VARIABLES AFFECTING GAS PRODUCTION IN MESOPHILIC ANAEROBIC DIGESTION

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A dissertation submitted to the Council
for National Academic Awards for the
degree of Doctor of Philosophy

The Polytechnic of Wales, Faculty of Engineering and
Science, Department of Mechanical and Production
Engineering, February 1980

DECLARATION

This dissertation has not been nor is being currently submitted for the award of any other degree or similar qualification.

D Hawkes
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Dennis L. HAWKES

ACKNOWLEDGEMENTS

I wish to thank Dr. J. D. Davies, Director, The Polytechnic of Wales, and his predecessor Dr. D. W. F. James for permitting the research to be undertaken.

I am indebted to my Director of Studies, Dr. B. G. M. Jenkins, Department of Chemical Engineering, The Polytechnic of Wales and to my Supervisor Dr. M. B. Bassett, Head of Department, Mechanical and Production Engineering, for their helpful guidance and encouragement during the course of this investigation.

The cooperation and advice of numerous colleagues is gratefully acknowledged especially that of the staff of the Computer Centre, in particular J. E. McBride, Senior Programmer.

My final thanks are due to my colleague Rex Horton whose research has progressed in parallel with my own providing much stimulating discussion.

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ABSTRACT

This dissertation presents the results of investigations into the factors which influence the net gas production in mesophilic anaerobic digesters. The major variables were examined during a six year period using equipment specially designed for the purpose. Continuous operation of these pilot plants over many months produced results which showed a relationship between gas yield and loading rate such that a lower loading rate produced a higher gas yield. A computer model demonstrated that the most significant parameters affecting net energy production were gas yield and the feed solids concentration.

Further work involving the analysis of previously published results confirmed that there was a relationship between gas yield and loading rate and this was shown to be more complex than originally thought. The relationship postulated between gas yield, retention time and feed solids concentration is expressed as the LYRS diagram. To obtain the maximum gas yield a digester needs to be operated with the highest solids feed but with the longest retention time possible to maintain a low loading rate. An increased retention time gives a larger and hence more costly digester. It is thus an optimisation exercise to find the best operating conditions to give either the maximum gas production possible or the minimum cost of the net energy produced which ever is required. The computer model developed can be used for this.

It is suggested that anaerobic digestion has a potentially significant part to play as one of the alternative processes for utilising energy in the form of renewable photosynthetically produced biomass.

NOTATION

B.O.D.	biological oxygen demand
C.O.D.	chemical oxygen demand
CST	capillary suction time
D	dilution rate
K	reaction constant
k_1	proportionality constant
k_s	substrate affinity constant or saturation constant
RT	retention time
s	available substrate concentration
TS	total solids
VFA	volatile fatty acids
X	cell concentration
Y	yield coefficient
μ	specific growth rate
μ_{max}	maximum specific growth rate

CHAPTER ONE

LITERATURE SURVEY

1.1 Introduction

The sunlight falling on the United Kingdom in one year is the equivalent of about 8.5×10^8 TJ (Holland 1978). This is more than enough to supply all the country's demands both industrial and domestic one hundred times over. Some of this energy is converted by photosynthesis into plant material and is available to us either directly or via animal converters. The term used to describe this material is biomass. Carbohydrates are formed in green plant matter as a result of photosynthesis, the chemical combination of carbon dioxide and water by means of the light activated chlorophyll molecules. These carbohydrates include simple sugars and the more complex polysaccharides such as starch, hemicellulose and cellulose. Energy can be extracted from the biomass surplus to food requirements or in the form of animal wastes in a variety of ways. Figure 1.1 shows some of the most common methods currently used. For wet biomass, that is with a moisture content of more than about 45%, the process of anaerobic digestion appears to be the most efficient method (Long et al 1976). With the exception of wood most plant material normally contains a high percentage of water so that wet methods of extracting the stored energy are to be preferred. In order to use other methods such as combustion wet materials have first to be dried. This can require a large input of energy.

Anaerobic digestion occurs in nature in two major habitats; in the mud at the bottom of ponds and in the rumen of animals. Gas bubbles can sometimes be seen breaking the surface of ponds whilst in animals the gas is expelled by belching! The rumen of the cow may contain 100 litres of fermenting vegetable matter and 200 litres or

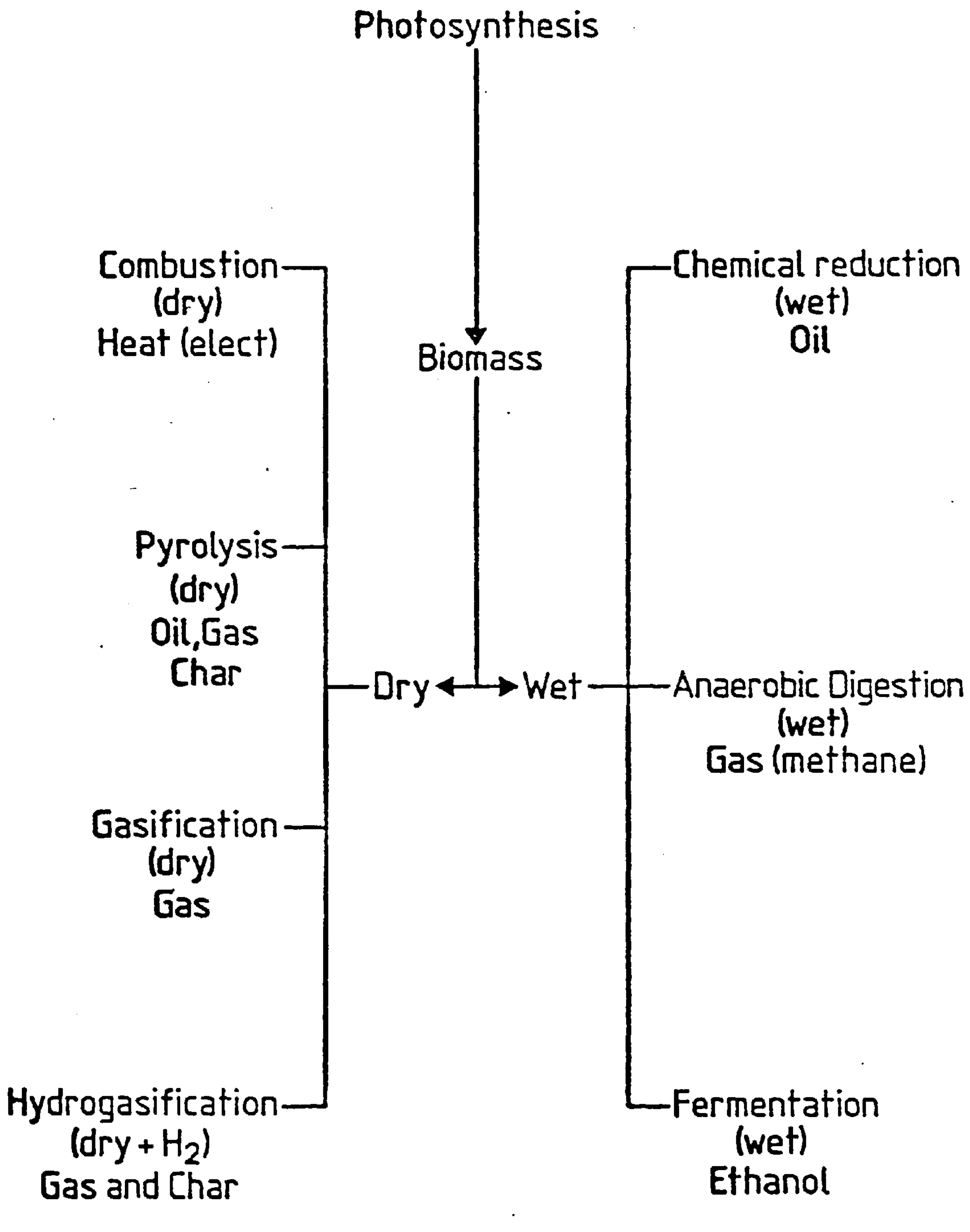


Figure 1.1 Some of the most commonly used methods for extracting energy from biomass

more of methane and carbon dioxide (Zehnder 1978) are produced each day. The microbial ecology of these habitats has recently been reviewed (Mah 1977) (Zeikus 1977).

The microbiology of anaerobic digestion has been reviewed by Bryant (1977) and Zehnder (1978) and is considered to be a three stage microbial process. That is three metabolically distinct groups of bacteria progressively break down organic material giving carbon dioxide and methane as the end products.

Each stage in this process is biologically complex and imperfectly understood but a simplified explanation is as follows.

In the first stage of anaerobic digestion the hydrolytic and fermentative group of bacteria can hydrolyse and metabolize polysaccharides, glycerides and proteins, producing mainly short chain fatty acids such as acetate, propionate and butyrate as well as carbon dioxide and hydrogen.

The second group, the hydrogen-producing acetogenic bacteria then break down these acids and produce acetate, carbon dioxide and hydrogen, the carbon dioxide only being produced if the acid is an odd numbered carbon compound (Bryant 1978).

The third group are the methanogenic bacteria. These use the hydrogen and carbon dioxide generated in the previous stages to produce methane, the reduction of carbon dioxide to methane being an energy yielding reaction. Methanogenic bacteria also utilise a small number of other organic substances e.g. formate and acetate.

The bacteria involved in an anaerobic digester are of many kinds and exist in a symbiotic relationship, each breaking down or utilising the others' products. A clear illustration of the type of symbiotic association which may exist in a digester is provided by the organism Methanobacillus omelianskii which oxidises ethanol to acetate and reduces carbon dioxide to methane. This organism was eventually found (Bryant 1967) to be not a pure culture as was first supposed but two; one an obligate hydrogen forming acetogenic bacterium that breaks down ethanol to acetic acid and hydrogen, and the other a hydrogen using methanogen that reduces carbon dioxide to methane.

Working together these two bacteria can ferment ethanol very effectively but isolation of the hydrogen former proved difficult as its growth is inhibited by the hydrogen it produces. A similar inhibition appears to occur in anaerobic digestion, where hydrogen is very important although rarely detected in digester gases. If hydrogen is not utilised as it is produced then the degradation of organic matter is prevented. Hydrogen has been detected in the gas from failing digesters (Bryant 1977). The methane bacteria have a great affinity for hydrogen giving half maximal growth rates at very low concentrations (Zehnder 1978). Hence it is expected that the hydrogen concentration in the digester fluid will be of this order or below.

1.2 Factors Influencing Digestion

The process of anaerobic digestion described above is clearly influenced by a number of variables, for each of which there is an optimum condition for the maximum production of methane.

In the remainder of this chapter the literature, up to Autumn 1979, concerning the effect of these will be reviewed.

1.2.A The Substrate for Digestion

i. Gas Yield

Organic materials such as fats, carbohydrates and proteins are the main source of nutrient for the bacteria involved in at least the first stage of digestion and if the amount of these present in the material is known then an estimate of the potential gas production can be made. This of course assumes that no inhibitory substances are present and that the digestion can proceed over an infinitely long period of time. Because this condition is not obtainable in practice, the theoretically possible gas production will be somewhat reduced.

