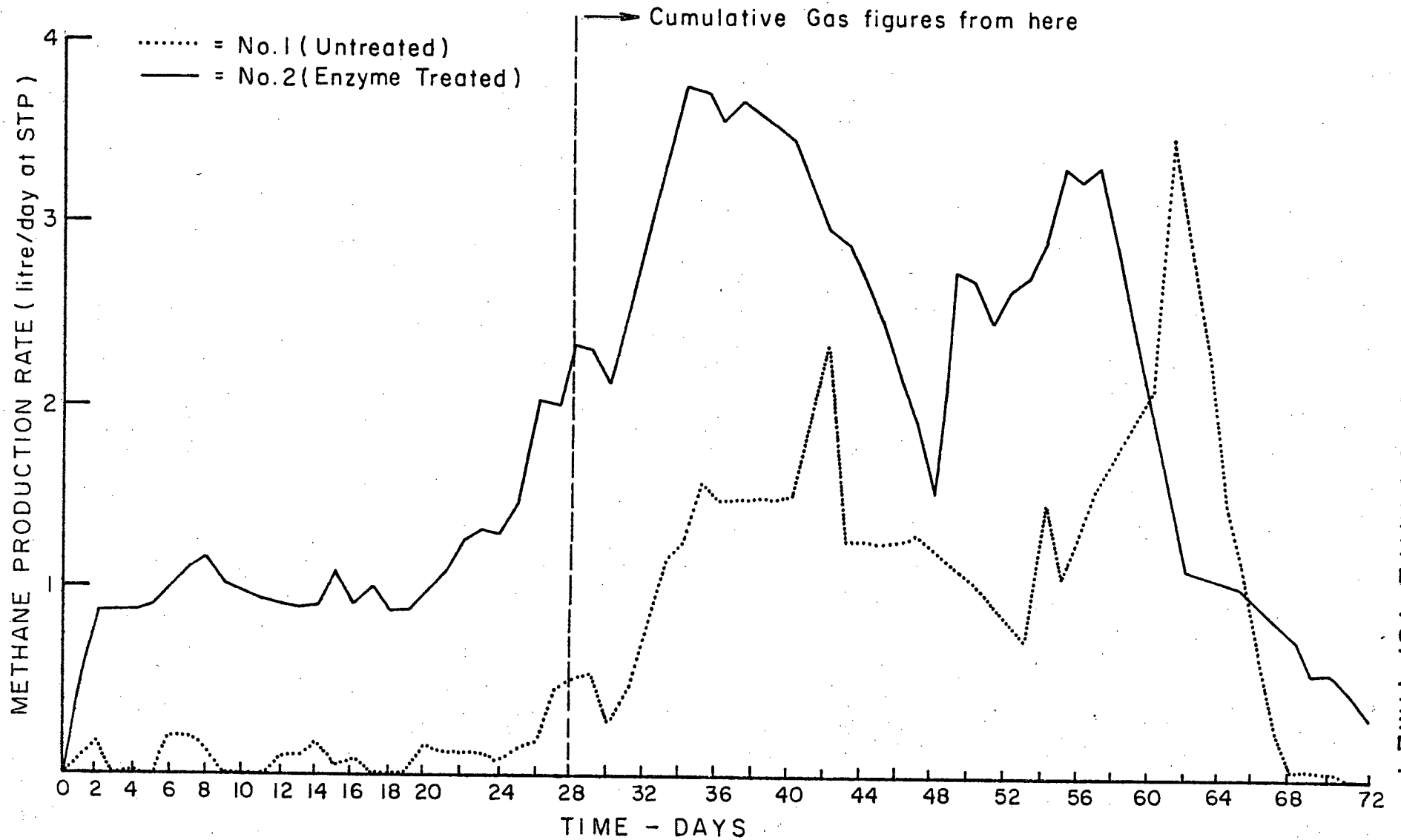
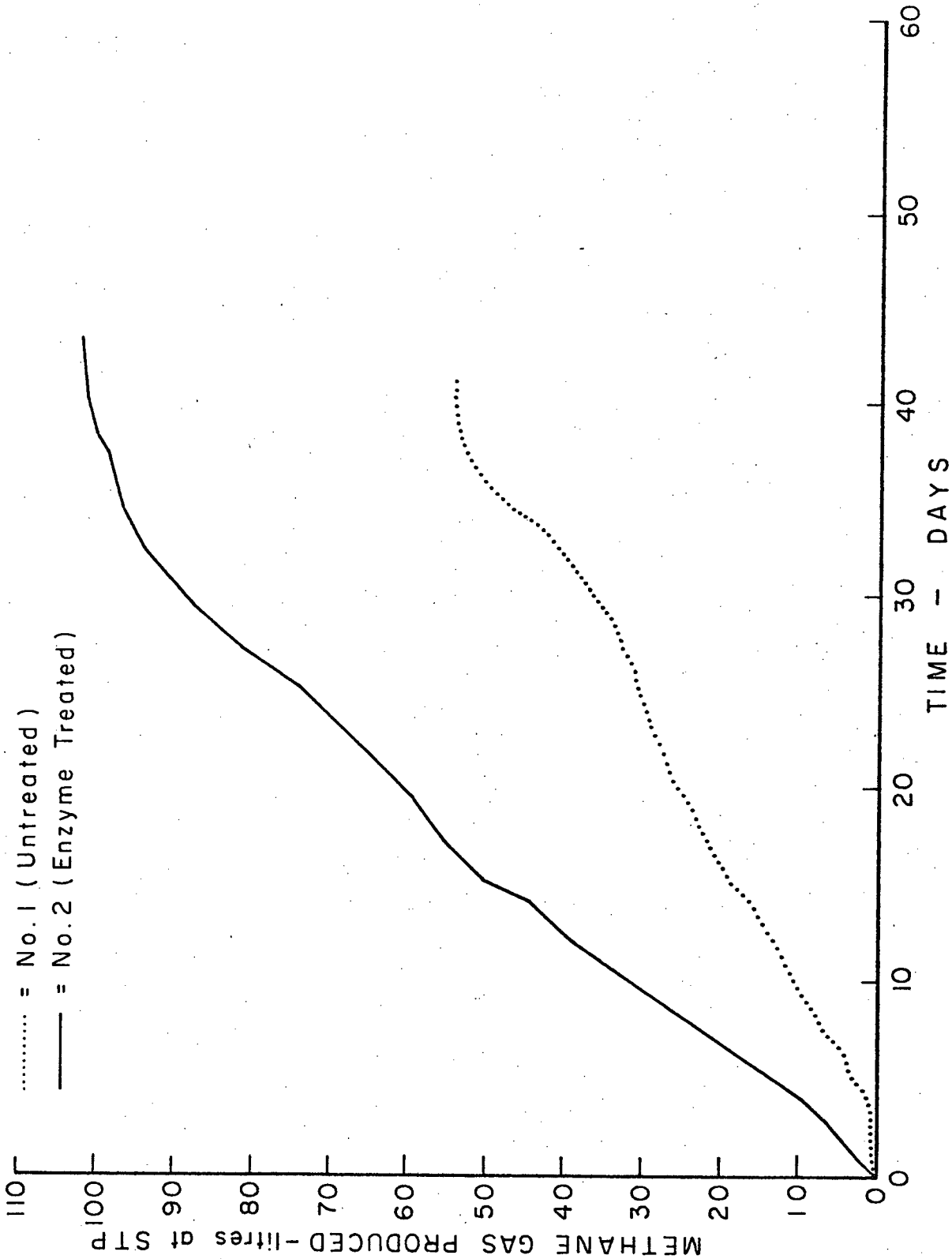


FIG. 3 - 1

METHANE PRODUCTION RATE VS. TIME.

FIG. 3-2

CUMULATIVE METHANE PRODUCTION VS. TIME.



As mentioned earlier, some difficulty was initially encountered in obtaining uniform results from the chemical tests. The mixing of the digester contents was found to be at fault and a standard procedure was adopted of giving the digester 20 minutes of rapid mixing prior to sampling. After this, less trouble was experienced and so the cumulative gas production plot was started from the first day of this standard procedure, and all figures and conclusions drawn from the tests taken after this time.

The gas rate curve exhibits a fairly typical form. If it is assumed that the gas production rate is an indicator of bacterial population, then one would expect the curve seen on Figure 3.1. The resurgence of production near the end of the test, at around the 50-day mark, may be due to a change-over of the system to endogenous respiration as the substrate becomes depleted. In any case, endogenous respiration is certainly a factor in the closing phases of a batch test such as this one, and hence results from this portion of the curve may be suspect as far as their application to a continuous system is concerned. This will be further referred to in subsequent sections of the present chapter.

3.4 Relationship of Methane Production to BOD and COD Removal

The decreases in effluent BOD and COD with time are shown in Figures 3.3 and 3.4 respectively. Even after standardised stirring was introduced, the COD test results showed considerable fluctuation. This was due largely to the nature of the waste. Wood chips, small pieces of cloth and string, sawdust, and large lumps of solid surface crust were all present in the digester contents. The presence of a small piece of wood, for example, can significantly affect the COD test, causing a higher value to be read than would be the case if it were not present.

FIG. 3-3
COD VALUES VS. TIME.

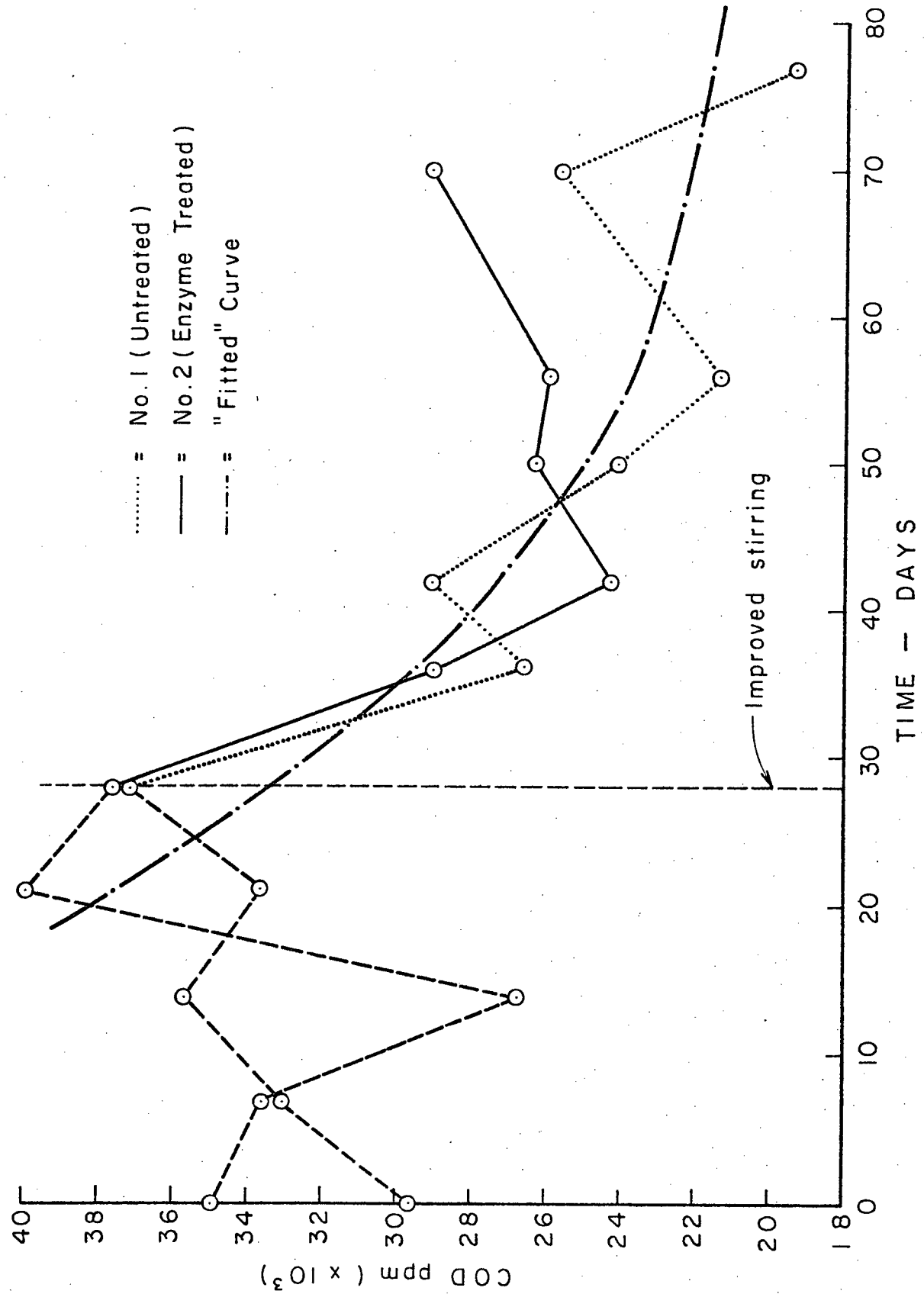
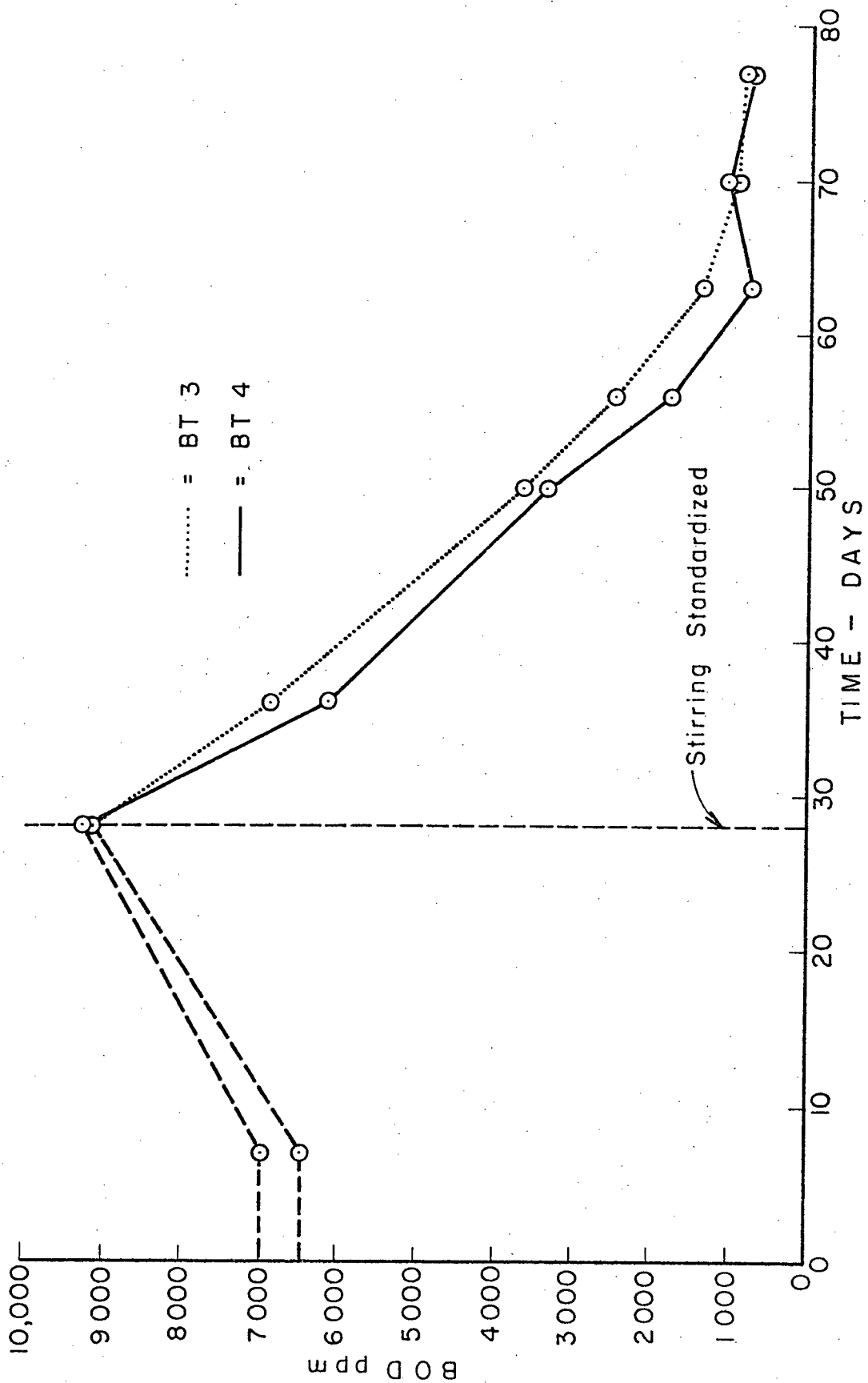