For a pure substrate it is possible to calculate the amount of gas which may be produced on the basis of a simple carbon balance. For example consider fatty acids of the general formula: $CH_3 (CH_2)_n COOH$. A typical fatty acid is palmitic acid where $n = 14$ and the molecular weight 256. Each atom of carbon, and there are 16 per molecule, could be used to give one molecule of gas either CH_4 or CO_2 so thus 1 mole (the molecular weight in grams) of palmitic acid would give 16 moles of gas.

Since 1 mole of gas occupies 22.4 dm^3 at stp then 0.256 kg of this fatty acid gives 22.4 x 16 dm^3 of gas, or 1 kg of this acid would give $\frac{22.4 \times 16}{256}$ m^3 of gas, that is, 1.4 m^3 of gas. Similarly 1 kg of glucose, if broken down completely to gas, would give 0.747 m^3. In general the more complex the substrate the longer it takes to be degraded to volatile acids and the higher the proportion of methane in the gas produced (Trevelyan 1975). Theoretical yields obtainable from the various typical components of plant matter and manures are shown in Table 1.1 (Burford and Varani 1976).

Table 1.1 Theoretical yields of gas from the various components of plant matter and manures

Component	% CH_4	Gas Yield m^3/kg VS Destroyed
Carbohydrate $(C_6H_{10}O_5)_n$	50	0.886
Fat $(C_{50}\ H_{90}\ O_6)$	70	1.535
Protein $6C\ 2NH_3\ 3H_2O$	84	0.587

Materials for anaerobic digestion are not however pure substrates such as a fatty acid or glucose but contain a wide variety of organic compounds.

Commonly they may be animal wastes or mixed vegetable matter. In this case the most common way of expressing gas yield is as cubic metres of gas per kilogram of volatile solids (VS), added to the digester. The standard method of analysing for volatile solids in sewage sludges is set out in "The Analysis of Raw, Potable and Waste Waters" (HMSO 1972) and involves heating a known weight of the already dried material to 600°C for 30 minutes. The loss in weight represents the material which is combustible and therefore presumably organic and thus biodegradable.

It is appreciated however that not all of the volatile material is biodegradable, at least not in the period usually allowed for digestion. A study on cattle waste (Pfeffer and Quindry 1978) estimated that the maximum gas production for the manure used could be 0.83 m^3/kg VS added if these solids were totally biodegradable. The experimental data in the same report can be extrapolated to give a theoretical maximum gas yield, at an infinite retention time, of between 0.25 m^3/kg VS added and 0.40 m^3/kg VS added. This indicates that only between 30.1% and 48.2% of the volatile solids were actually degraded to gas in this case.

ii. Carbon : Nitrogen Ratio

The microbial populations involved in anaerobic digestion require sufficient nutrients to grow and multiply. Each species requires both a source of carbon and of nitrogen. If there is too little nitrogen present the bacteria will be unable to produce the enzymes which are needed to utilise the carbon. If there is too much nitrogen particularly in the form of ammonia it can inhibit the growth of the bacteria. It is often suggested that an optimum ratio of carbon : nitrogen is between 20 : 1 and 30 : 1 although it has been reported (Sanders and Bloodgood 1965) that for one series of experiments there was a minimum C : N ratio of 16 : 1 and increasing the nitrogen content did not appear to improve digestion. Experiments with paper pulp and sewage mixtures (De Renzo 1977) showed that digestion was feasible up to a point at which the C : N ratio was 45 : 1. Digester failure occurred when the ratio reached 52 : 1. However digestion of paper pulp, very low in nitrogen, to which chicken manure was added as the nitrogen source, proceeded up to a ratio as high as 70 : 1.

iii. Suspended Solids Content

It is believed that at least some of the consortia of bacteria involved in digestion attach themselves to surfaces of particles if these are present (Hobson, Bousfield and Summers 1974). In wastes such as sewage sludge there are plenty but with pure substrates for example there are often no particles present to act as a support medium. Work carried out at New Mexico State University (Speece and Engelbrecht 1964) showed that the addition of powdered asbestos to a digester working on a soluble synthetic medium containing acetate resulted in a greater than double acetate utilization rate over the control. This was believed to be mainly due to the surface area provided by the asbestos particles.

Similar experiments but using powdered coke were conducted with sewage sludge digesters (Morgan 1954). Eight digesters of 8 l capacity were used, three pairs with different quantities of coke and one pair with no coke. Gas recirculation was used to mix the contents in all digesters except those with no coke addition. The digesters were operated at a nominal 10 day retention time although this reduced as grit formed on the bottom of the digesters. The length of time over which they were operated before failure occurred was in excess of 100 days.

The digesters with coke additions failed in order of the quantity of coke added; that is the highest coke addition failed last and the one containing the least coke failed first. Each of the duplicates checked well and there was indication that the coke was of value. However the digesters without coke did not confirm this trend although these also did not have gas recirculation. Morgan's conclusion was that on balance the addition of coke to the digester had no effect.

The evidence suggests that coke additions did have some effect when the digester became stressed but the fact that the control did not fail first confuses the interpretation. The control not only had no coke addition but also had no gas recirculation. The addition of coal and flyash was similarly reported (Spencer 1978) to have no appreciable effect on digesters working with sewage sludge and in unstressed conditions. However the addition of 1500 mg/l of powdered activated carbon resulted in a 12% increase in methane production with the digesters operating on a 10 day retention time or less.

Further studies (McConville and Maier 1978) have shown that the addition of powdered activated carbon at an optimum dosage of 150 mg/l resulted in an increase of 10 - 15% in the gas volume at a 15.2 day retention time with larger increases at shorter retention times.

It is thought that particles may provide a microclimate for the bacteria in which the concentrations of metabolites may be higher than in the bulk liquor. Metabolites may be produced by neighbouring bacteria or adsorbed on to the surface of the particle.

iv. Synergistic Effects

Experiments carried out in Korea using eighteen 20 l digesters (Park 1979) showed that there was an improvement in gas produced from a particular waste if it was mixed with some other waste. For example Table 1.2 shows the average gas production for various wastes, with the percentage increase observed for the mixture over that for the average of the two wastes taken separately. Cattle waste on its own gives a gas yield of 0.380 m^3/kg VS added and pig slurry gives 0.569 m^3/kg VS added. When mixed together however in the proportions 50 : 50 the gas yield is 0.51 m^3/kg VS added, an increase of 7%.

The largest increase is 39% for the mixture of sewage and weeds. (The type of weeds were not specified.)

The retention time used in these experiments was 40 days.

Table 1.2 Increase in gas yields obtained with mixtures of wastes at a retention time of 40 days

Wastes	Gas Production m^3/kg VS Added	% Increase
Cattle	0.380	-
Pig	0.569	-
Poultry	0.617	-
Sewage	0.265	-
Weeds	0.277	-
Cattle and pig (50 : 50)	0.510	7
Cattle and poultry (50 : 50)	0.528	6
Cattle and sewage (50 : 50)	0.407	16
Cattle and weeds (50 : 50)	0.363	5
Pig and poultry (50 : 50)	0.634	6
Pig and poultry and cattle (50 : 25 : 25)	0.585	11
Poultry and sewage (50 : 50)	0.413	1
Poultry and weeds (50 : 50)	0.495	1
Sewage and weeds (50 : 50)	0.387	39

1.2.B Volatile Fatty Acids

Volatile fatty acids (also known as short chain fatty acids) are organic acids of the general formula R.COOH where R = H - (formic acid) or $CH_3\ (CH_2)_n$ - where n is between 0 — 4. During anaerobic digestion the acid forming bacteria produce mainly fatty acids whose R group contains between 0 and 3 carbon atoms, that is, formic, acetic and propionic acids. Butyric acid is also often present, though at lower concentrations. The volatile fatty acid (VFA) concentration is measured (see Chapter 3.3.B) and expressed in terms of acetic acid and a value of below 200 mg/l has been considered as preferable for an efficiently working digester (Kotze, Thiel, Hattingh 1969). It is quite common however for digesters to run at much higher levels than this and it has been reported that a well balanced digester working on farm wastes can cope with at least 600 mg/l (Hobson, Bousfield, Summers 1974).

In fact the safe level of VFA content has been a debating point amongst researchersin the past (Buswell 1959). Most would prefer the use of a sudden change in a constant VFA level as an indicator of performance rather than setting an artificial safe level below which to work.

1.2.C Alkalinity and pH

The term alkalinity is used in water treatment to express the quantitative measure of the capacity of liquids to neutralise acids. It is a result of the presence of the bicarbonate, carbonate, and hydroxide compounds of calcium, magnesium, sodium and potassium. However the alkalinity value obtained by the standard titration method is expressed as being solely due to calcium carbonate and it is expressed as mg of calcium carbonate per litre of the sludge as a whole. A value of about 2500 mg/l is considered to be normal for the sewage digester contents with that of raw sewage sludge about 1000 to 2000 mg/l. Provided the alkalinity, titrated to pH 6.0, is greater than 1000 mg HCO_3^-/l sufficient buffering capacity should be available to counteract sudden increases in fatty acid content. A more desirable range of 2500 - 5000 mg/l provides a buffering capacity for which a much larger increase in volatile acids can be accommodated with a minimum drop in pH. Capri and Marais (1975) using experimental laboratory digesters working on spent wine wastes showed that within the range pH 6.0 - 7.5 the dissociation of carbonic acid accounts for almost all the buffering capacity. In this range there were negligible effects from, for example, the ammonium, volatile fatty acids, phosphate and bisulphate systems.

It is important to note however that at high VFA concentrations alkalinity measurements tend to be inaccurate due to the interference of volatile fatty acid buffering (Capri and Marais 1975). At high values of VFA it is practical and convenient to express changes in the acid/base state of a digester in terms of pH and the carbon dioxide partial pressure.

If the pH changes, control can be exercised by adding a base such as lime (calcium hydroxide). The major advantage of this substance is that it is cheap. Since some of the calcium salts which will form in the digester are relatively insoluble, care is needed to ensure that the minimum quantities are added. A better substance is thought to be sodium bicarbonate or ammonium bicarbonate although these are more expensive. The pH falls usually as a result of organic overload and where possible the best remedial action is to stop feeding the digester or reduce the rate of feeding.

1.2.D Retention Time

The retention time is the time, usually measured in days, that the material is retained in the digester and is therefore in contact with the anaerobic bacteria. In most conventional digesters the term refers to the hydraulic retention time (HRT) and is simply given by:

$$\text{Hydraulic retention time} = \frac{\text{volume of digester}}{\text{volume of feed per day}} .$$

In some types of digester the flow from the digester is separated into a liquid and a solid portion and the solid material is returned to the digester. In this case one can refer to a 'solids retention time' (SRT) which is the mass of solid material in the digester contents, divided by the mass of solid material in the feed added each day. For a conventional digester the values for hydraulic retention time and solids retention time will be the same.