FIG. 3 - 4
BOD VALUES VS. TIME.

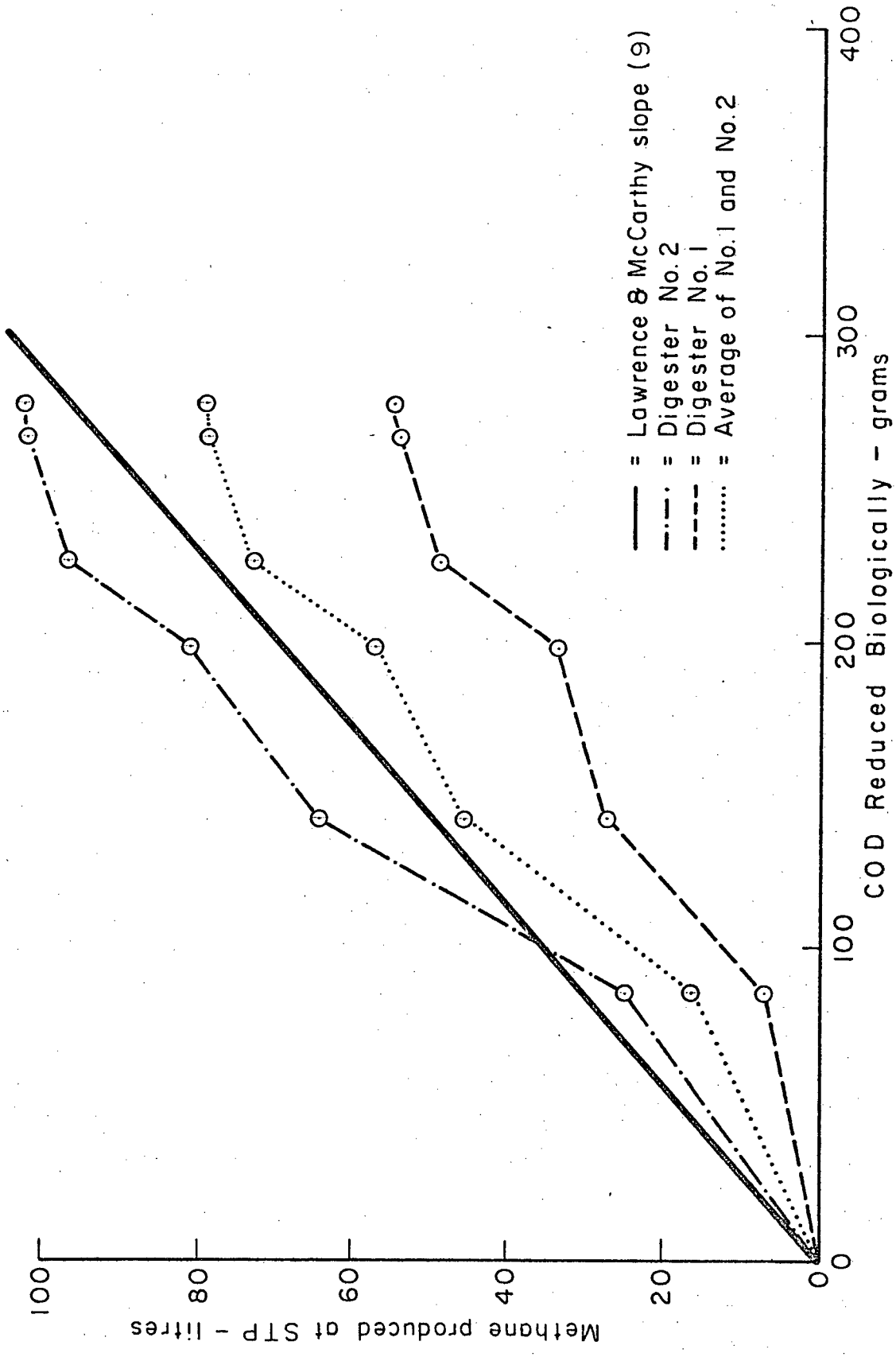


To allow somewhat for these fluctuations, a fitted curve was drawn through the points obtained for both digesters, placing more emphasis on the points obtained from digester number 1, which exhibited far less fluctuation than number 2. However, the points from number 2 lay fairly close to this line also, with the exception of some towards the end of the test.

Using the gas production data and calculating the amount of COD removed by bacterial action as in Appendix A, Figure 3.5 was developed to show COD removal versus methane production. The fitted COD curve of Figure 3.3 was used in conjunction with the mean methane production from the two tests, representing an average of both COD removal and gas production from the two units. A line having the slope given by Lawrence and McCarty[9] of 5.62 $ft.^3$ of methane per lb. of COD destroyed (35.15 ℓ of methane per 100 gm. of COD destroyed) was drawn for comparison. The Lawrence and McCarty figure is based on theoretical as well as experimental considerations. The line obtained from the average of the two tests correlated quite well with this theoretical slope, with a tendency toward a slightly lower production of methane per unit of COD destroyed. The lines obtained from the individual gas production figures from the two digesters are shown also on Figure 3.5, showing that unit number 2 apparently reduced much less COD per unit of methane produced than number 1. However, due to the erratic nature of the COD results, the approach of taking the average value for gas production and applying it to the fitted COD curve seems to be justified.

On the basis of these findings, it can be stated that the use of the figure of 0.35 mℓ methane per mg of COD destroyed is perfectly justified

FIG. 3 – 5
COD REMOVAL VS. METHANE PRODUCTION.



in calculations involving the particular waste under test. This figure was accordingly employed in subsequent calculations.

An identical procedure was followed in calculating BOD removal as related to gas production. The two tests were again averaged out with regard to BOD removal and gas production. The curve obtained is shown in Figure 3.6, along with the line obtained from the Lawrence and McCarty figure given above[9]. This should hold good for BOD_L (BOD_{ult}) as well as COD, since the bacteria remove BOD_L only, and COD is the sum of the BOD_L and those constituents which can be chemically oxidised only.

In the case of the BOD results, much more consistency was obtained than with the COD results, as the small pieces of wood, hog hairs, etc., are not readily bio-degradable and thus do not affect the BOD test as they would the COD test. As may be seen from Figure 3.6, the results agreed quite well with the figure given by Lawrence and McCarty[9], especially when averaged out. Thus, it may again be stated that, on the basis of these results, the use of the figure 0.35 ml methane per mg of BOD destroyed is fully justified in calculations concerning the hog waste in question.

3.5 Relationship of Methane Production to Volatile Solids Removal

Volatile solids removal was calculated as in Appendix A. Since all samples were taken fully mixed, the concentration of the samples was the same as the overall concentration in the digester, enabling the weight of volatile solids in the digester to be calculated for the date of sampling. Figure 3.7 shows the volatile solids concentration in the two digesters plotted against time, starting from the beginning of the improved mixing in the digesters for sampling purposes. To allow for the fluctuations in the

FIG. 3 - 6
BOD REMOVAL VS. METHANE PRODUCTION.

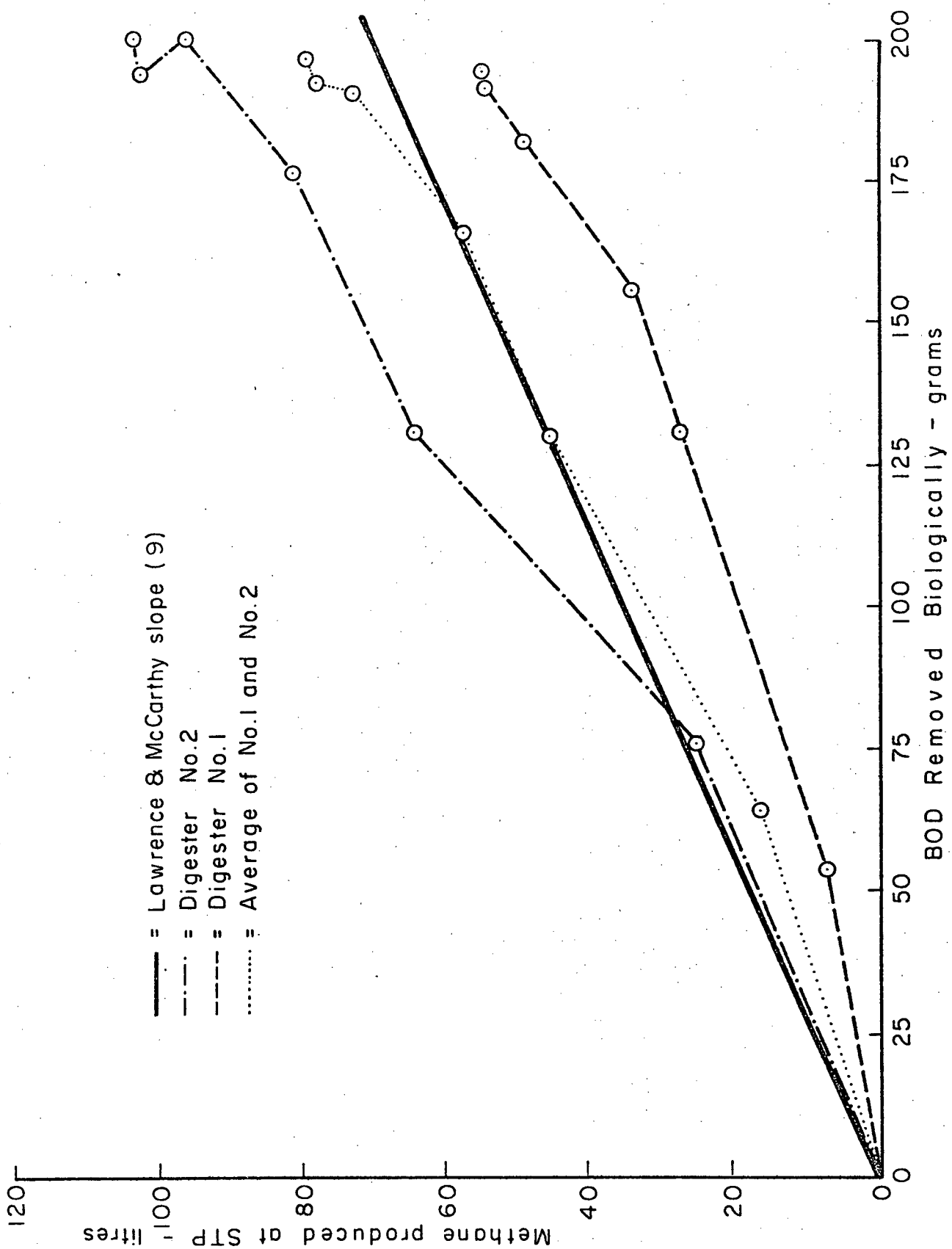
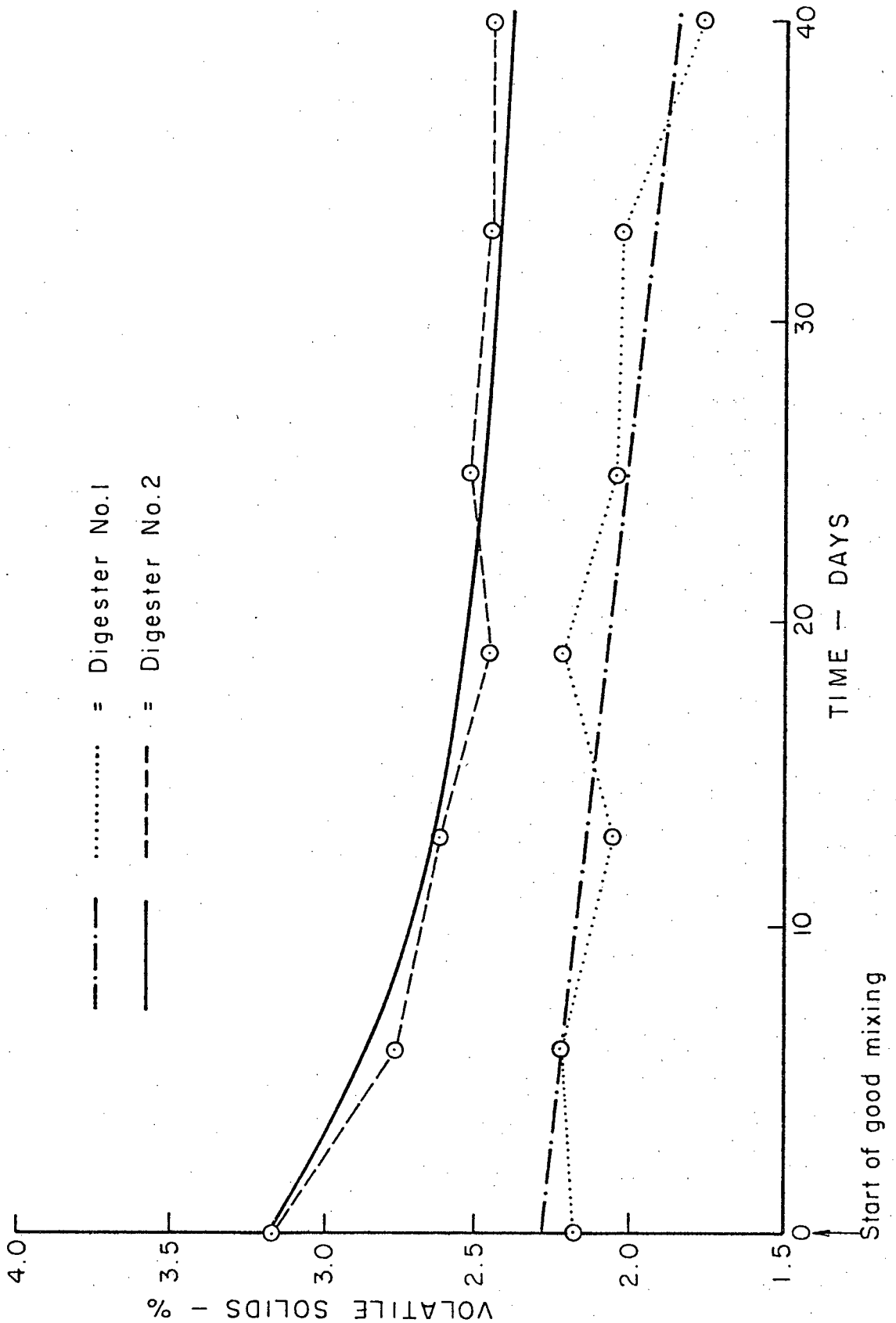


FIG. 3 – 7
VOLATILE SOLIDS VS. TIME (BATCH TESTS).



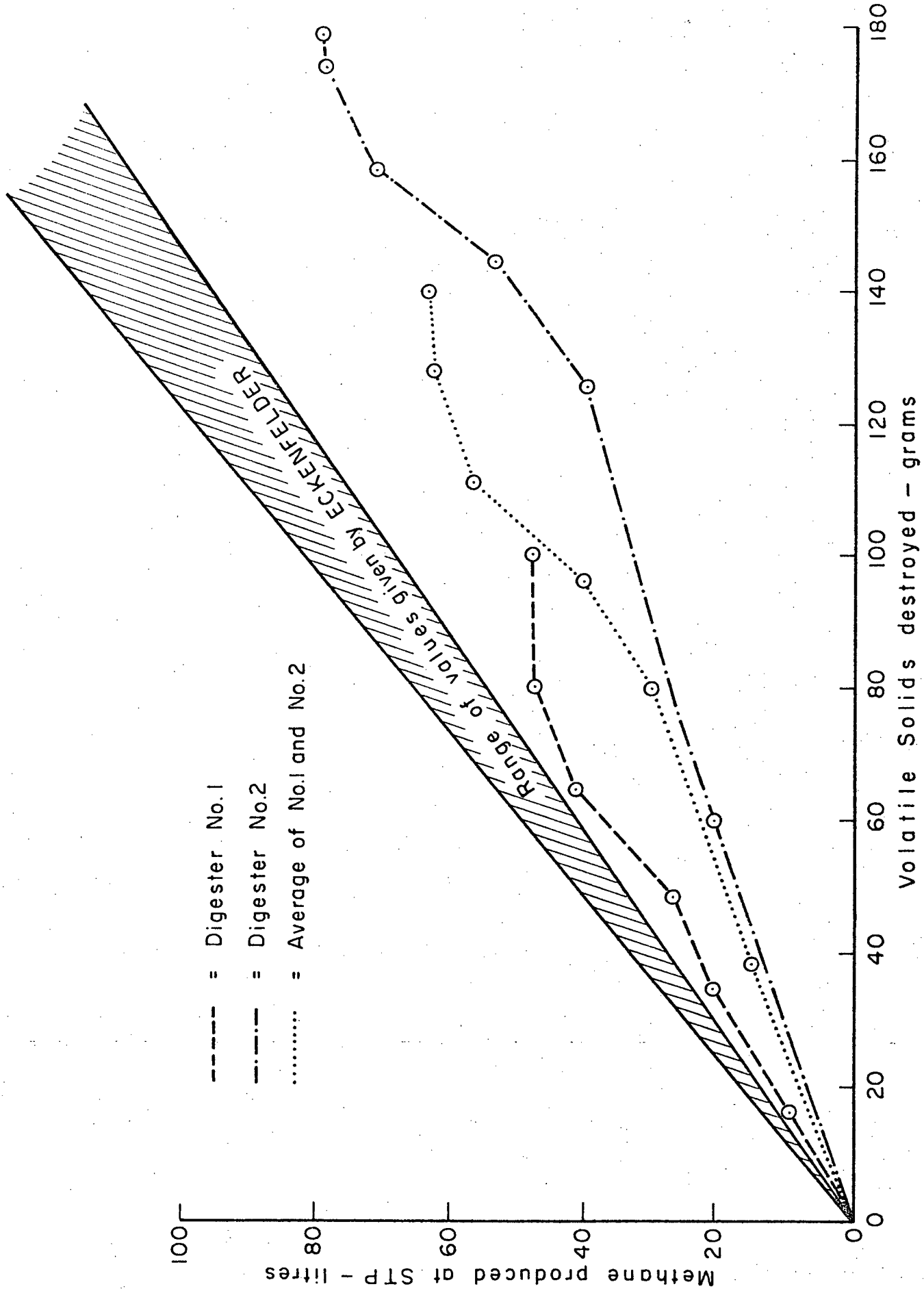
results, fitted curves were drawn through the points obtained, and these were used to obtain the figures for volatile solids reduction as related to methane production.

Figure 3.8 shows the gas production related to the removal of volatile solids, with the published range of values plotted for comparison. Eckenfelder[2] gives a range of 17 to 20 ft.^{3} of gas produced per lb. of VS destroyed with a methane content of around 65%. This is equivalent to 69 to 81 ℓ of methane produced per 100 gm. of VS destroyed. In the same work, Eckenfelder notes that these values are a maximum, assuming complete conversion of volatile solids to methane. This may explain why the slope obtained initially for digester number 2 is lower than the Eckenfelder figures[2], although the same digester gave a higher gas production per unit of BOD destroyed than the Lawrence and McCarty figure[9], as seen from Figure 3.6. Volatile solids may be destroyed by conversion to volatile acids, with no production of methane and no reduction in BOD[2]. The low initial slope is probably therefore due to a lag in efficiency of the methane-forming bacteria as opposed to the acid-forming bacteria. After the first two points on the curve, the slope steepens to match that given by Eckenfelder[2]. The results from digester number 1 agreed quite well with the Eckenfelder value. Eckenfelder's figure was accordingly used in further calculation involving the hog waste under test.

With regard to solids degradation in the batch units used in the tests, overall volatile solids reduction from start to finish was 19% for digester number 1 and 22% for digester number 2. Since gas production had fallen off to nearly zero in both cases at the conclusion of testing, any further volatile solids reduction would be of an extremely

FIG. 3 – 8

VOLATILE SOLIDS REDUCTION VS. GAS PRODUCTION.



long-term nature. The volatile/total solids ratio in both cases averaged out at approximately 69% at the end of the test, indicating that at least 30% of the remaining solids were definitely non-degradable in nature. Thus, allowing a digester or lagoon to stand unfed will not prove of much value in reducing sludge accumulations.

CHAPTER 4. TWO-STAGE DIGESTER RESULTS

4.1 Introduction

The primary objective of the flow-through experiment was to acquire knowledge concerning the relative performance of a two-cell anaerobic system as compared to a single-stage system of the type employed in previous research[4]. Results obtained from the two systems at corresponding Liquid Detention Times (LDT) were compared. A further area of study was the determination of the manner and degree of the contribution of each of the two cells in a two-stage system to the overall treatment efficiency.

4.2 General Discussion

As previously mentioned, the one problem encountered during the test program was a shortage of feed during the latter stages of the experiment. After completion of the tests for the 50-day and 25-day LDT stages, it was realised that insufficient feed remained to complete the whole schedule of testing on all units. A decision was therefore made to run the final 17-day LDT test on the 30°C and 10°C digesters only. Even with this limitation, only 13 days of feeding could be completed with the remaining feed. Thus there is considerable doubt that equilibrium was achieved or even approached on the 17-day LDT. In fact, the effluent BOD, COD and solids values were still rising, although not rapidly, at the conclusion of the test. Hence the results for percentage removals on the 17-day LDT are probably a little high.

The amounts of methane produced by the immediate (24-hour) degradation of the feed material, and by the continuing degradation of the

accumulated sludge were determined by multiplying the total methane production by percentages determined in previous research[4] with similar substrate. The characteristics of the raw feed and effluents respectively are shown in Tables I and II. These data form the basis for results discussed herein.

TABLE I. Average Raw Waste Characteristics.

THEORETICAL LDT DAYS	BOD_5 ppm	COD ppm	SOLIDS %
50	4410	24,100	T 2.964 V 2.146
25	6185	25,232	T 2.696 V 1.508
17	4113	20,500	T 2.049 V 1.459

4.3 Effectiveness of Modifications to Cell

The two-stage flow-through digesters had two cells each of 12.5 ℓ capacity, giving the same 25 ℓ capacity of the previously used single-stage units[4]. The first cell of the two-stage system could be considered as a half-size single-stage unit for comparison purposes. Comparative performance should thus be achieved in a given single-cell reactor used in previous research[4] and the first cell of a two-stage reactor being fed at half the daily rate of the single-cell reactor.

Percentage removal figures for the two-cell types are shown in Table III and mass removal figures in Table IV.

TABLE II. Average Effluent Characteristics.

BOD ppm

TEMP / LDT DAYS	30°C		23°C		10°C	
	1st CELL	2nd CELL	1st CELL	2nd CELL	1st CELL	2nd CELL
50	565	470	777	578	3583	2266
25	1035	850	1735	1352	5966	5680
17	1450	850	----	----	4100	4660

COD ppm

TEMP / LDT DAYS	30°C		23°C		10°C	
	1st CELL	2nd CELL	1st CELL	2nd CELL	1st CELL	2nd CELL
50	6780	5203	7630	6120	10,626	7,983
25	6995	5750	7680	6190	12,710	11,363
17	7690	6330	----	----	11,020	10,200

TOTAL AND VOLATILE SOLIDS %

TEMP / LDT DAYS		30°C		23°C		10°C	
		1st CELL	2nd CELL	1st CELL	2nd CELL	1st CELL	2nd CELL
50	T	0.657	0.545	0.661	0.651	0.717	0.631
	V	0.400	0.320	0.402	0.362	0.467	0.408
25	T	0.676	0.569	0.728	0.617	0.769	0.705
	V	0.411	0.329	0.450	0.366	0.492	0.438
17	T	0.730	0.629	-----	-----	0.909	0.780
	V	0.455	0.379	-----	-----	0.629	0.525

TABLE III. Comparison of Percent Removals in Original 25 ℓ Cell and Modified 12.5 ℓ Cell.

12.5 DAY LDT

UNIT	25 ℓ CELL			12.5 ℓ CELL (MODIFIED)		
Temp °C	30	23	10	30	23	10
% BOD Rem.	84.0	80.5	27.0	83.2	72.0	3.6
% COD Rem.	77.0	78.0	52.0	72.2	69.6	49.6
% VS Rem.	79.0	80.5	74.5	72.7	73.0	67.4
% TS Rem.	74.0	74.0	69.5	74.9	73.0	71.5

25 DAY LDT

UNIT	25 ℓ CELL			12.5 ℓ CELL (MODIFIED)		
Temp ° C	30	23	10	30	23	10
% BOD Rem.	88.0	85.0	43.5	87.2	82.4	18.7
% COD Rem.	82.5	81.5	64.5	71.9	68.3	55.7
% VS Rem.	79.5	81.0	79.0	81.4	81.2	78.2
% TS Rem.	73.5	74.0	73.0	77.8	77.6	75.8

TABLE IV. Comparison of Mass Removed Per Unit Cell Volume for 25 ℓ Single-Stage Cell and 12.5 ℓ First Cell of Double-Cell Digester.