Retention times can be reduced by either increasing the rate of feeding that is the loading rate (see section 1.2.E) whilst maintaining the feed solids concentration, or by diluting the feed and keeping the loading rate constant. This is illustrated in Figure 1.2. With a dilute feed and a long hydraulic retention time a larger volume digester would be required with consequently higher production costs and greater heat losses from the increased surface area.

Experiments by Hindin and Dunstan (1960) on the effects of retention time on anaerobic digestion were conducted keeping the loading rate constant. That is, the amount of solids added to the digester was kept the same, but the percentage solids was varied to give different hydraulic retention times. They showed that at decreased loading levels an increase occurred in for example VFA, BOD (biological oxygen demand) and volatile solids whilst there was a decrease in alkalinity, ammonia nitrogen and the rate of reduction of the volatile matter. In practice this method of increasing the retention time by diluting the feed would rarely be used, except perhaps for counteracting an inorganic toxicity, and feeding at a higher solids

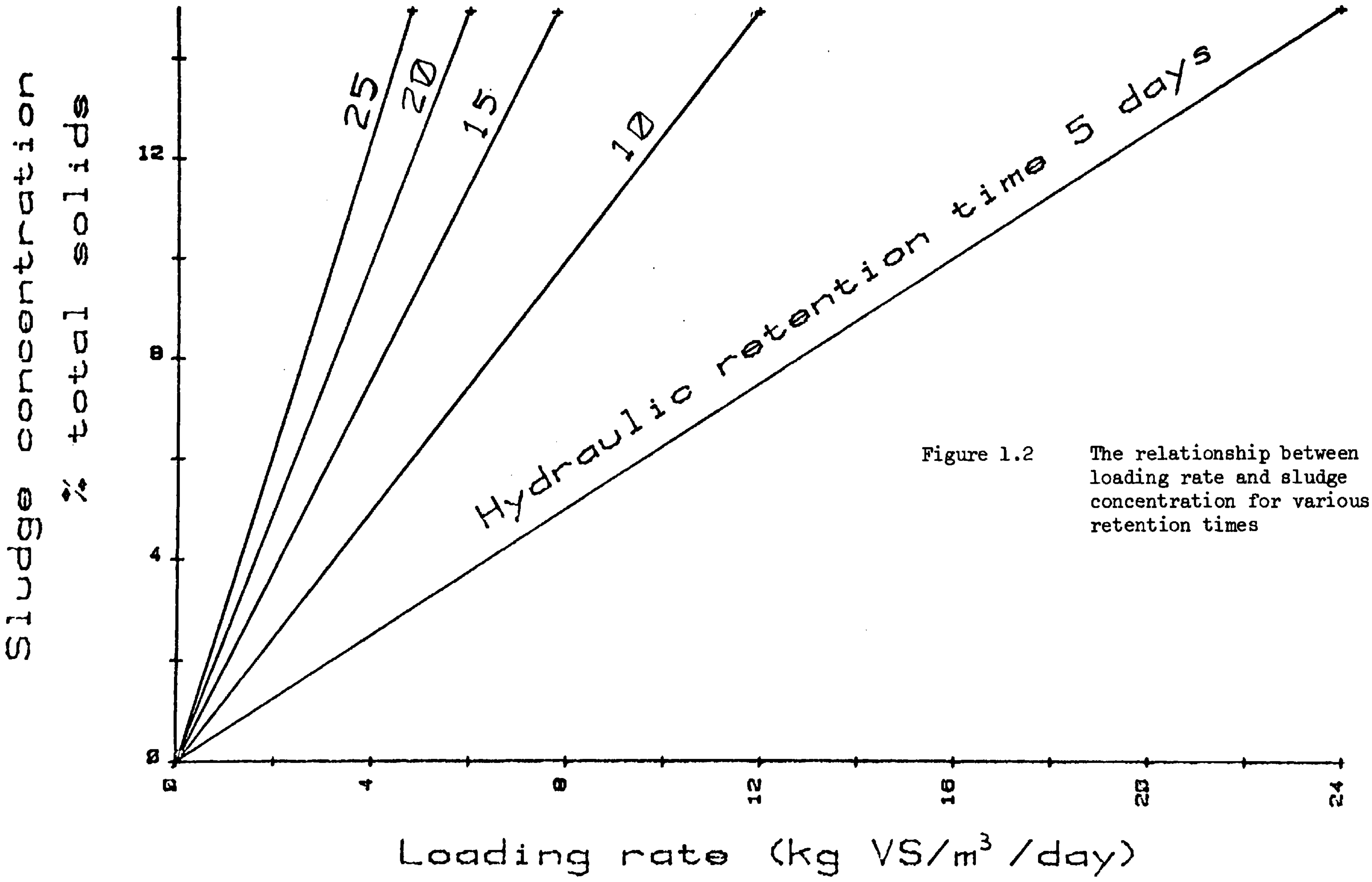


Figure 1.2 The relationship between loading rate and sludge concentration for various retention times

concentration is generally desirable since there is less water to heat up and a greater net energy recovery is possible.

Gas yield expressed as m^3/kg VS added increases asymptotically as retention time increases, that is, more gas is given off but the increment becomes less. A gas production rate quoted as volumes of gas per volume of digester per day is of little use as a measure of digester performance unless retention time is also quoted. Obtaining say 6 volumes of gas per volume of digester from a certain digester might be considered a better performance than obtaining 2 volumes per volume on another digester fed on the same quantity of identical waste. However if the retention time on the former is 3 days and the latter 20 days, then it is in fact a far worse performance, producing less than one half as much gas per volume of waste added as the digester giving 2 volumes per volume.

1.2.E Loading Rate

The loading rate is an important parameter since it is an expression of the influent substrate concentration. The two most common indicators of substrate concentration used with anaerobic digesters are Chemical Oxygen Demand (COD) or Volatile Solids concentration (VS). There are difficulties with the use of either. The feed for digesters is usually high in COD so that the laboratory test for this requires at least 100 times dilution. This introduces large errors and yields unreliable data. An error which may occur in the alternative determination, that of volatile solids, is that some of the volatile acids in the material are volatilised during the drying procedure prior to the determination of VS. Since these are substrates for the methane fermentation their loss causes errors in the calculated amount of substrate available which may be appreciable in the case of wastes containing high VFA concentrations. Volatile solids are more easily determined than COD for concentrated and complex substrates and the accuracy is greater, so this is usually the parameter chosen in which to express loading rate.

Loading rate is then the mass (kg of volatile solids)added per day to a volume (m^3) of digester.

For any particular waste the proportion of volatile solids which is biodegradable is fairly constant. A study conducted by Morris (1976) on dairy cattle manure showed that 42.5% of the total influent volatile solids concentration was found to be biodegradable under the anaerobic digestion conditions examined.

In the same study the ratio of influent biodegradable total COD to influent biodegradable volatile solids was also found to be constant with a value of 1.43. This would suggest that either COD or volatile solids is suitable for assessing the biodegradability.

The maximum loading rate that a digester will tolerate depends upon both types of digester and the nature of the substrate but can be determined by experimentation.

The effect of solids concentration and hydraulic retention time on the volatile solids loading rate can be seen in Figure 1.3. This is based on a 70% VS content of the feed material and it can be seen that a loading rate of 5.0 kg VS/m^3/day can be achieved at 5% TS at a 7 day retention time or at a retention time of 15 days at a total solids content of almost 11%. For a retention time of 30 days the

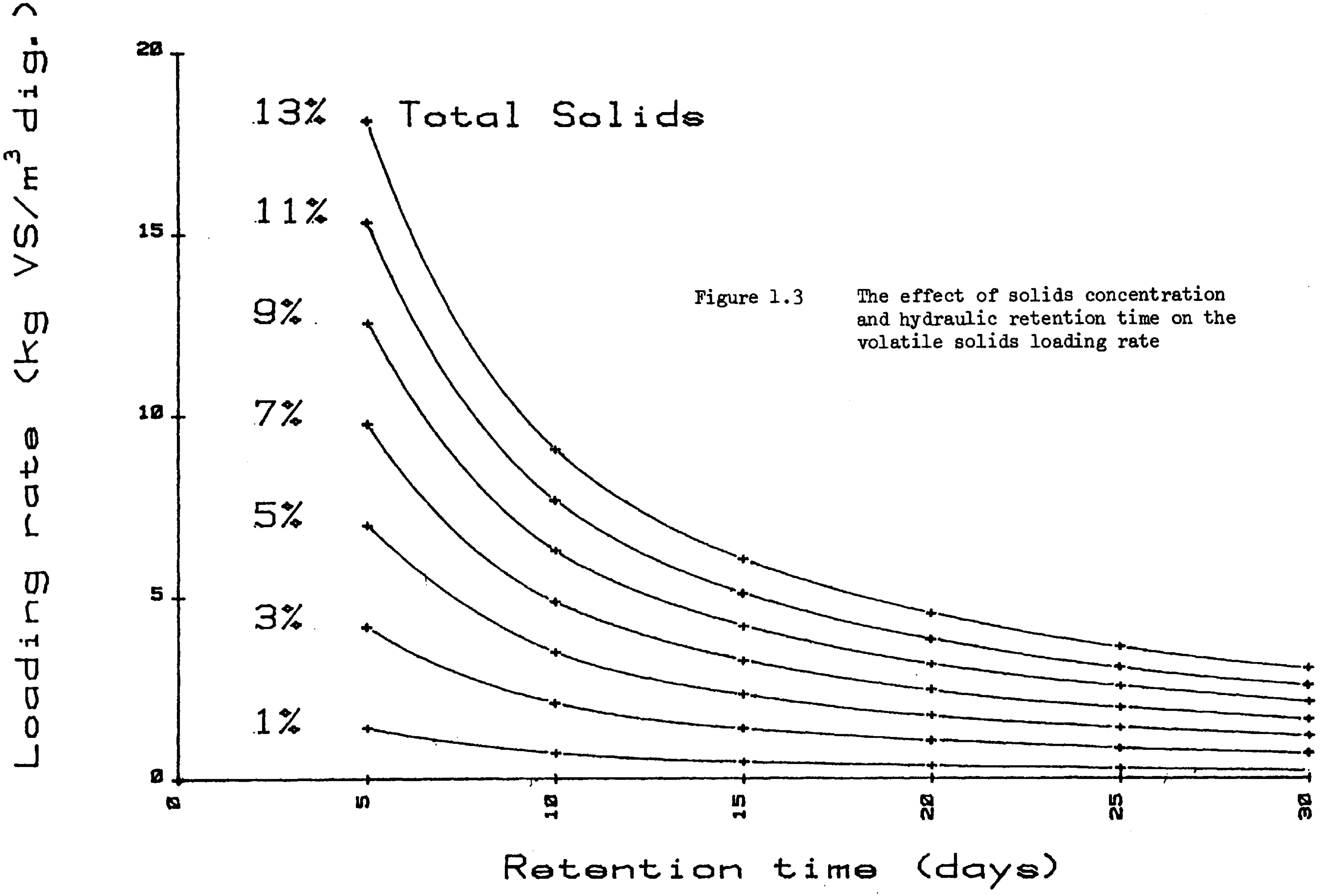


Figure 1.3 The effect of solids concentration and hydraulic retention time on the volatile solids loading rate

same loading rate would necessitate a solids content of about 24%.

The total solids content of the feed is of itself not very important and can usually be as high as handling restrictions will permit. Studies on sewage sludge digestion (Shulze 1958) showed that a laboratory scale digester could be loaded at concentrations of up to 37% TS as long as the volatile acid concentration was maintained at below 2000 mg/l. Similar work by Pfeffer and Liebman (1974) showed that increasing feed solids concentration had no effect on the gas production per unit of dry solids up to 35%. The limiting factor for the continuous system used was thought not to be the total solids percentage but the loading rate which depends upon the solids content and the retention time.

In tests conducted by Mueller et al (1959) digesters were loaded at different rates whilst the retention time was kept constant. At increased loading rates there was observed to be an increase in total volatile acids, alkalinity, suspended solids in the supernatant and proportion of CO_2 in the gas. At the same time a decrease in the gas production per unit of volatile matter added per unit of time as well as in the volatile solids reduction and in the relative quantity of acetic acid were observed.

1.2.F Digester Operating Temperature

i. Temperature Optima

Within the mesophilic range 5 - 45°C it is generally found that an optimum gas production occurs around 30 - 35°C.

A different set of bacteria predominate in the thermophilic range 45 - 60°C and at about 45°C neither type of bacteria is favoured.

As with many biological processes the rate of activity increases with increasing temperature up to an optimum. Figure 1.4 shows the effect of temperature on gas production during the digestion of sewage sludge for four experiments (Fair and Moore 1934) (Hatfield 1928) (Rudolfs 1927) and (Viel 1941). In general the last three of these suggest a levelling out at around 35°C whilst for the experiment of Fair and Moore the slope of the graph does not level out so clearly. Figure 1.5 shows the effect of temperature on gas production during the batch digestion of sewage sludge (Koziorowski et al 1972). As can be seen from the graph the gas yield after 10 days at 30°C is more than 6 times as great as at 10°C. Even after 30 days it is still almost 3 times as high.

Malina (1962) in a series of experiments on the digestion of activated sludge concluded that temperature has a significant influence on digester performance and that the effect of temperature is independent of loading rate and retention time. He studied three temperatures 32.5°C, 42.5°C and 52.5°C and found that the gas production was least at 42.5°C. In a later study (Malina 1964) he again looked at the effect of temperature this time at 30, 35, 40, 45 and 55°C. Again the conclusion was that the total gas production was greatest at about 30°C, decreased to a minimum near 40°C and rose again as the temperature was increased.

With the digestion of solid wastes (domestic refuse) however, studies by Pfeffer (1973) showed that there was a maximum gas production in the mesophilic range at about 40°C and in the thermophilic range the optimum was near 60°C. Domestic refuse with the addition of nutrients in the form of sewage and lime to maintain an acceptable pH, gave

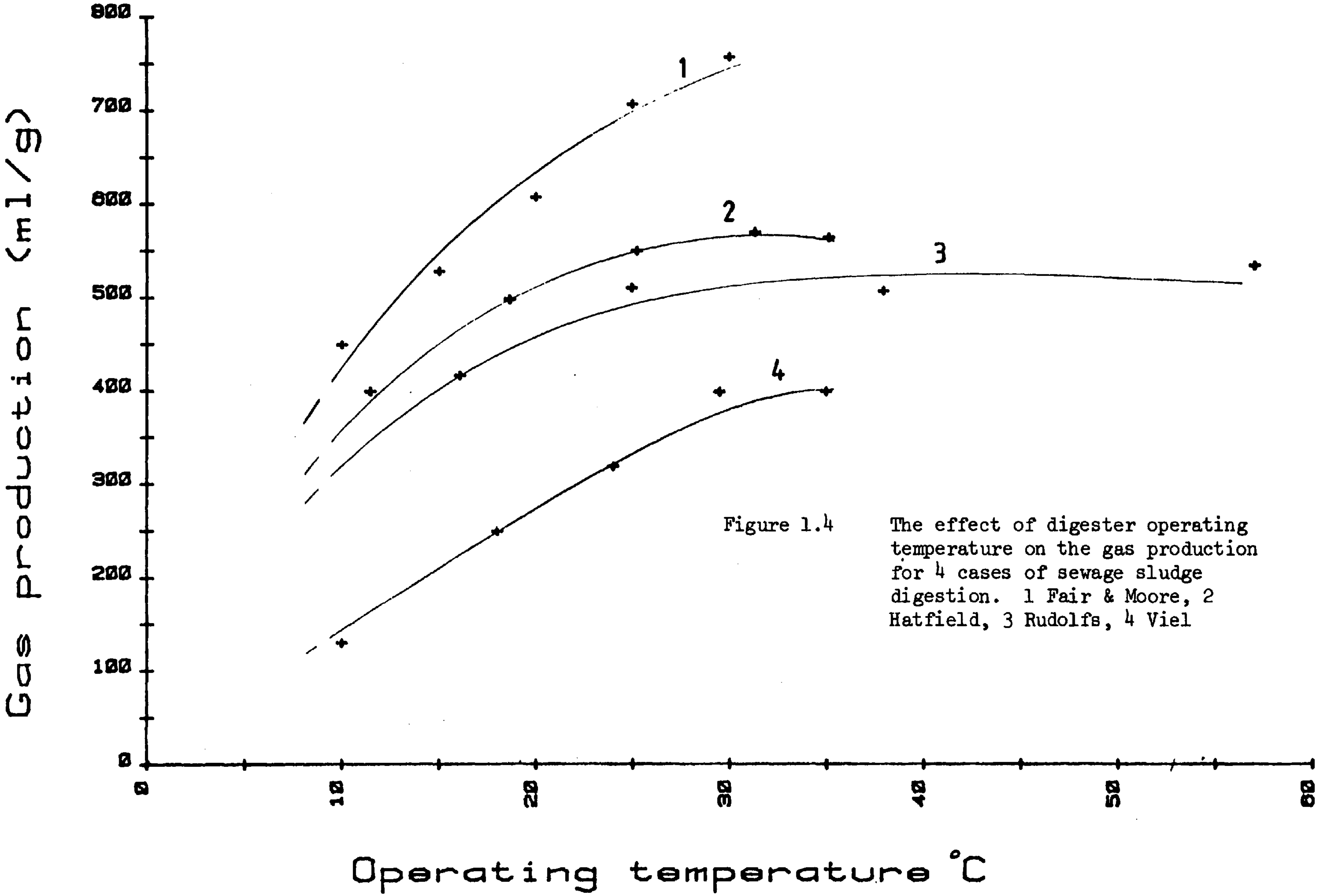


Figure 1.4 The effect of digester operating temperature on the gas production for 4 cases of sewage sludge digestion. 1 Fair & Moore, 2 Hatfield, 3 Rudolfs, 4 Viel

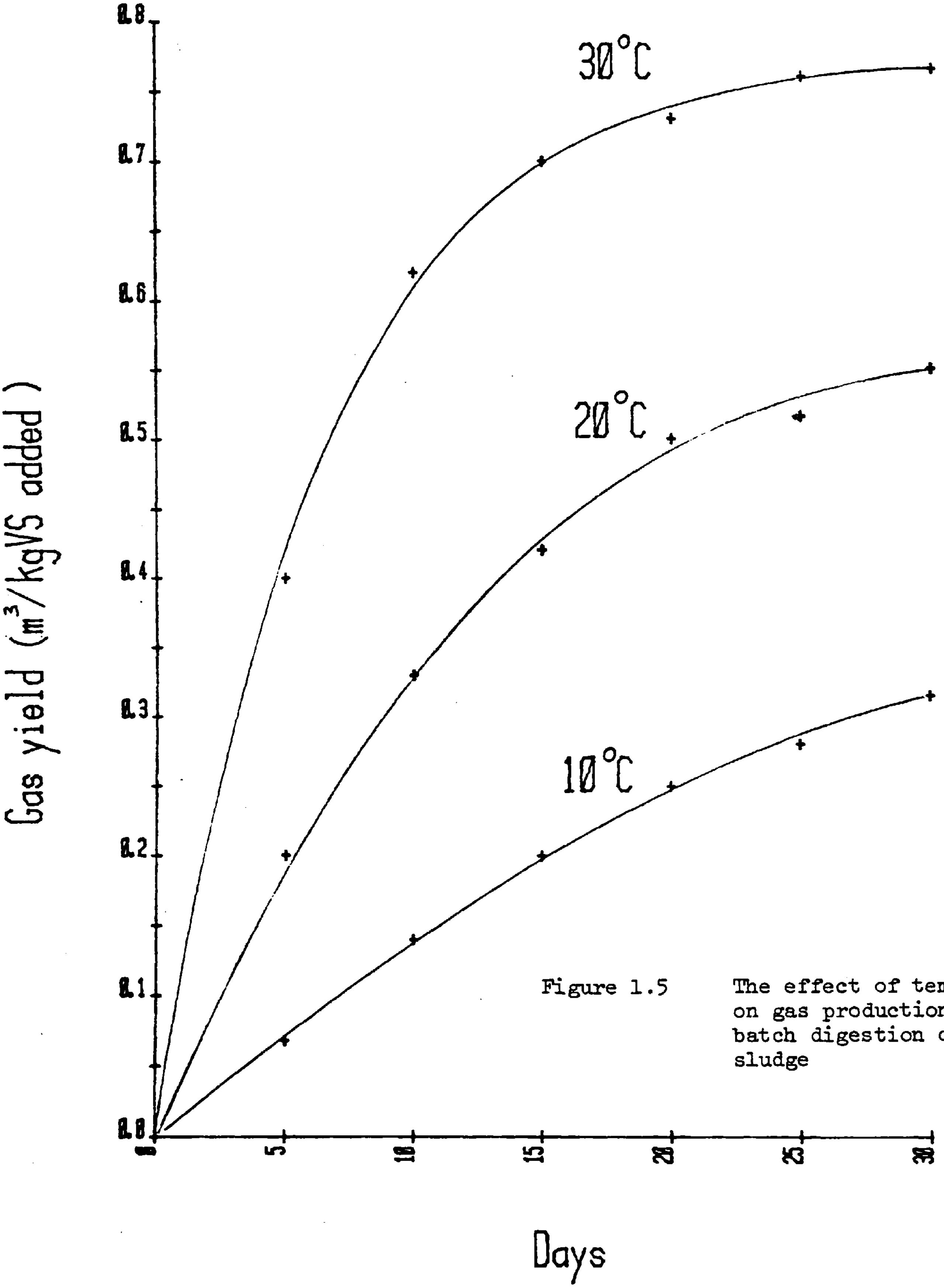


Figure 1.5 The effect of temperature on gas production during batch digestion of sewage sludge

optimum gas yields at about the same temperatures, 42°C for mesophilic

Table 1.3 Gas production figures (ml/g) for various digester operating temperatures

(relative gas production shown in brackets)

Temperature of Digestion °C				Reference
35	25	20	15	
775 (1)	700 (.9)	620 (.8)	525 (.68)	1
560 (1)	540 (.96)	500 (.89)	450 (.8)	2
510 (1)	480 (.94)	455 (.89)	395 (.77)	3
400 (1)	340 (.85)	260 (.65)	200 (.5)	4
- (1)	- (.8)	-	- (.4)	5
(1)	(.89)	(.8)	(.63)	mean values

Key to references

1 Fair and Moore 1934
2 Hatfield 1928
3 Rudolfs 1927
4 Viel 1941
5 McCarty 1966

digestion for example. Similar results were obtained by Golueke (1958) and others using different wastes and it may be concluded that the optimum temperature is around 35 - 40°C for mesophilic digestion but varies somewhat depending on the type of waste.