25 DAY LDT

UNIT	25 ℓ CELL			12.5 ℓ MODIFIED CELL		
Temp °C	30	23	10	30	23	10
BOD_5* Removed	344	332	169	153	145	33
COD Removed	985	976	769	692	658	538
VS Removed	661	674	657	698	697	671
TS Removed	829	834	823	922	921	898

12.5 DAY LDT

UNIT	25 ℓ CELL			12.5 ℓ MODIFIED CELL		
Temp °C	30	23	10	30	23	10
BOD_5* Removed	334	320	107	206	178	8
COD Removed	1009	1022	681	729	702	500
VS Removed	601	612	566	438	423	406
TS Removed	803	803	754	808	787	770

* All removals in mg/ℓ of cell/day.

Points to note were:

a) Percentage BOD removals were almost identical at the 30°C temperature, but dropped off much more sharply with decreasing temperature in the case of the first 12.5 ℓ cell of the two-stage system. On a mass basis, the removal of the 12.5 ℓ cell never approached that of the 25 ℓ cell. This may be due to the fact that the BOD of the material used as feed for the 12.5 ℓ cell was very much lower than that used for the 25 ℓ cell. The resulting decrease in the amount of available substrate per unit of cell volume could give rise to the lower mass removal figures obtained. Also, any short-circuiting during feeding of the cell would lower the actual mass feeding rate for the cell in terms of raw waste feed, as the amount of raw waste remaining in the cell after feeding would be lower. This would favour the single-stage digesters, as the two-stage cells were designed to avoid short-circuiting. However, this effect would be offset to an indeterminate degree by the increase in effluent strength due to the short-circuited raw feed.

b) COD removal, both on a percentage and mass basis, was greatly superior for the 25 ℓ cell as compared to the 12.5 ℓ two-stage cell. Again the two-stage cell type fell off in removal efficiency much more with decreasing temperature than did the 25 ℓ cell. This decrease in effectiveness of treatment with decreasing temperature noted also for BOD, can only be due to decrease of biological activity with decreasing temperature. Since both two-stage and single-stage systems were subjected to similar temperature variations, the fact that the two-stage system responded more noticeably can only be due to a difference

in the nature of the bacterial population in the cell. The bacteria in the two-cell system were less tolerant of temperature changes. Since no bacteriological studies were undertaken in the course of this research, the actual nature of the bacteria present in both cases is unknown.

c) Total solids removal was, on a percentage basis, slightly better for the 12.5 ℓ two-stage type of cell, and was significantly better on a mass basis for this cell. Variation with temperature was only slight in the case of total solids removal. Volatile solids removal was slightly better for the 12.5 ℓ cell at the 25-day LDT, but was not as good at the 12.5-day LDT as that obtained with the 25 ℓ cell.

From the total solids removal figures, it can be stated that the modified cell does give somewhat improved settling efficiency as predicted. The variation in removal efficiencies of the other parameters can be attributed to differences in the composition of the feed material, which was considerable in the case of BOD content, and to short-circuiting in the 25 ℓ cells. The BOD concentration of the feed used in the two-stage cells was less than half that used in the single-stage experiments[4] and thus there was much less readily degradable material present. This would not affect parameters such as total solids removal, which are dependent largely on settling, but could appreciably affect parameters such as BOD which can be expected to be more dependent on bacteriological action. Short-circuiting, which was probably present during feeding of the 25 ℓ cells would give better apparent results for these cells due to the actual feeding rate being lower than the theoretical level. These points will be discussed further in the subsequent sections of this thesis.

4.4 Overall Treatment Efficiency

The results obtained from percentage removal in each cell of the two-cell units, and for the overall system, are shown in Tables V - VIII.

Results noted were:

a) Removal efficiency decreased with decreasing LDT: this effect was more marked from 25 days to 17 days than from 50 days to 25 days. The decrease was not nearly so pronounced in the case of solids removal as in the cases of COD and, particularly, BOD. This seems to indicate that much of the BOD and a certain portion of the COD is of a non-settleable nature, depending on bacteriological action for removal. The figures for the 10°C digester, which showed minimal bacteriological action, support this view, as a volatile solids removal of 64% was obtained with essentially no BOD removal at the 17-day LDT. The conclusion here is that most of the settleable volatile solids are essentially non-degradable, as found in the earlier research[4] and in the batch tests discussed in Chapter 3.

b) A similar effect was noticed for the decrease in efficiency with decreased temperature. Again the decrease in solids removal was somewhat less pronounced than the decrease in COD removal, and very much less pronounced than the decrease in BOD removal.

Since the only factor in the treatment process significantly affected by temperature is biological action, it may be concluded that most of the solids and much of the COD are removed by settling, but that supernatant

biological action removes most of the BOD. This conclusion is further examined in the following section.

4.5 Settling vs. Biological Degradation

Tables IX - XII show the percentage BOD removal figures broken down into removals due to immediate bacteriological action and removals due to settling. These figures were arrived at by taking the 24-hour methane production due to the raw feed addition and multiplying this by the appropriate coefficient as discussed in Chapter 3 to obtain the amount of each parameter biologically degraded each day. Knowing the feed and effluent characteristics, the total removal per day could be simply calculated, and from this the removal due to settling was obtained. All figures were then converted to percentages.

Points to note were:

a) Immediate bacteriological degradation of volatile solids was of very small importance compared to the settling effect. Removal due to bacteriological degradation never exceeded 13% of the total removal, and this was only achieved at the 30°C temperature.

b) The proportion of COD removal due to bacteriological action was somewhat higher than that found for solids, reaching a maximum of 19.3% of the total removal, also at the 30°C temperature, but again the settlement factor predominated.

c) BOD removal was far more dependent on immediate bacteriological degradation than either solids or COD. At the 30°C temperature,

TABLE V. Percentage BOD Removals.

TEMP / LDT DAYS	1st CELL			2nd CELL			OVERALL		
	30	23	10	30	23	10	30	23	10
50	87.2	82.4	18.7	2.1	4.5	29.8	89.3	86.9	48.5
25	83.2	72.0	3.6	4.1	6.2	4.6	87.3	78.2	8.2
17	64.7	----	0	14.7	---	0	79.4	----	0

TABLE VI. Percentage COD Removals.

TEMP / LDT DAYS	1st CELL			2nd CELL			OVERALL		
	30	23	10	30	23	10	30	23	10
50	71.9	68.3	55.9	6.5	6.3	11.0	78.4	74.6	66.9
25	72.2	69.6	49.6	4.9	5.6	5.3	77.1	75.2	54.9
17	62.5	----	46.3	6.6	---	3.9	69.1	----	50.2

TABLE VII. Percentage Volatile Solids Removals.

TEMP°C / LDT DAYS	1st CELL			2nd CELL			OVERALL		
	30	23	10	30	23	10	30	23	10
50	81.4	77.6	78.2	3.7	0.4	2.7	85.1	78.0	80.9
25	72.7	73.0	67.4	5.5	4.1	3.6	78.2	77.1	71.0
17	68.9	----	56.9	5.2	---	7.1	74.1	----	64.0

TABLE VIII. Percentage Total Solids Removals.

TEMP°C / LDT DAYS	1st CELL			2nd CELL			OVERALL		
	30	23	10	30	23	10	30	23	10
50	77.8	77.6	75.8	5.8	0.4	2.9	83.6	78.0	78.7
25	74.9	73.0	71.5	7.4	4.1	2.4	82.3	77.1	73.9
17	64.4	----	55.7	13.6	---	6.3	78.0	----	62.0

TABLE IX. Percentage BOD Removals Due to Settling and Bacteriological Action.

LDT DAYS \ TEMP°C		1st CELL			2nd CELL			OVERALL		
		30	23	10	30	23	10	30	23	10
50	B	75.3	61.2	12.0	0	3.1	0	75.3	64.3	12.0
	S	11.9	21.2	6.7	2.1	1.4	29.8	14.0	22.6	36.5
25	B	44.6	34.1	3.3	4.1	2.4	0	47.9	36.5	3.3
	S	38.6	37.9	0.3	0	3.8	4.6	38.9	41.7	4.9
17	B	57.6	----	0	8.6	---	0	66.2	----	0
	S	7.1	----	0	6.1	---	0	13.2	----	0

B = Bacteriological S = Settling

TABLE X. Percentage COD Removals Due to Settling and Bacteriological Action.

LDT DAYS \ TEMP°C		1st CELL			2nd CELL			OVERALL		
		30	23	10	30	23	10	30	23	10
50	B	13.8	11.2	2.2	0	0.6	0	13.8	11.8	2.2
	S	58.1	57.1	53.7	6.5	5.7	11.0	64.6	62.8	64.7
25	B	10.9	8.4	0.8	1.0	0.6	0	11.9	9.0	0.8
	S	61.3	61.2	48.8	3.9	5.0	5.3	65.2	66.2	54.1
17	B	11.6	----	0.9	1.7	---	0	13.3	----	0.9
	S	50.9	----	45.4	4.9	---	3.9	55.8	----	49.3

TABLE XI. Percentage Volatile Solids Removal Due to Settling and Bacteriological Action.

LDT DAYS \ TEMP°C		1st CELL			2nd CELL			OVERALL		
		30	23	10	30	23	10	30	23	10
50	B	7.9	6.4	1.2	0.0	0.3	0.0	7.9	6.7	1.2
	S	73.5	74.8	77.0	3.7	1.5	2.7	77.2	76.3	79.7
25	B	9.3	7.1	0.7	0.9	0.5	0.0	10.2	7.6	0.7
	S	63.4	63.1	66.7	4.6	5.1	3.6	68.0	68.2	70.3
17	B	8.3	----	0.6	1.2	---	0.0	9.5	----	0.6
	S	60.6	----	56.3	4.0	---	7.1	64.6	----	63.4

B = Bacteriological S = Settling

TABLE XII. Percentage Total Solids Removal Due to Settling and Bacteriological Action.

LDT DAYS \ TEMP°C		1st CELL			2nd CELL			OVERALL		
		30	23	10	30	23	10	30	23	10
50	B	5.7	4.6	0.9	0.0	0.2	0.0	5.7	4.8	0.9
	S	72.1	73.0	74.9	5.8	0.2	2.9	77.9	73.2	77.8
25	B	5.2	4.0	0.4	0.5	0.3	0.0	5.7	4.3	0.4
	S	69.7	69.0	71.1	6.9	3.8	2.4	76.6	72.8	73.5
17	B	5.9	----	0.5	0.9	---	0.0	6.8	----	0.5
	S	58.5	----	55.2	12.7	---	6.3	71.2	----	61.5

a maximum of 84% of the total removal was achieved by bacteria in the supernatant. A fair portion of the BOD did appear to be settleable, however, with a maximum of 41.7% removal due to settling being obtained in the 10°C reactor. The negligible removals for the 10°C digester at the 25- and 17-day LDT values are probably due to the fact that the BOD of the raw feed was decreasing with time at the end of the 25-day LDT and throughout the 17-day LDT. This would clearly give rise to decreased apparent removal figures for this digester, especially since the 10°C digester would be the slowest by far to react to changes in feed strength. The decrease in feed strength would not show as soon in the effluent of the 10°C digester as in that of the others. Thus the results from the 10°C digester are probably suspect, and more reliance can be placed on the results from the other two units.

d) At a given LDT, total solids removal by settling was essentially independent of temperature. Differences in total solids removal were mainly due to bacteriological reduction of non-settleable volatile solids. Much of the gas produced was due to the degradation of settled volatile solids, but this was allowed for as previously mentioned.

4.6 Relative Importance of 1st and 2nd Cell

Tables V - XII show removal figures for each cell of the system as well as the overall removals. From these tables the following points are noted:

a) The first of the two cells was responsible for the major portion of the removal of all parameters. The general trend was to a greater second-cell contribution at a lower LDT, which would be logically expected due to the rising strength of the 1st cell effluent at lower LDT supplying more feed material to the second cell.

b) Bacteriological activity in the second cell was minimal at any temperature, and non-existent at 10°C. The contribution of the second cell was thus almost entirely due to settling.

c) The contribution of the second cell to treatment efficiency, although small, was nonetheless significant in view of the high raw feed strength. For a waste of the strength used in this experiment, a 1% reduction in any of the important parameters represents a worthwhile gain in effluent quality.

4.7 Single-Stage vs. Two-Stage System

Two methods of comparison were employed. The first method was to compare relative performance figures obtained from the earlier research[4] and from the present study at corresponding LDT values. These figures are presented in Tables XIII and XIV. The difficulty here was that only two corresponding LDT's, 50 days and 25 days, were available, and the data from the 50-day LDT was rather incomplete for the single-stage test. A further point was the probability, discussed in Section 4.3, of varying results due to feed characteristics and short circuiting. A second method of comparison was therefore used also. This entailed the consideration of the results from the first cell of the flow-through systems as being from a single-stage

TABLE XIII. Comparison of Single- and Two-Stage Systems.

(LDT = 50 days)

UNIT	SINGLE-STAGE (25 ℓ)			TWO-STAGE (25 ℓ)		
Temp°C	30	23	10	30	23	10
% BOD Removed	89.0	87.0	--	89.3	86.9	48.5
% COD Removed	83.0	80.5	--	78.4	74.6	66.9
% VS Removed	----	----	--	85.1	78.0	80.9
% TS Removed	----	----	--	83.6	78.0	78.7

TABLE XIV. Comparison of Single- and Two-Stage Systems.

(LDT = 25 days)

UNIT	SINGLE-STAGE (25 ℓ)			TWO-STAGE (25 ℓ)		
Temp°C	30	23	10	30	23	10
% BOD Removed	88.0	85.0	43.5	87.3	78.2	8.2
% COD Removed	82.5	81.5	64.5	77.1	75.2	54.9
% VS Removed	79.5	81.0	79.0	78.2	77.1	71.0
% TS Removed	73.5	74.0	73.0	82.3	77.1	73.9

unit of 12.5 ℓ capacity. At a feeding rate of 0.5 ℓ/day, this gave an LDT of 25 days, which could be compared with the results from the total system of two cells at a feeding rate of 1.0 ℓ/day, giving a corresponding 25-day LDT. The only problem here would be the possibility of the volume difference of the two systems giving rise to some scale effect. Also only one LDT, that of 25 days, could be compared. The results for this comparison are shown in Table XV.