The optimum temperatures for gas production however may not be the optimum temperature for net energy yield since operating at a higher temperature consumes more energy. It is interesting to note that the shape of the curves in Figure 1.4 is similar although the value of gas production is different in each case. Table 1.3 summarises the relative gas production at temperatures below 35°C for the cases shown in Figure 1.4 and also for results evaluated by McCarty (1966). The final row shows mean relative gas production figures for the five cases quoted.

These show for example that if the digestion process proceeds at a temperature of 25°C instead of 35°C, 89% of the gas will still be produced. Even at 15°C, 63% will be generated so that this must be taken into account when considering the optimum temperature of operation for net as opposed to gross gas production. Figure 1.6 shows these mean values between 15°C and 35°C. Running the digester at 25°C instead of 35°C means a considerable saving in energy put into the system, especially at low retention times, for a small reduction in gas produced.

ii. Temperature Changes

The response of methane forming bacteria to temperature changes is almost immediate since these affect the rates of enzyme - catalysed reactions. Clearly in order to maintain a digester performance at its maximum gas production rate then it will be necessary to keep the temperature constant at the optimum level.

No lasting harm is done to the bacterial population however even with fairly large fluctuations in temperature. For example in one experiment (Pfeffer 1973) using a digester which normally operated at 35°C the temperature was reduced to 10°C for 15 minutes and then raised

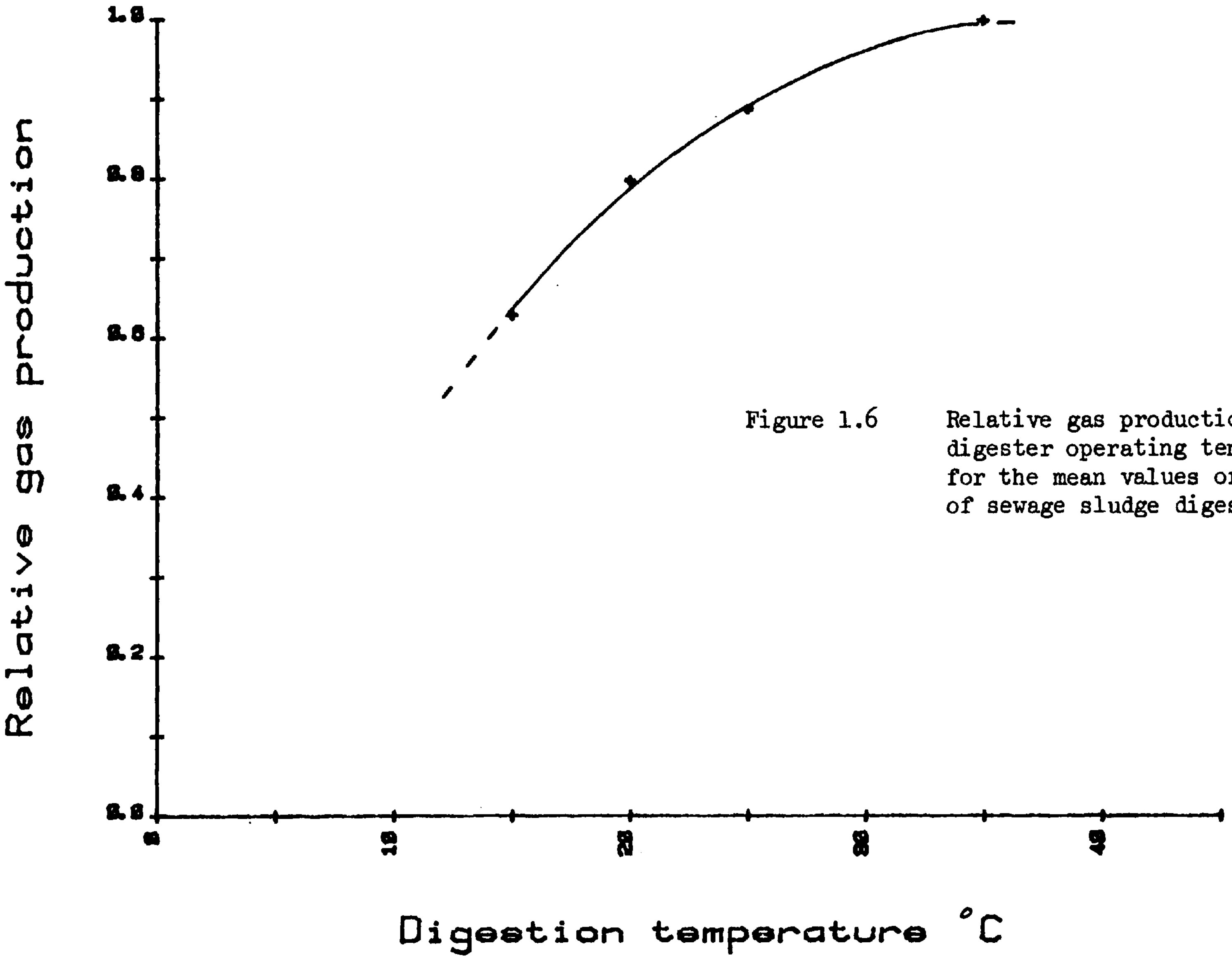


Figure 1.6 Relative gas production versus digester operating temperature for the mean values of 5 cases of sewage sludge digestion

again to 35°C when the gas production quickly resumed its former rate. Similar results were obtained when the temperature was lowered to 10°C for 2 hours although the gas production rate rose to its former level more slowly.

In an experiment reported by De Renzo (1977) the rate of reduction of volatile fatty acids was found to be greater at 45°C than at 35°C.

Starting with a VFA concentration of about 1800 mg/l, in less than 30 hours the level had dropped to the original level of 300 mg/l in the digester running at 45°C. However in the same period for the 35°C digester the volatile acid concentration dropped to only 1400 mg/l. This result suggests that raising the digester temperature may be one method for quickly reducing the VFA level after overloading. Normally the digester feed is turned off or greatly reduced and one may have to wait several days before feeding can safely be resumed. Perhaps if the temperature of the digester is raised this waiting period can be shortened considerably.

iii. Optimum Retention Times at Various Temperatures

A study carried out in Korea (Park 1979) investigated the optimum retention times for different temperatures with chicken manure and cattle manure fed to 20 l laboratory digesters.

A number of digesters were operated at the same temperature but different retention times and the optimum gas production determined. The experiment was repeated several times at different temperatures and the results of this study are summarised in Table 1.4. This shows that for cattle manure the optimum retention time was found to be 30 days at both 30°C and 35°C although at the higher temperature more gas was produced. Chicken manure gave a higher gas yield at each temperature and at a shorter retention time.

Table 1.4 Optimum retention time and gas production at different temperatures

Digester Operating Temperature (°C)	Optimum Retention Time (days)	Gas Production (l/l/day)	VS Destroyed (%)
Chicken			
15	55	0.48	50.8
20	40	0.72	60.5
25	30	1.38	61.1
30	24	1.80	71.0
35	20	1.45	75.0
Cattle			
15	60	0.24	40.0
20	45	0.42	41.4
25	35	0.48	60.0
30	30	0.58	59.0
35	30	0.66	65.0

1.2.G Inhibitors

The most common inhibitors in anaerobic digesters are heavy metals, antibiotics, phenols, chloride compounds, detergents, etc. Heavy metals can enter the digester from industrial wastes, in particular with sewage sludges. Here a spillage from an engineering firm or metal plating factory can reach the sewage treatment works and hence the anaerobic digester. Metals such as lead can reach toxic levels from, for example, surface water in city areas from leaded petrol. Copper is often added to pig feed material and has been found to be inhibitory to digesters working on pig manure although less toxic to anaerobic than aerobic processes (Taiganides 1963).

Other substances sometimes present in farm wastes are phenols from disinfectants used in dairy cleaning and detergents from equipment washing. Both of these can easily reach toxic proportions from an accidental spillage or over-generous use. Where the average concentration of synthetic detergent in settled sewage sludge is higher than about 30 mg/l it is thought (Bruce et al 1966) to result in inhibition. Animal wastes may contain high levels of antibiotics which have been added to the feed to reduce disease or may even be naturally toxic to digesters due to a high ammonia content. For example concentrations of 1500 - 3000 mg/l ammonia nitrogen are believed to be inhibitory at higher pH levels and above 3000 mg/l it is toxic (McCarty 1964). This is particularly likely in the case of chicken manure as the form in which nitrogen is excreted by birds is as the sparingly soluble compound uric acid present in the droppings rather than the soluble urea found in the urine of mammals. Chlorinated hydrocarbons which occur in some pesticides must, if possible, be excluded from a digester as quite small amounts can result in inhibition.

Fortunately there is usually sufficient dilution capacity with most wastes to dilute these toxic materials and the problems outlined above are therefore rather rare. The most obvious solution to a toxic overload is to stop feeding that particular waste, if necessary dilute the digester contents to below the toxic threshold and if possible remove or counteract the toxic material in the waste before resuming the feed routine.

Factors which have been shown (McCarty, Nov. 1964) to reduce the availability of heavy metals to inhibit anaerobic digestion are: high concentrations of soluble sulphides, high concentrations of ferrous sulphide, high carbonate ion concentrations and high chloride concentrations. It is possible to remove or reduce heavy metal ions by various means for example by precipitation. Precipitation of metals as insoluble sulphide salts has been shown to be effective (Mosey et al 1971) for iron, nickel, zinc, lead, cadmium and copper but not for chromium.

Precipitation of the metals as sparingly soluble carbonate salts gives protection against some of the heavy metals providing the pH value of the digesting sludge is high enough (above 7.2 for cadmium for example).

1.2.H Mixing

For high rate digesters mixing is considered essential (Hobson et al 1974); it achieves several objectives, even distribution of substrate and bacteria at uniform temperature, efficient utilization of digester volume by preventing the formation of dead spots which allow pockets of high VFA to form, and prevention of scum formation. Mixing can be carried out in a number of ways notably by mechanical agitation, digester contents recirculation or by digester gas recirculation.

Mixing by gas recirculation appears to offer the most advantages although the explanation for the improvement in digester performance that this brings is not clear. Finney and Evans (1975) suggest that at high substrate concentrations the gas generated by digestion tends to surround the bacterium and thus interfere with substrate diffusion. If this is correct then digester reaction may be increased by physically removing the minute gas bubbles from around the bacteria. This can be achieved in a number of ways but needs to be done gently to avoid removing the bacteria from the substrate to which they tend to be attached. Other research (Konstandt 1977) supports the view that with gas mixing the ascending bubbles displace the gas adhering to the microbial flocs and that any increase in digester performance is due not to a biological phenomenon but a mechanical process of physically removing minute gas bubbles allowing a more rapid contact between the bacteria and their substrate.

1.2.I Microorganism Recycle

The process of anaerobic digestion being a microbial one has been described (Pfeffer and Quindry 1978) (Chen and Hashimoto 1979) using conventional bacterial process kinetics (see also Appendix A). The importance of equation 12 in Appendix A for digester design is obvious; it shows that the gas production is directly proportional to the microbial cell concentration. Thus there is a need to endeavour to increase this in order to increase the gas production. This can be achieved with some methods of feedback for the microbial mass that leaves the digester.

A chemostat is a culture vessel into which substrate is flowing continuously and within which a population of bacteria is maintained in a steady state at a particular growth rate. With adequate mixing and the correct geometry of the digester it is possible to achieve a chemostat type of design which is very efficient. One way of increasing the process rates above those possible with a simple chemostat is by increasing the microorganism concentration in the fermenter.

The theory of a chemostat with feedback has been formulated (Pirt and Kurowski 1970) and various methods by which it can be brought about have been described. In the simplest system (Figure 1.7) the out-flow from the fermenter goes via a sedimentation device which concentrates the cell material and feeds this back to the influent line whilst the remainder passes out of the system. The second method (Figure 1.8) is similar but in this case only a part of the concentrated cell material is fed back whilst the remainder passes on. Figure 1.9 shows a third system in which a filter is used to remove from the culture a dilute suspension of microorganisms thus allowing a greater concentration to remain in the fermenter. The final method (Figure 1.10) consists of a fermenter with a sedimentation zone. A baffle plate separates an active stirred zone from an unstirred zone in which the cell material settles out. Concentrated biomass is removed from the base of the fermenter and diluted biomass from the top. Pirt and Kurowski (1970) point out that the first system is impractical since it is difficult to conceive of any device which would allow only the right amount of material to be returned to give a steady state. The third and fourth systems are identical although different methods are used to achieve the same effect. Methods two, three and four were used experimentally (Pirt and Kurowski 1970) and steady states were obtained over a wide range of flow rates; the values of cell material and growth limiting substrate were in good agreement with the theory. The maximum biomass output rate of chemostat by using feedback was increased fourfold. The theory assumes a soluble substrate with the bacteria suspended throughout. In practice this is not the case as the waste entering

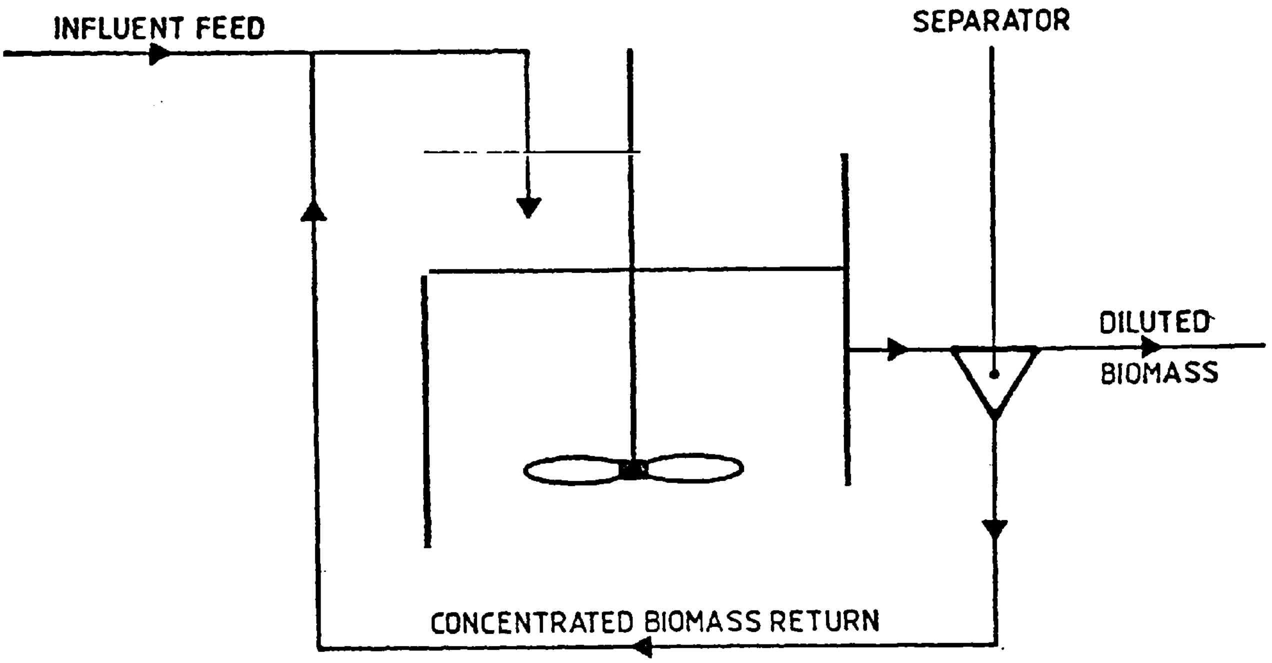


Figure 1.7 A simple system for a chemostat with feedback

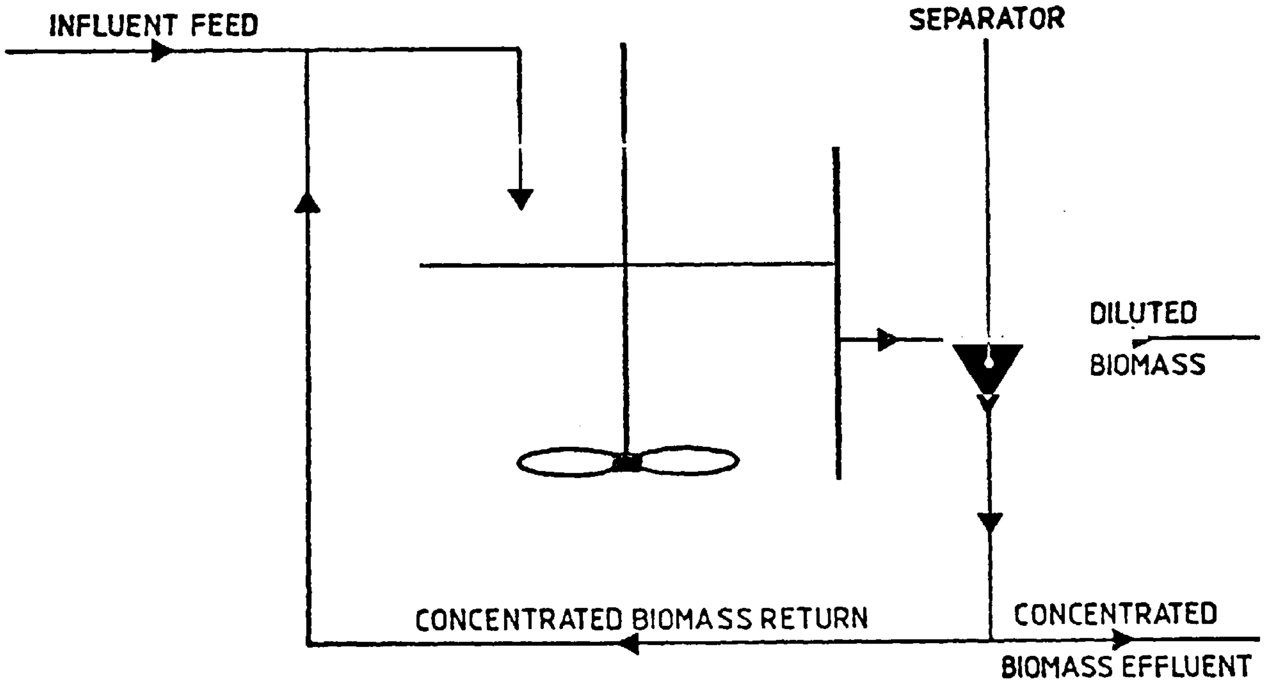


Figure 1.8 In this system only a part of the concentrated cell material is returned

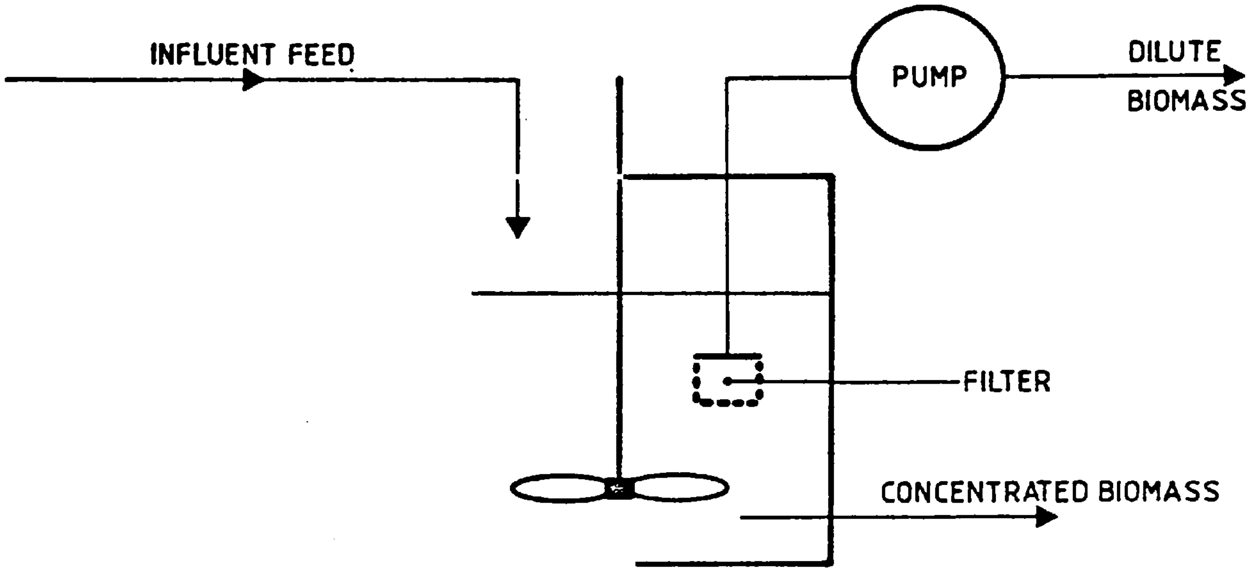


Figure 1.9 A filter may be used to allow a greater concentration of micro-organisms to remain in the fermenter