Regarding the comparison of the original single-stage tests[4] and the two-stage tests, points to note are:

a) BOD removal was almost identical at the 30°C temperature for both systems, but decreased much more rapidly with decreasing temperature at the same LDT in the case of the two-stage test.

b) The variation in COD removal figures was somewhat wider, the single-stage unit giving considerably better removal at both LDT's.

c) Volatile solids removal at the 25-day LDT, the only one for which comparison was possible, was of a very similar level at 30°C, but again the two-stage unit fell off in performance more rapidly with decreasing temperature.

d) Total solids removal was considerably better for the two-stage system at the two higher temperatures of 30°C and 23°C, but was almost identical at 10°C. Again the two-stage unit fell off in performance with decreasing temperature, while the single-stage unit remained essentially constant regardless of temperature.

TABLE XV. Comparison of 1st Cell Only Vs. 1st and 2nd Cells at 25-Day LDT.

Percentage Basis

UNIT	1st CELL (12.5 ℓ)			TWO-STAGE (25 ℓ)		
Temp°C	30	23	10	30	23	10
% BOD Removed	87.2	82.4	18.7	87.3	78.2	8.2
% COD Removed	71.9	68.3	55.9	77.1	75.2	54.9
% VS Removed	81.4	81.2	78.2	78.2	75.8	71.0
% TS Removed	77.8	77.6	75.8	82.3	77.1	73.9

Mass Removed Basis

UNIT	1st CELL (12.5 ℓ)			TWO-STAGE (25 ℓ)		
Temp°C	30	23	10	30	23	10
BOD* Removed	153	145	33	213	193	20
COD Removed	692	658	538	779	761	554
VS Removed	698	697	671	471	456	428
TS Removed	922	921	898	850	831	796

* All removals in mg/1 of cell/day.

From these observations, it may be stated that the two-stage units did give better settling efficiency, but variations in the composition of the feed used in the two tests caused lower efficiencies to be recorded for removal of parameters other than total solids. The results could well be explained if it were the case, for example, that there was less settleable BOD and COD in the waste used for the two-stage tests, thus placing more emphasis on biological action as the chief removal factor. The fact that removal fell off with temperature for the two-stage system, but did no do so to any great extent in the single-stage system indicates that there was more dependence on bacteriological action for the two-stage removals than for the single-stage. This would clearly be tied up with feed characteristics such as settleable volatile solids, dissolved BOD or COD as opposed to settleable BOD or COD. Clearly non-settleable, BOD, COD or volatile solids can only be removed by bacterial action, so a higher level of these parameters in solution or suspension would certainly give rise to a more marked temperature effect. Thus the indication is that, although the two-stage system does give improved settling, as indicated by the total solids removal, the percentage removals of BOD, COD and volatile solids as a result of this will be considerably influenced by relatively minor changes in raw waste characteristics.

With regard to the comparison of the first cell only against the total two-cell system, both at 25-day LDT, points to note are:

a) On a percentage basis, BOD removal was again the same at the 30°C temperature, but fell off more rapidly for the two-stage

system with decreasing temperature. However, the BOD of the feed used at 25-day LDT for the two-cell system was considerably higher than that used for the run from which the 25-day LDT figures were obtained for the first cell only. As a result of this, on a mass basis the two-cell system gave considerably better removal figures except at the 10°C temperature, at which temperature the BOD removal was very small in both cases.

b) On both a percentage and a mass basis, the COD removal for the two-cell system were considerably better again with the exception of the 10°C units, which were almost identical in removal efficiency.

c) On a percentage basis, total solids removal was very similar for both systems, although on a mass basis the first cell alone gave better results. This can be explained by the fact that the feed total solids concentration was higher for the first cell only, than for the two-cell system. If the percentage of settleable solids were the same in both cases, as seems not unreasonable, then clearly the lower total incoming solids level for the two-stage unit would result in a lower total solids mass removal, as found in this test. The same observation holds true for volatile solids removals, which were far lower in the case of the two-cell system than for the first-cell only. In this instance, lower removals were obtained both on a percentage and a mass basis for the two-cell system.

On the basis of these results, it would appear that there is little difference in settling capacity of the two-cell system and the first cell of

that system working alone. The two-cell system gave considerably better performance on a BOD - COD removal basis, despite the absense of appreciably improved settling, indicating that, compared to the first cell alone, the two-stage system is somewhat more effective biologically. Again, feed composition differences appear to have a marked effect on the results obtained. A true evaluation of the relative merits of the two systems would require a series of concurrent tests on both single- and two-stage systems of the same type using identical feed material. These, and other conclusions, will be discussed in Chapter 6.

4.8 Copper Concentrations

Towards the end of the series of tests made on the two-stage digesters, it was decided to sample the cell contents and determine the levels of copper present due to corrosion of the brass digester fittings and copper cooling coils. This was not done in the case of the earlier tests[4], but it would be of interest since copper has a significant effect on the BOD test, causing reduction in apparent BOD values, and will also inhibit bacteriological action.

Copper concentrations were determined by the atomic absorption technique using samples of the fully mixed digester contents. Two separate sets of analyses were made, the first at three months from the conclusion of the experiment and the second at the conclusion of testing. Results are shown in Table XVI.

Eckenfelder[2] gives data indicating that the results given by the BOD_5 test will be reduced up to 50% by the presence of 4.0 mg/ℓ copper. Levels below 1.0 mg/ℓ copper have a relatively insignificant effect on this test. However, McKee and Wolfe[10] state that the concentration necessary

to reduce BOD_5 by 50% has been variously determined at between 8.4 mg/ℓ and 35 mg/ℓ. Thus there is a considerable diversity of information regarding this topic.

TABLE XVI. Copper Concentrations in Two-Stage Digester Cells

CELL NUMBER		COPPER CONCENTRATION (mg/ℓ Cu)*	
		Test Number 1	Test Number 2
1-1	30°C	1.67	0.67
1-2		4.30	1.66
2-1	23°C	2.80	4.38
2-2		6.30	1.53
3-1	10°C	11.60	16.12
3-2		3.20	1.90

Test Number 1 -- 3 months prior to end of experiment.

Test Number 2 -- at end of experiment.

*All samples fully mixed and acid-digested to ensure all copper in solution.

With regard to toxicity of copper to micro-organisms, McKee and Wolfe[10] report that copper concentrations as low as 0.1 to 0.5 mg/ℓ are toxic to certain micro-organisms. The Committee on Water Quality Criteria recorded[11] that sewage organisms in particular are inhibited to 50% of oxygen utilisation by 21 ppm copper. The copper inhibits activity by tying up the proteins in the key enzyme systems, preventing these from reacting normally[12].

With regard to the results of the tests reported herein, the copper concentrations are certainly in the range reportedly required to cause

significant decreases in the results given by the BOD test and to cause some inhibition of microbiological activity. In particular, the levels encountered in digester number 3 (10°C) which had cooling coils made of pure copper, were high enough not only to affect the BOD test, but to significantly affect utilisation of oxygen by sewage organisms. Since no microbiological studies were undertaken to classify species of bacteria present, no estimate can be made as to the actual effect of the copper upon the results of these tests, but it can be said that the results were almost certainly affected to some degree. It is significant that the 10° digester showed practically no gas production throughout the tests. However, the measured BOD of the effluent from this unit was close to that of the raw waste, as reported earlier in this chapter, so indications are that the BOD test was not affected to a serious degree.

The single-stage digesters used in the earlier work[4] were constructed of identical materials. Hence, the comparative results between the two, forming the main basis of this study, should still be valid, although absolute values may be suspect.

It should also be noted that with the exception of cells 2-1 and 3-1, the copper concentrations in the other cells fell significantly over the three months between the first and second tests. This indicates that copper was not going into solution as fast as it had been earlier. This was undoubtedly due to the formation of a layer of copper compounds on the metal surfaces which formed a barrier between the copper and the digester contents. When the cells were emptied at the conclusion of testing, a crust of corrosion products was in fact found on all metallic fittings. It is reasonable to conclude that operation over a longer period

of time would probably bring copper concentrations down to acceptable levels. However, the use of brass or copper fittings in experiments of this nature is clearly shown by these results to be undesirable and potentially ruinous to the obtaining of accurate absolute values for experimental data. Stainless steel should be utilised whenever possible.

CHAPTER 5. VOLATILE ACIDS AND TOTAL ORGANIC CARBON RESULTS

5.1 Introduction

Neither Volatile Acids nor Total Organic Carbon (TOC) were studied in depth in the previous work[4], due to lack of suitable equipment. However, the necessary instruments were available for the present work, and accordingly it was decided to study these parameters in some detail.

It has been reported by McGhee[13] that volatile acids levels in batch-fed systems vary considerably, reaching a peak approximately 4 hours after feeding and falling back to a base level at about 16 hours after feeding. The peak is typically greater than the base level by a factor of 5 or 6. Figure 5.1 shows a typical curve of volatile acid concentration versus the number of hours after feeding; the data are taken from the work of McGhee[13]. The volatile acid data presented herein are base-level figures, since they were determined immediately prior to feeding.

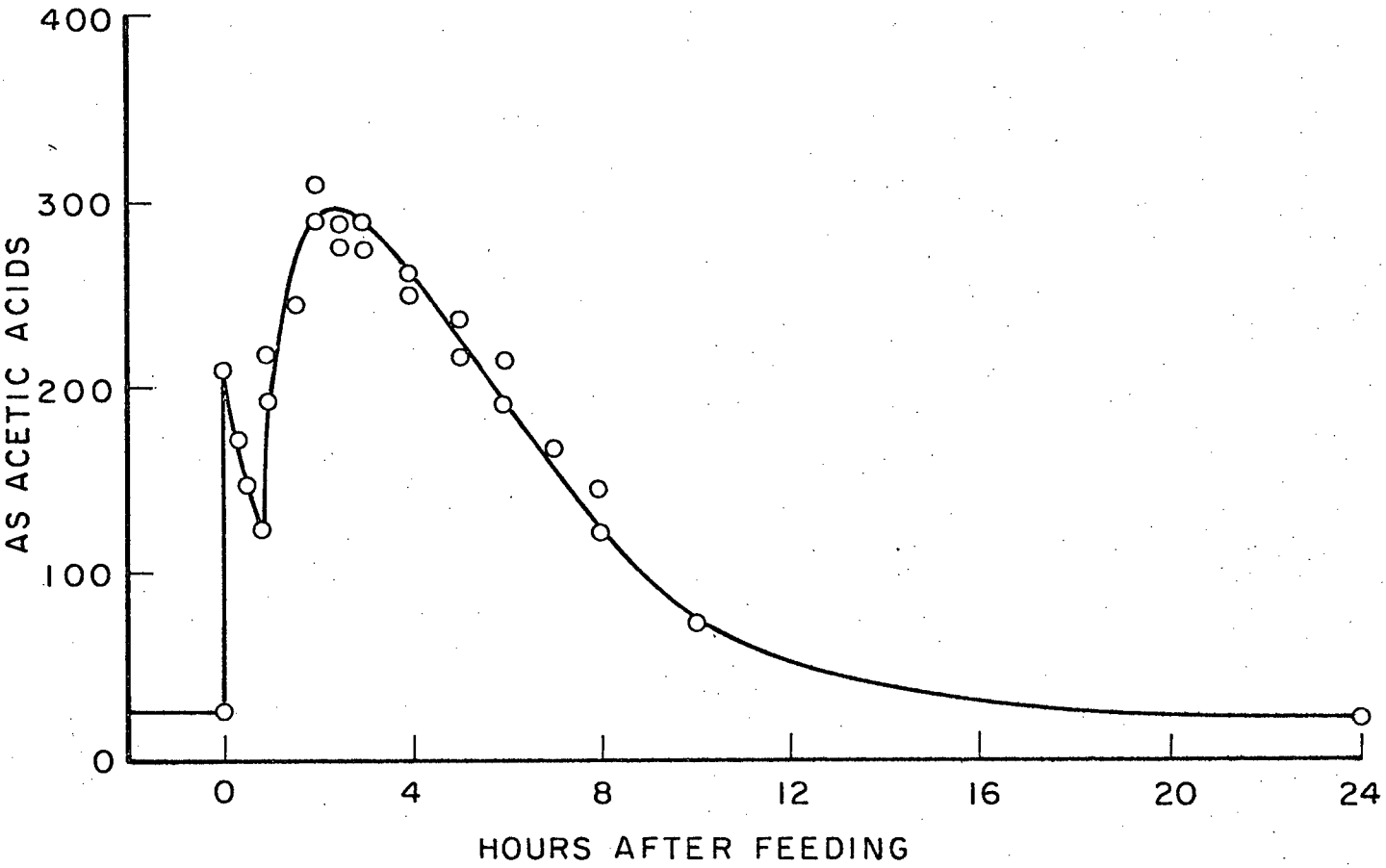
5.2 Volatile Acids and pH Levels in Anaerobic Systems

It is considered[12] that a volatile acids level above 2,000 mg/ℓ in anaerobic systems is an indication that trouble is imminent. This rise in volatile acids can depress pH to the point where the methane bacteria are severely inhibited, and thus cannot keep pace with the acid-formers. In this situation, the volatile acids will continue to rise, and the pH will fall further, resulting in a total cessation of methane production and an upset in the system.

FIG. 5 - 1

VARIATION OF VOLATILE ACID CONCENTRATION.

(AFTER McGHEE [13])



Volatile acids are not in themselves toxic to methane-forming bacteria, as laboratory studies have shown that it is possible to operate a digester at levels of up to 20,000 mg/ℓ volatile acids as long as the pH is maintained above 6.5[12]. In such cases, the rate of matabolism of the methane-formers is limited by the concentration of soluble cations added while neutralising the volatile acids to the desired pH[12]. Lime is commonly used for this purpose, and it was employed during this experiment as reported earlier. Lime is most suitable for this purpose, as calcium is the least soluble cation usable in a neutralising situation, and thus causes the least possible upset to the methane formers; it is also very cheap and readily available.

5.3 Volatile Acids and pH in the Two-stage Digester

The measured volatile acids levels in the two-stage digesters are presented in Figures 5.2 to 5.4, with pH data being presented in Figures 5.5 to 5.7.

Points to note are:

a) The volatile acids concentrations in the 30°C and 23°C digesters were generally relatively low, in the 100-600 mg/ℓ range, indicating that both biological systems were functioning in a stable manner. The pH of these two digesters was also in a stable range, being of the order of 7.2 - 7.6. At no time did the volatile acids levels of either system exceed 1,200 mg/ℓ, except for number 1-1, which went to 3,500 when the feed rate was changed from 1.0 to 1.5 ℓ/day. Recovery was quick from this load, however, as the pH at this time remained at around 7.3, indicating a very well-buffered system.

FIG. 5-2

VOLATILE ACIDS VS. TIME FOR 2-STAGE DIGESTER #1(30°C).

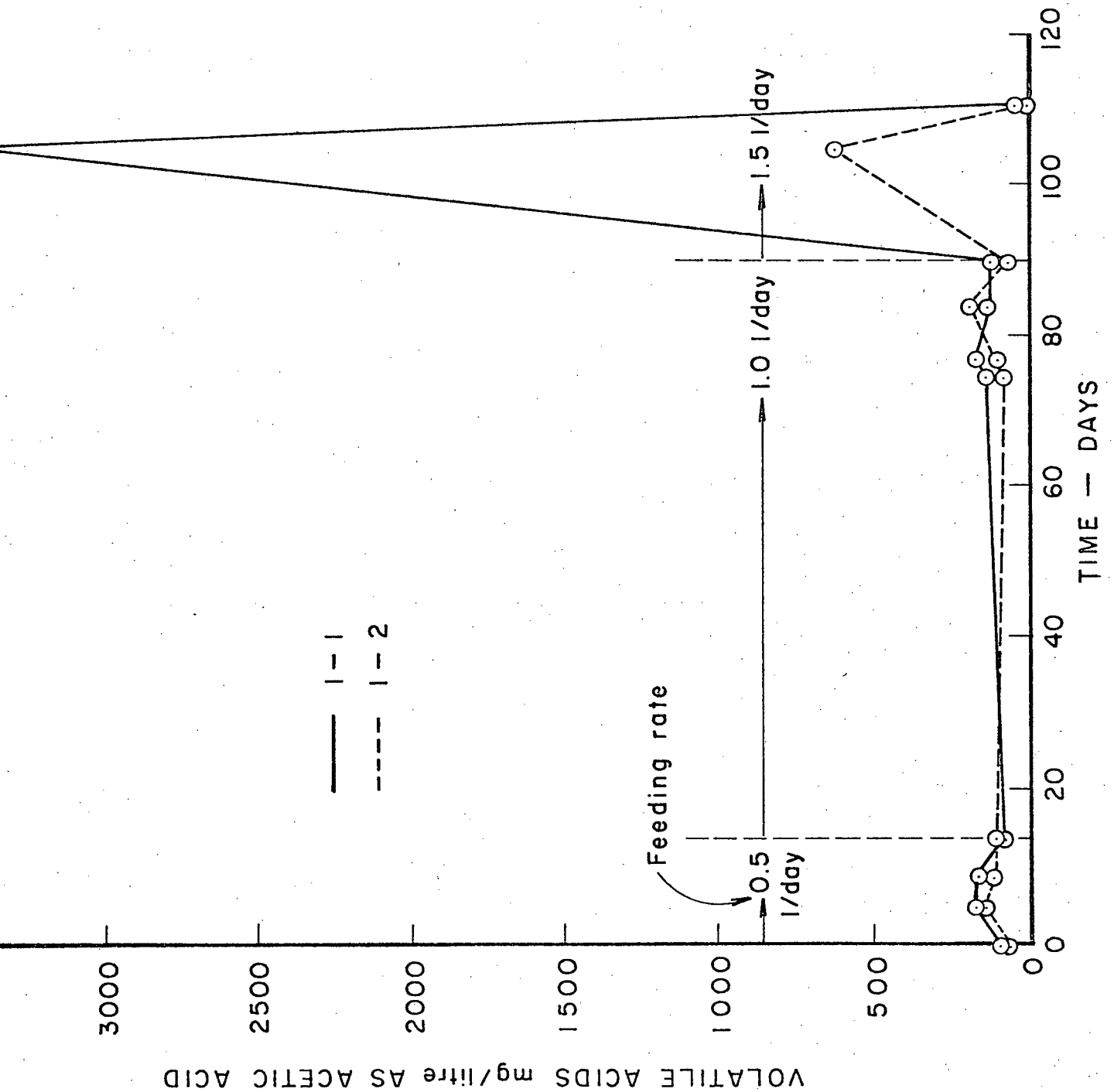


FIG. 5-3

VOLATILE ACIDS VS. TIME FOR 2-STAGE DIGESTER #2(23°C).

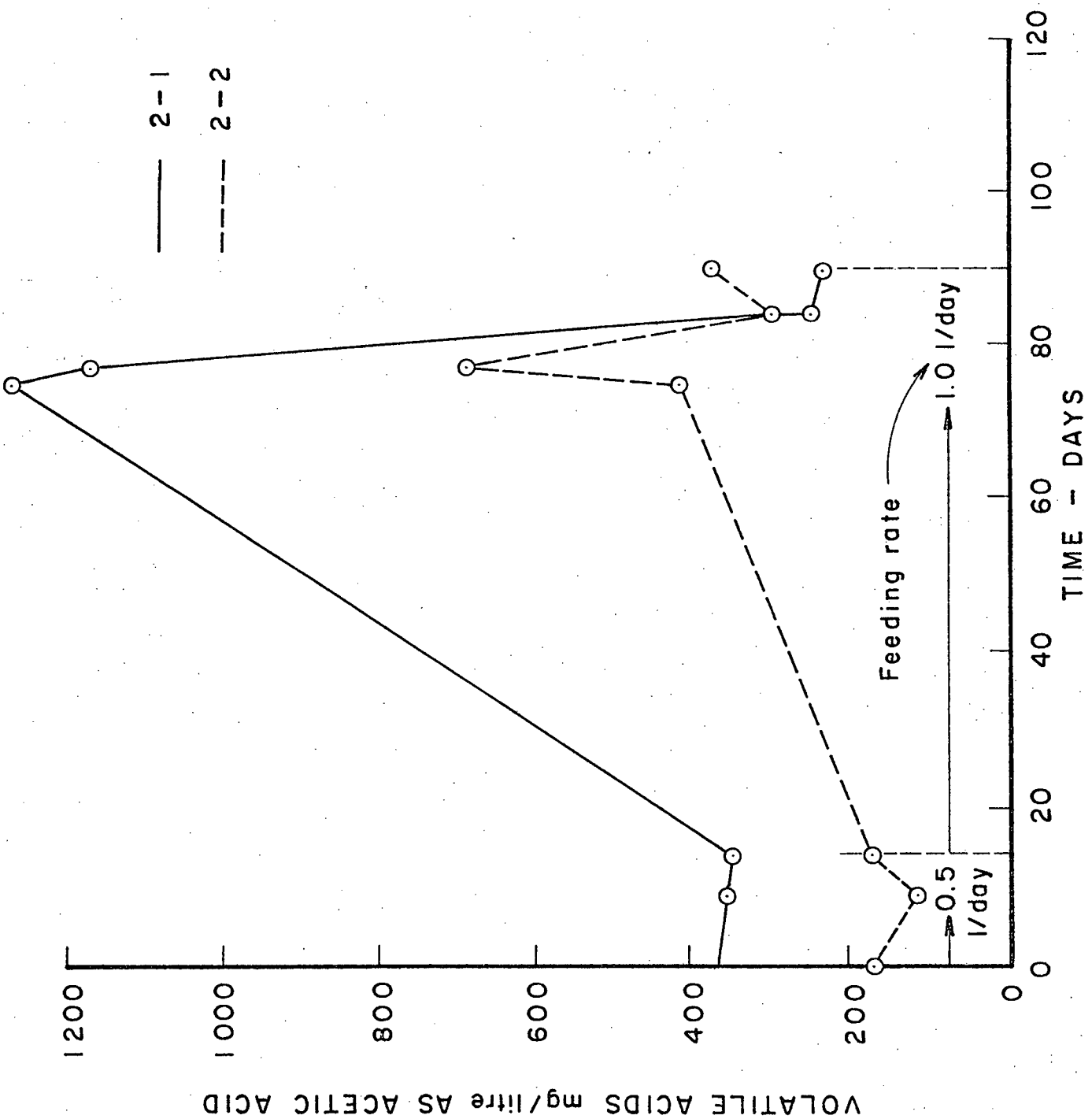


FIG. 5 - 4

VOLATILE ACIDS VS. TIME FOR 2-STAGE DIGESTER #3(10°C).

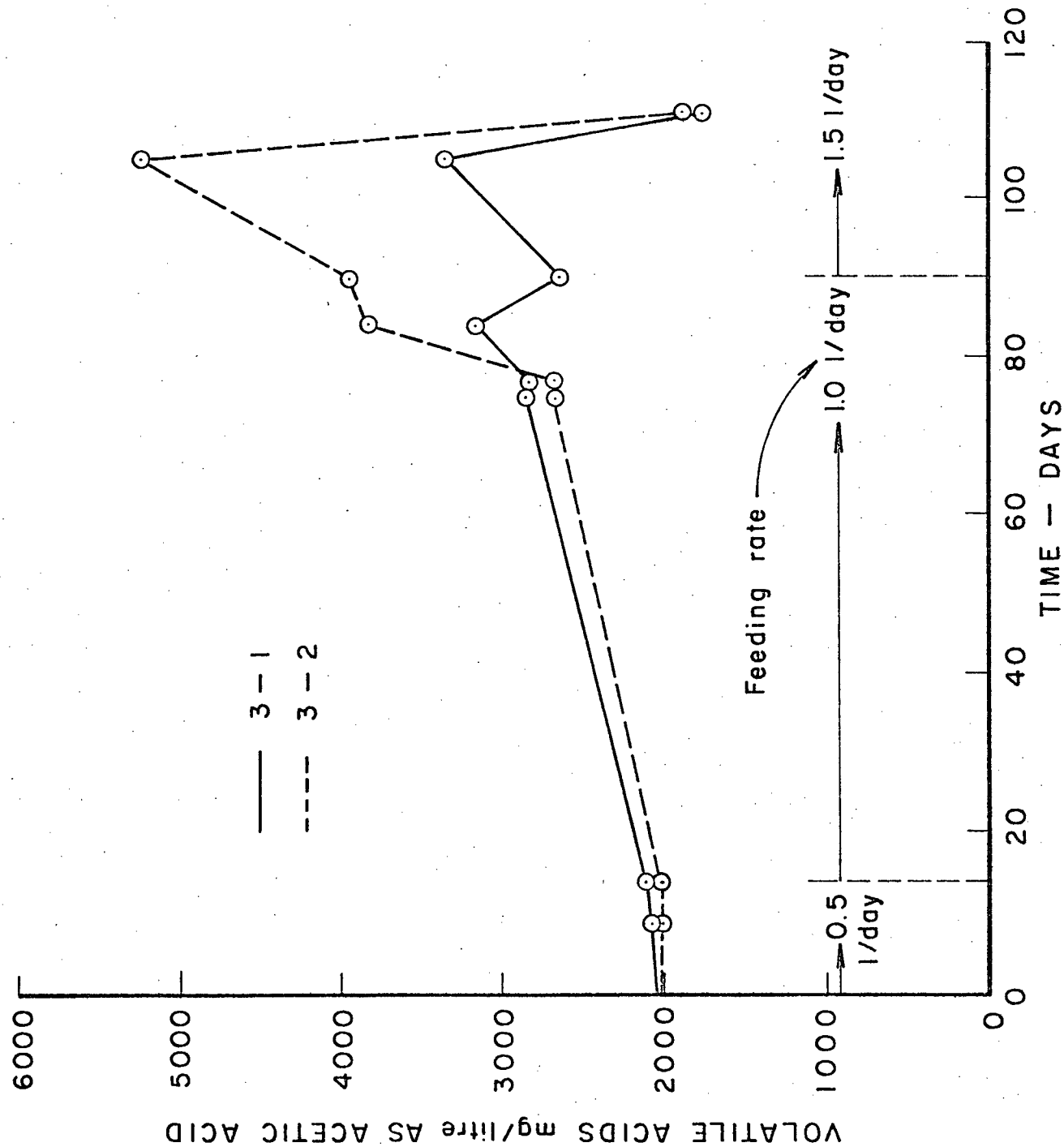


FIG. 5-5

pH VS. TIME FOR 2-STAGE DIGESTER # 1 (30°C).