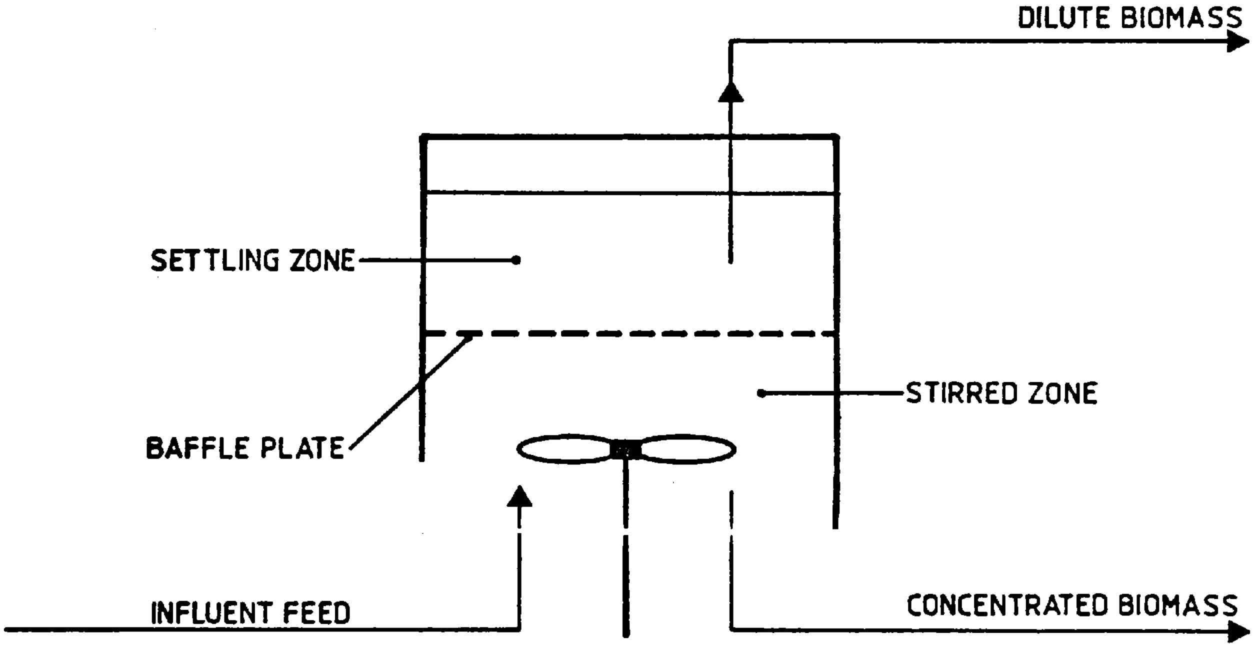


Figure 1.10 A sedimentation zone is used here and despite the different method has the same effect as that shown in Figure 1.9

the digester will include biodegradable material in the form of solid particles. The bacteria are known to be attached to these (Hobson et al 1974) and it would be difficult to detach them without damage. Many of the systems developed to separate bacterial mass and return it involve a period in which the bacteria will be cooled. Even if death does not result there will be some time needed for the bacteria to readjust.

The requirements for an ideal system for microorganism feedback can be summarised as follows:

1. There should be continuous loading with organism recycle.
2. Feedback should be as near as possible to instantaneous.
3. Means of achieving 2 should not detach the bacteria from the solid or it may be that the time taken to regain active colonisation on return to the digester may detract from the efficiency.
4. The system should be inexpensive both in terms of capital cost and energy utilisation.

CHAPTER TWO

OPERATING EXPERIENCE DIGESTING CHICKEN LITTER

2.1 The Equipment

In order to obtain some practical experience in operating a pilot scale digester and to test some ideas for equipment for continuous loading and microbial retention especially, an experimental rig was built.

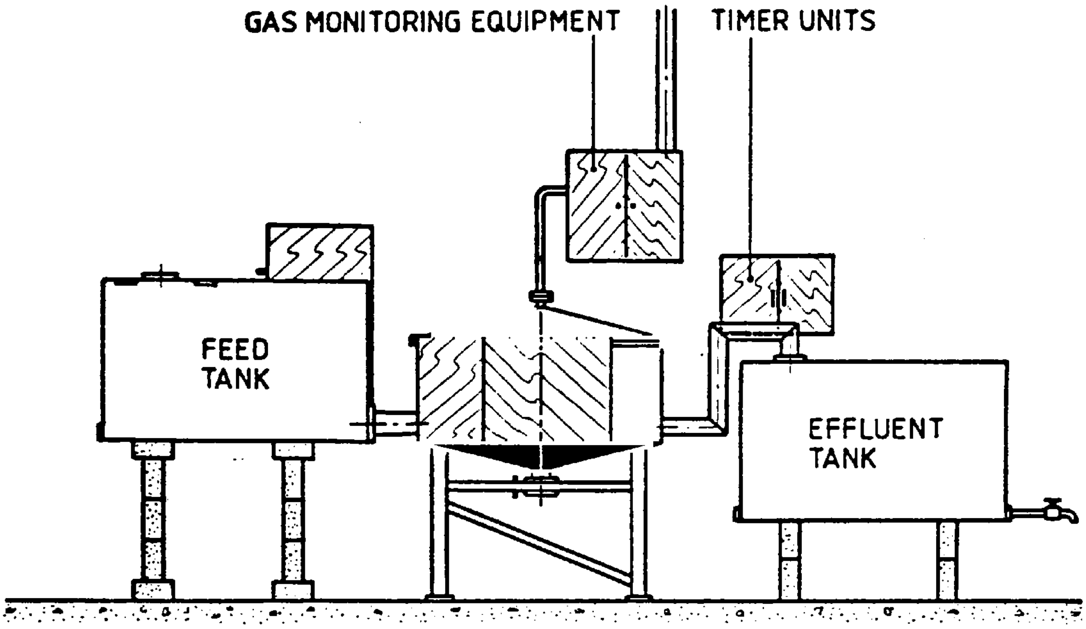
Figure 2.1 shows a drawing of the digester plant, Plate 1 gives a clear indication of the components.

This first pilot plant was built during autumn 1974. Due partly to lack of finance at this stage and partly to the philosophy of simplicity and economy the plant was built cheaply, where possible incorporating used components. It consisted of 3 main parts. The feed tank was made from a 2.7 m^3 (600 gal.) central heating oil tank with a bucket elevator feed mechanism. The main digester tank, 0.84 m^3 capacity, was insulated with 50 mm weatherproofed rigid polyester foam. The digester had a feed tube and an effluent settling tube and was equiped with electric immersion heater and a mixing device. The effluent tank was for storage of the treated waste and once again was a modified 2.7 m^3 (600 gal.) oil storage tank.

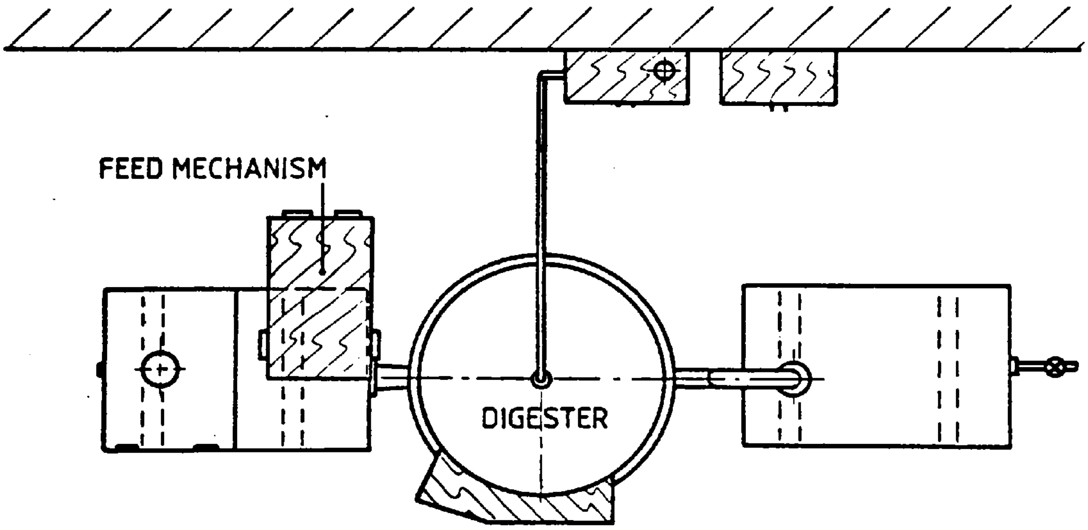
No gas collection was attempted although the volume produced was monitored by means of a domestic gas meter of the bellows type (Parkinson Cowan).

The frequency and period of operation of both the feed and mixing mechanisms were controlled by a cam timer.

For the pilot plant operation it was decided to use waste that was unmacerated. This was because maceration considerably alters the surface area: mass ratio making the waste more amenable to bacterial breakdown. Although this is often done in the laboratory situation

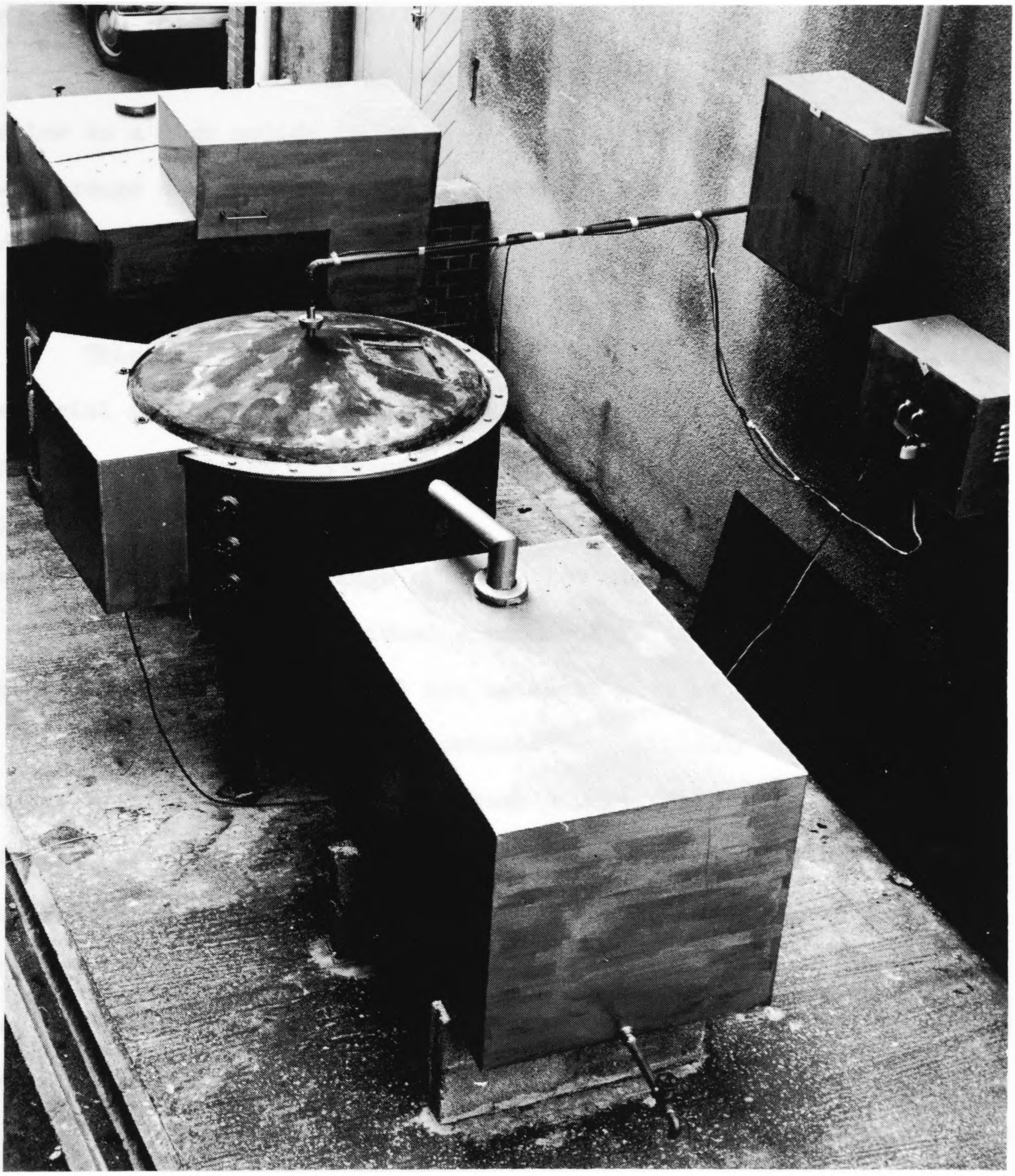


ELEVATION



PLAN

Figure 2.1 A drawing of the first experimental pilot scale anaerobic digester situated at The Polytechnic of Wales