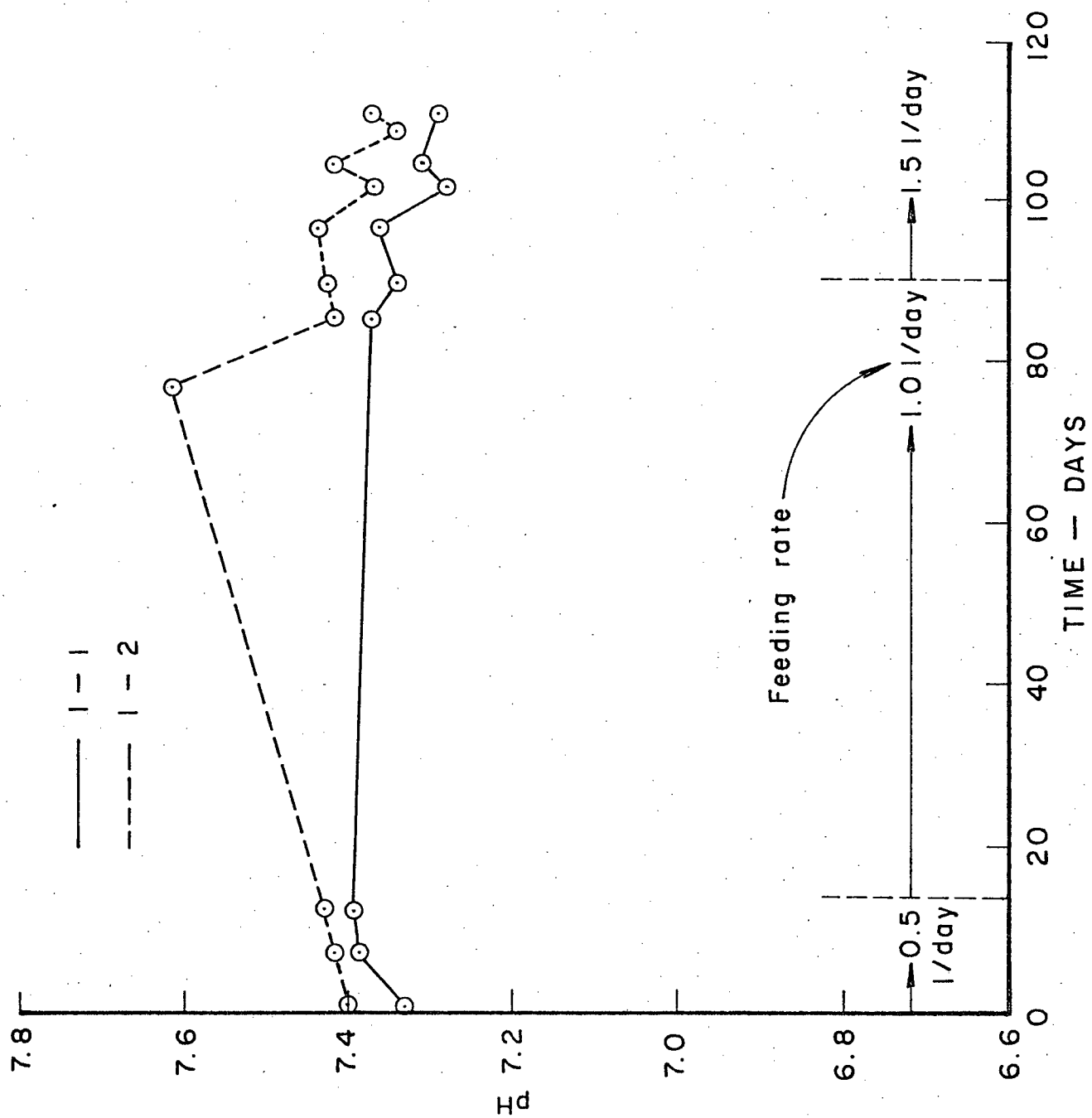


FIG. 5-6

pH VS. TIME FOR 2-STAGE DIGESTER #2(23°C).

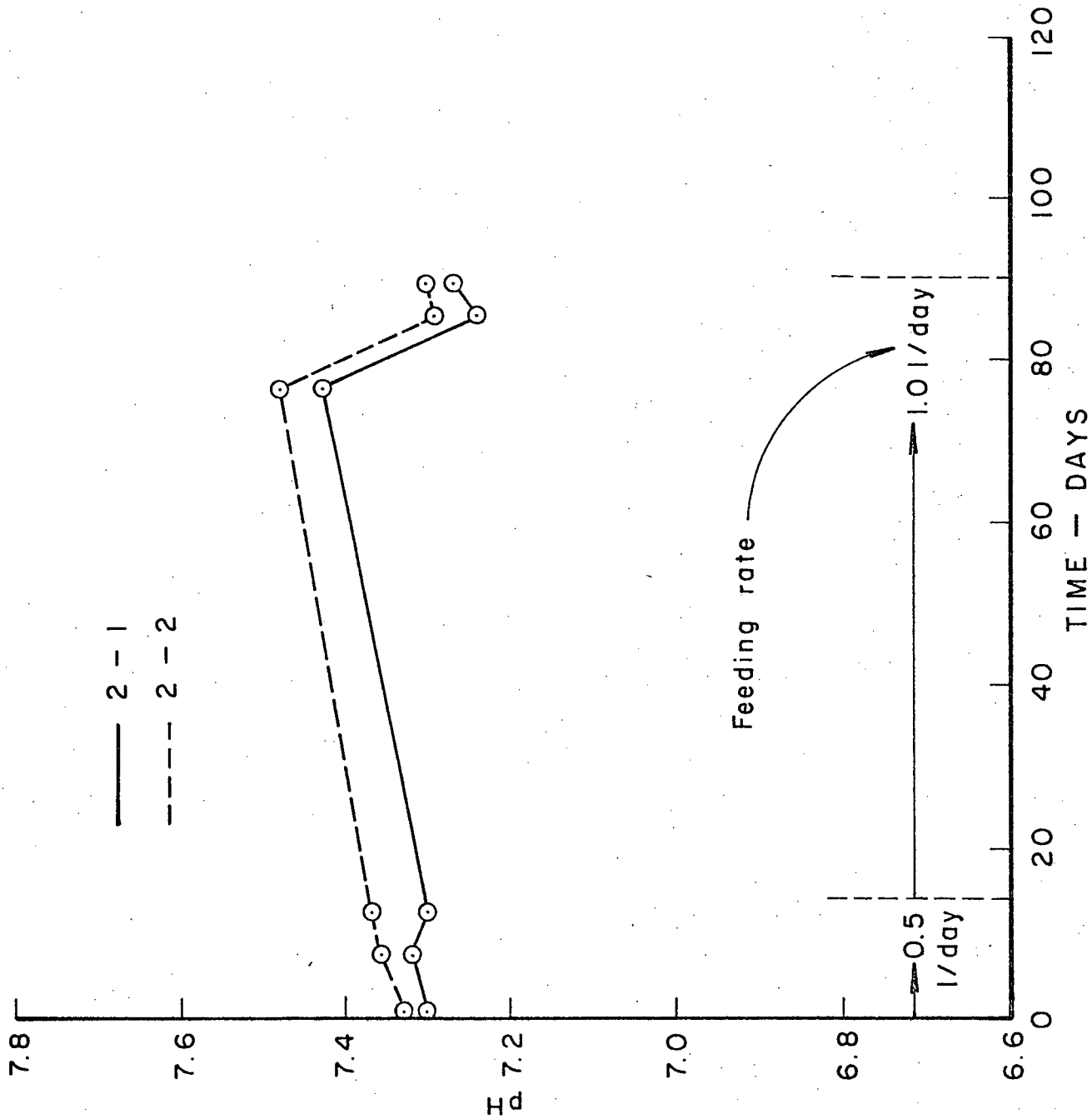
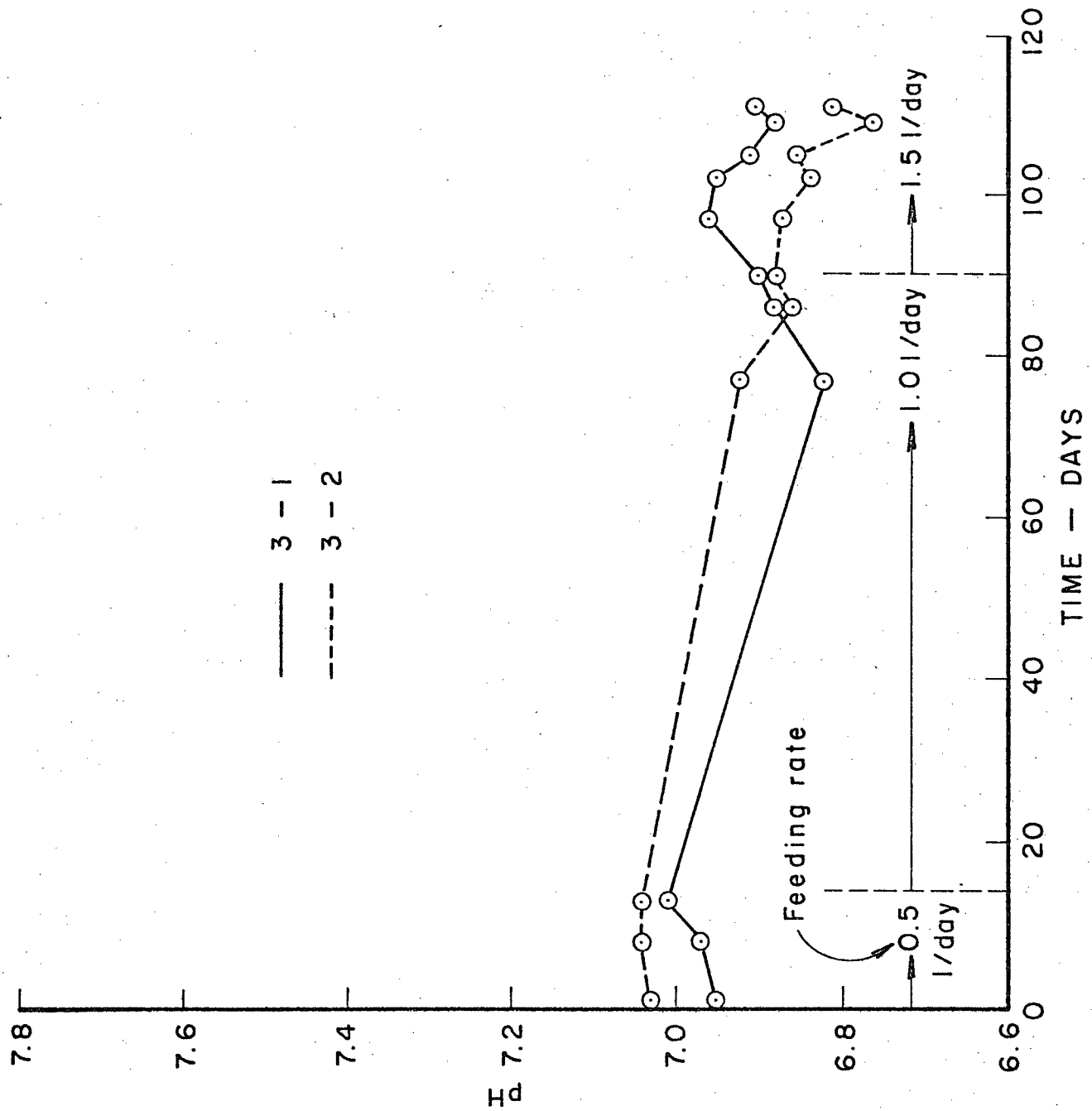


FIG. 5-7

pH VS. TIME FOR 2-STAGE DIGESTER #3(10°C).



b) The second cells of the 30°C and 23°C digesters exhibited less fluctuation in volatile acids than did the first cells. This would be expected, as they were not subject to the direct shock loading of raw waste. At no time did these second cells indicate any tendency to upset, although it must be borne in mind that bacteriological activity in the second cells was very limited, as reported earlier. This limited activity cannot be attributed to upset conditions on the basis of these results, but must have been due to limited availability of substrate to further biological degradation.

c) The 10°C digester gave results for both volatile acids and pH which indicated upset conditions. Volatile acids levels of 2,000 to 3,000 mg/ℓ were encountered, together with pH values down in the 6.8 - 6.9 range. It can be stated that conditions in this unit were not conducive to good metabolism of the methane-formers, and in fact there was very little methane produced from these cells. The volatile acids did rise with increased feed rate, but remained in the same general range, indicating that the acid-formers themselves were in a state of inhibition. This may have been due to the copper levels reported earlier, but the temperature was doubtless a factor here.

d) The two digesters (30°C - 23°C) which operated in the stable range of pH and volatile acids values had no trouble adjusting to the 1.0 ℓ/day feed rate and the 30°C digester adapted well to the 1.5 ℓ/day rate. It was unfortunate that lack of feed material prevented more extensive testing of the 1.5 ℓ/day

rate. In this regard, it would certainly have been most instructive to observe the response of the 23°C digester to the 1.5 ℓ/day feeding rate, but the shortage of feed material at the close of the test forced the abandonment of feeding of one digester and the 23°C unit was chosen.

e) The 30°C digester showed an abrupt jump in volatile acids concentration at the change of feed rate to 1.5 ℓ/day, but recovered quickly, indicating excellent system stability.

5.4 Total Organic Carbon Measurements in the Two-Stage Digesters

The Total Organic Carbon analyser has been developed over the past decade or so into a very precise instrument capable of giving excellent and reproducible results with a minimum expenditure of time and effort. A sample can be tested in two minutes quite easily. Thus, it is felt by many to be a far better test than the currently-used BOD and COD analyses.

Robbins, Howells, and Kriz have conducted an extensive program of research into the use of TOC in characterisation of swine wastes. Their published conclusions[14,15] may be stated as follows:

a) TOC is a more reproducible and convenient test for swine wastes than either BOD or COD.

b) The BOD test in particular is not applicable to characterisation of concentrated swine wastes and lagoon effluents, due to the presence of toxic substances, high solids contents and to errors associated with the high dilution requirements for

testing.

c) No general BOD/TOC correlation was found for concentrated swine wastes and effluents, although once the effluents were diluted by runoff, TOC results could be used to yield a figure for BOD for estimating purposes. In addition, the TOC test is far more convenient for this than the BOD test.

d) The variation of the BOD/TOC ratio gives an indication of the presence of toxic materials, as the BOD test responds most markedly to these, whereas TOC does not.

e) The actual value of the BOD/TOC ratio gives an indication of the ease of biodegradation and degree of stabilisation of a swine wastewater. In general, this ratio is less than one, except for raw wastes or those which are not stabilised to a great degree.

For the present work, TOC tests were performed routinely on both feed material and effluent from all three digesters. Hence, a wide range of TOC, BOD and COD values was generated for comparison purposes. These data were plotted as shown in Figures 5.8 and 5.9 for BOD and COD respectively.

The results for BOD agreed well with the observations recorded by Robbins et al[15]. The BOD/TOC ratio varied from 1.35 down to 0.22 with a "best-fit" mean of 0.57. The fluctuation could be caused by the presence of the copper affecting the BOD test, based on the toxicity indication theory. Robbins et al[15] reported ratios ranging from 0.41 to 1.25 for concentrated effluents.

FIG. 5 - 8

BOD VS. TOC FOR RAW FEED AND DIGESTER EFFLUENTS.

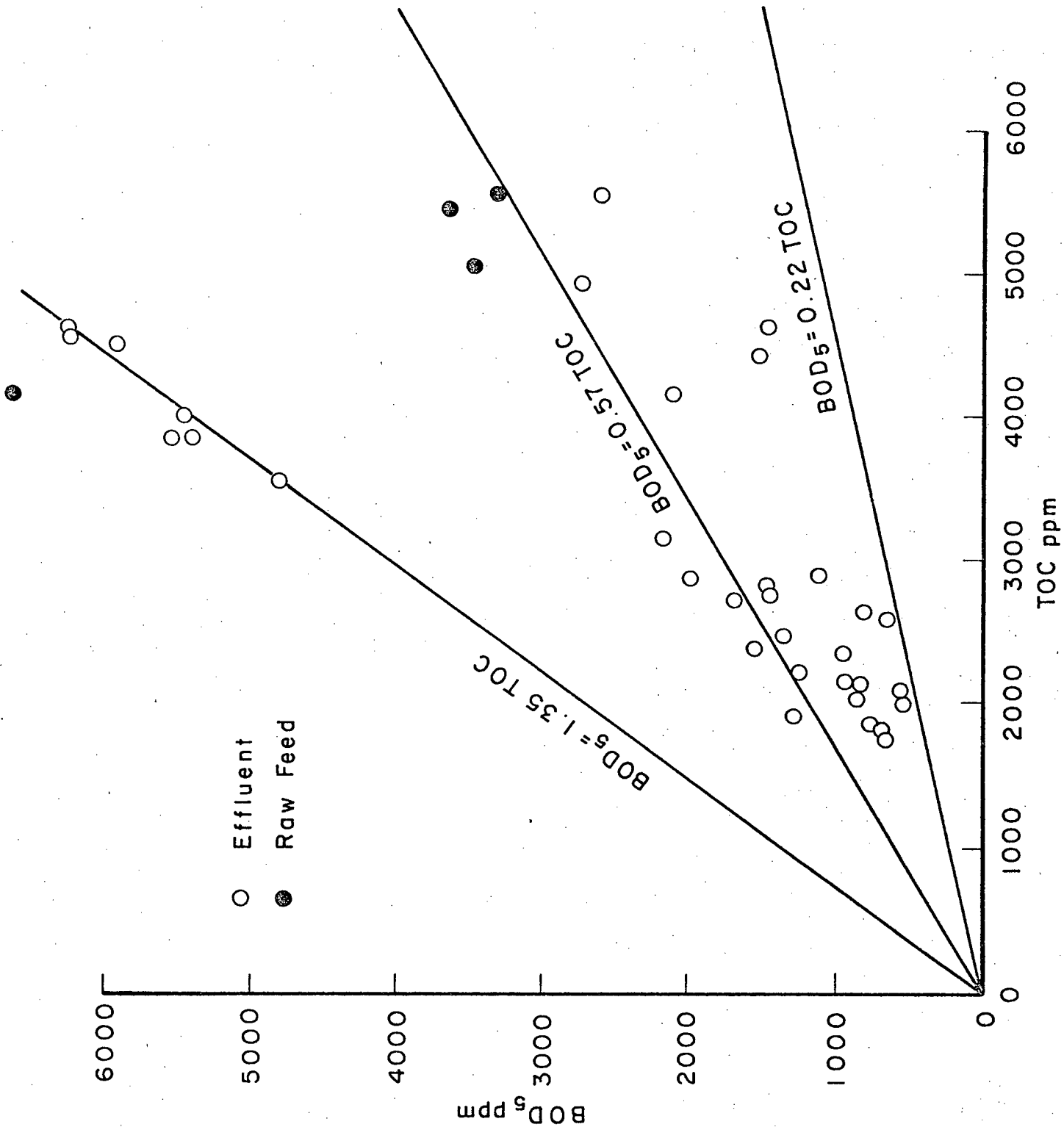
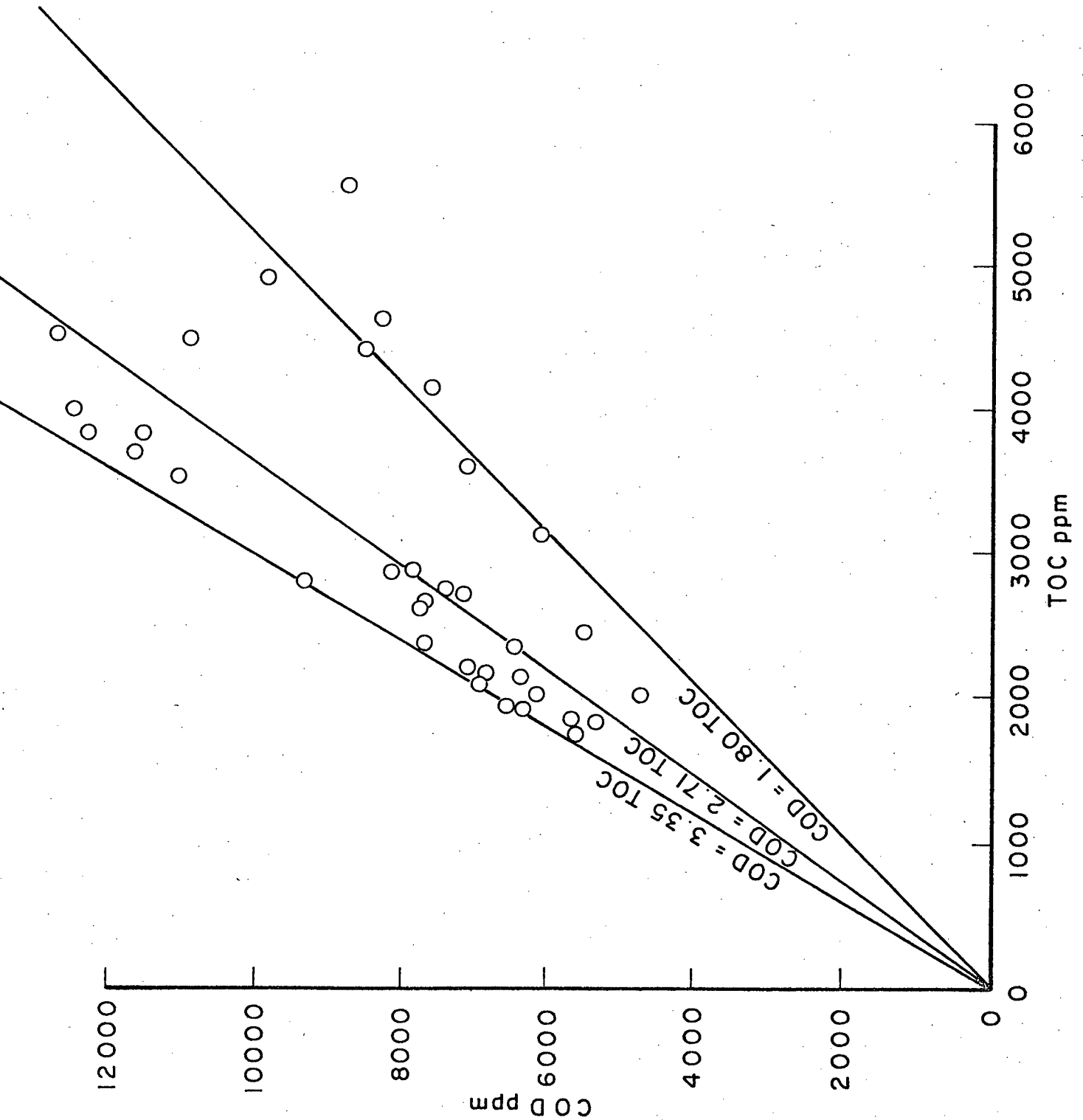


FIG. 5 – 9

COD VS. TOC FOR DIGESTER EFFLUENTS.



A similar variation was found for COD. The COD/TOC ratio varied from 1.8 to 3.35 with a "best-fit" mean of 2.71 Since no other work has apparently been done on COD and TOC correlations, no comparison can be made here.

It should be noted that a regression equation was not obtained for these curves, as the wide spread of results would make this a meaningless exercise. The chief conclusion in fact is that due to a number of factors not identified, correlation between BOD and COD with TOC is very poor for concentrated swine wastes.

The effluents had BOD/TOC ratios of well under one in most cases, indicating that they were well stabilised in general. There was no marked difference in distribution between first and second cell effluents, and thus these could not meaningfully be plotted as separate graphs.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATION

6.1 Introduction

In this chapter, the basic findings of the study are summarised. The conclusions reached as a result of this study may conveniently be distributed under several distinct subheadings. These are presented in the following sections.

6.2 Conclusions from Batch Test Results

a) On the basis of the batch test results, the use of the figure given by Lawrence and McCarty[9], 0.35 ml methane produced per mg of COD or BOD_L destroyed, is fully justified in calculations involving anaerobic digestions of hog wastes.

b) The same tests indicated that the use of the figures published by Eckenfelder[2], 69 to 81 ℓ of methane produced per 100 gm of Volatile Solids destroyed, is fully justified in calculations involving anaerobic digestion of hog wastes.

c) The practise of allowing a lagoon to stand unfed for a period of time in order to reduce solids build-up is of limited value, as the majority of solids in hog waste of the type employed in these tests are not readily biodegradable. The main benefit resulting from allowing a lagoon to stand would be reduction of sludge volume in the lagoon resulting from gravity consolidation of the solids layer in the lagoon, which is occurring anyway whether the lagoon is fed or not. Biological degradation

would be of secondary importance.

6.3 Conclusions from Two-Stage Continuous-Feed Digester Results

a) Settling is the major removal mechanism in the case of COD and solids removal. However, BOD removals are dependent on biological action to a considerable extent. As a result of these observations, it is clear that waste characteristics play a major role in governing treatment efficiency of a system. Based on results presented in this report, it may be stated that relatively minor changes in waste characteristics can have an appreciable effect on system efficiency. BOD removal in particular is very sensitive to changing conditions in both the treatment process and the waste characteristics.

b) The first cell in a two-cell system achieves most of the removal obtained in the system. The contribution of the second cell is small by comparison, but with a high-strength waste such as hog waste, even small percentage removals are significant on a mass basis. The second cell in these tests exhibited very little biological activity, indicating that the supernatant from the first cell was not readily bio-degradable by the anaerobic process despite its high residual BOD. Second-cell removals were almost entirely due to settling.

6.4 Conclusions Regarding Two-Cell Vs. One-Cell Systems

a) The two-cell system does give improved settling efficiency and solids removal capacity. Whether or not this improves BOD or

COD removal significantly will depend to a great extent on waste characteristics such as settleable BOD and COD, dissolved BOD and COD, relative percentage of volatile and total suspended solids, etc.

b) The two-cell system does have a higher capacity for removal on a mass basis, of BOD and COD, based on the comparison of removal efficiency of the first cell only against that of both cells (same total detention time in each system). Thus, the unit loading capacity of the two-cell system is somewhat higher.

6.5 Conclusions from Copper, Volatile Acids, pH and Total Organic Carbon Tests

a) The anaerobic system can accept changes in loading rate without upset conditions developing, provided temperatures are kept up in a range favourable to biological activity. At the 10°C temperature, the methane-forming bacteria are adversely affected, and are unable to cope with sudden upswings in volatile acids concentractions, or in fact to keep up at all with the acid formers, even at steady feed rates.

b) Lack of biological activity observed in the second cells was not due to upset conditions, and must therefore have been due to limited availability of substrate, or some other factor not determined.

c) The use of brass or copper fittings in equipment used for anaerobic digestion gives rise to seriously high levels of copper in the substrate, and is potentially disastrous from

the point of view of obtaining meaningful results.

d) There is no readily identifiable correlation between BOD, COD, and TOC.

6.6 Recommendations

a) In the design of an anaerobic lagoon system for hog wastes, use of two lagoons of a given total volume, rather than a single lagoon of the same volume, should be considered where space permits, as loading capacity and removal efficiency will be increased for a very small increase in the area of the lagoon system.

b) In design of such a system, waste characteristics should be thoroughly investigated, as they will play a major role in determining the efficiency of treatment which can be obtained from a given lagoon system. The waste should be tested for such characteristics as settleable BOD and COD, settleable solids, and treatability of the raw supernatant resulting from settling out of the solids. This should form an important part of any future laboratory research also.

c) Anaerobic lagoons will only exhibit worthwhile biological activity at temperatures above approximately 20°C. At 10°C, there is practically no activity. Hence, for year-round operation, such lagoons should be considered as settling ponds only, and the two-stage system is better suited to this than the single-stage system.

d) All laboratory equipment used in anaerobic research should have stainless steel fittings, as copper and brass both cause unfavourably high levels of copper to dissolve in the substrate.

e) Consideration should be given to the possible improvements in treatment efficiency resulting from aeration of the second lagoon. The supernatant from the first cell of a two-cell system is not, on the basis of this study, readily degradable by anaerobic bacteria, but may well respond to aerobic treatment.

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APPENDIX A. Sample Calculations

a) Amount of COD removed by bacteriological action in batch tests

Volume of liquid in digester at start of experiment = 23.7 ℓ
(after removal of test sample)

COD at start = 30,600 ppm.

∴ Total COD in digester = 23.7 x 30,600
= 726,000 mg.

At time of next sampling:

0.2 ℓ sample taken, leaving volume of 23.5 ℓ in digester.

COD of sample = average COD in digester since sample taken fully mixed.

COD = 27,200 ppm.

COD remaining in digester = 27,200 x 23.5
= 640,000 mg.

COD removed in sample = 0.2 x 27,200
= 5,440 mg.

∴ COD removed by bacteriological action = Drop in COD in digester - COD removed in sample.

COD removed bacteriologically = (726,000 - 640,000)
- 5,440 mg = 80,560 mg.

b) Identical procedure followed to calculate BOD and VS removed by bacteriological action.