<u>PLATE 1</u> First experimental pilot plant (digesting chicken manure), installed at The Polytechnic of Wales

because of the size of equipment that is used, the results are not necessarily then representative of the waste as it would be fed to a full size unit.

The feeding mechanism was designed to handle waste varying from a low to a high solids content possibly containing large particles. A wide range of wastes could be expected in practice and the pilot plant was designed to cater for this variation. To test the equipment chicken litter was chosen as the feed material.

This can be of a very high solid content with feathers, bedding material and grit and is notoriously difficult to handle. The pilot plant used a bucket elevator device for feeding to overcome the problems usually experienced with conventional pumps and this was variable to provide a range of retention times.

The design of individual components is the subject of another study (Horton 1980) and will not be dealt with in detail here.

Mixing of the digester contents was initially accomplished by means of a liquid recirculating pump using a filter with back flushing facilities. The liquid flowed through an orifice situated in the line as it passed through the gas space above the digester contents. Immediately down stream of this orifice were a series of small holes at the point of minimum pressure through which the gas was drawn to be entrained in the liquid flow. (See Figure 2.2.)

This method of gas diffusion worked well at first when the solids content of the liquid was low but later after repeated clogging of the filters it had to be abandoned. This occurred near the beginning of the experimental run and thereafter the digester was mixed by manual stirring once daily except weekends.

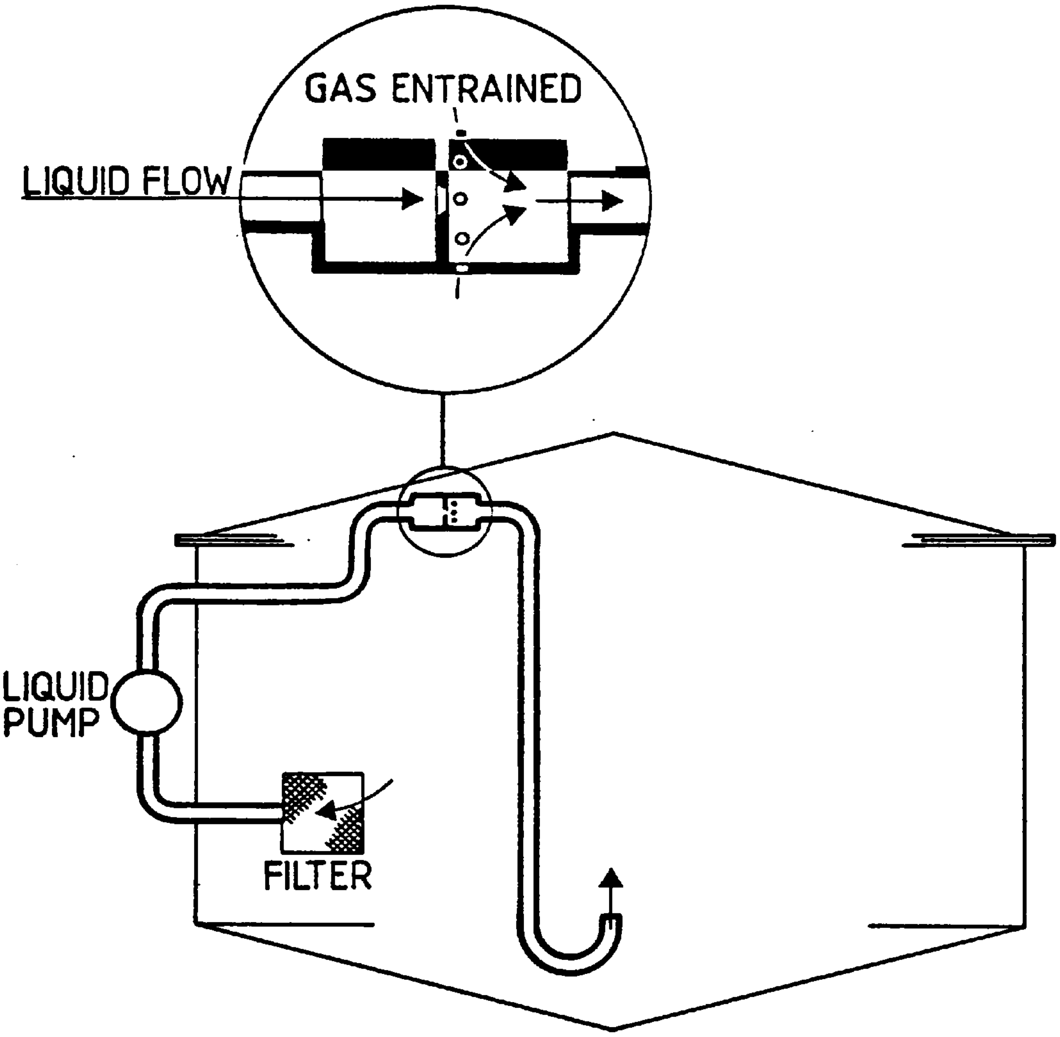


Figure 2.2 Mixing of the digester was initially accomplished by means of a pump forcing liquid through an orifice at which point gas was entrained to give a degree of gas diffusion as well as liquid recirculation

The digester was operated at 35°C since this was believed to be about the optimum for maximum gas production with sewage sludge and no data was then available for chicken manure digestion.

Heating was by a 3 kW electric immersion heater since this was a method by which an accurate account could be kept of the energy required to run the system. A thermister with a simple on - off controlling circuit was used although later an overriding thermostat was also incorporated following an accidental overheating which occurred when the thermister failed.

The outlet from the digester was via a settling tube by which it was hoped that a proportion of the solid particles and hence the bacteria which adhered to them would be retained in the digester for a longer period.

The feed was by the bucket elevator to a feed tube open to the atmosphere. The effluent flowed by displacement up the settling tube and into the effluent tank in which it was collected for final disposal. Since the chosen digester feed material was chicken litter and very dry (about 80% TS) some of this effluent was used to water-down the feed to about 11% TS to make handling easier.

Pressure in the digester was maintained at a few millimetres of mercury by means of a simple pressure regulator.

The pilot plant was sited in the open because of the possibility of gas leaks and so that the behaviour of the equipment under normal weather conditions could be monitored. Safety requirements necessitated a 3 metre high chain link fence topped with barbed wire to be erected around it.

Apart from measurements of digester temperature and gas volume the other parameters which were regularly monitored were gas composition, pH, volatile fatty acid levels and total and volatile solids. These latter were carried out according to standard methods (Analysis of Raw Potable and Waste Waters, HMSO 1972) and are described in chapter 3. Occasional determinations of B.O.D. were also made.

2.2 The Digester Feed Material

The chicken litter used for this pilot plant experiment was obtained from Madeley Farm, Sun Valley Chickens, Hereford. It was in the form of dry broiler chicken litter (18% moisture) obtained at the end of the eight week growing cycle. During the cycle the total organic content i.e. proteins, lipids, carbohydrates, uric acid rose from 9.3% to 30% thus providing considerable organic carbon which could potentially be converted to methane and carbon dioxide.

The analysis of the litter as received at the end of the eight week cycle is shown in Table 2.1.

During this experiment on chicken litter we were indebted to University College Cardiff for most of the chemical analysis as well as for the majority of total and volatile solids determinations.

The chicken litter contained a very large proportion of wood shavings (30%) and since using the standard method for volatile solids determination they would be considered volatile, although not readily biodegradable in an anaerobic digester, it was decided not to include them for the volatile solids determination. This resulted in a very low volatile solids (20%) but it was felt to be more representative of the waste than had wood shavings been included as part of the volatile solids.

Table 2.1 Analysis of chicken litter (supplied by University College Cardiff)

Component	% by Weight
Water	18.3
Protein	15.7
Uric acid	7.2
Lipids	3.6
Carbohydrates	3.54
Phosphate	1.8
Total nitrogen	3.15
Ammonia	1.2
Ash	14.3
Wood shavings	30.0
Total	98.79

This highlights the problem that exists with all anaerobic digester experimentation, that of quantifying the results so that performance may be compared (see chapter 1.2.E, Loading Rate). At least by not including the wood shavings in the volatile solids determination it is possible to compare the digestion of chicken litter with for example other digesters operating on fresh chicken manure.

Total solids were determined by the standard method (HMSO 1972) which involves drying at 105°C; usually this takes several hours. In order to try to find a way in which this can be done more quickly and without the use of water baths or other equipment not usually available on chicken farms, an experiment was conducted to see if specific gravity could be used to approximately determine total solids. A number of samples of chicken litter in water were made up to give a range of total solids. A hydrometer of the kind used for measuring alcohol content in wines was used to measure the specific gravity. Figure 2.3 shows the relationship between hydrometer readings and percentage total solids. This result suggests a simple way of estimating total solids under field conditions providing the hydrometer is first calibrated for that particular waste.

2.3 Summary of Results

2.3.A Commissioning

The construction of the digester was complete on 6th January 1975 and the experiment was stopped on 14th October 1975. During this period there were approximately six months of operation for which results of gas production figures were available. The first three months were spent getting the equipment working properly especially the feeding device and the temperature controller. The thermistor was repositioned when it was found to be directly in the path of the liquid recirculation flow which contained entrained gas (air at this stage). This had a cooling effect and the temperature control was poor. The simple modification corrected this.

2.3.B Start Up

During March the digester was filled with a starter culture from a working digester at Avonmouth Sewage Works, Bristol. Chicken litter was then fed at very low loading rates until the bacterial population had adapted to the new conditions. Figure 2.4 shows the accumulative gas production during the first month of start up with an exponential curve as the adapted bacterial population increases.

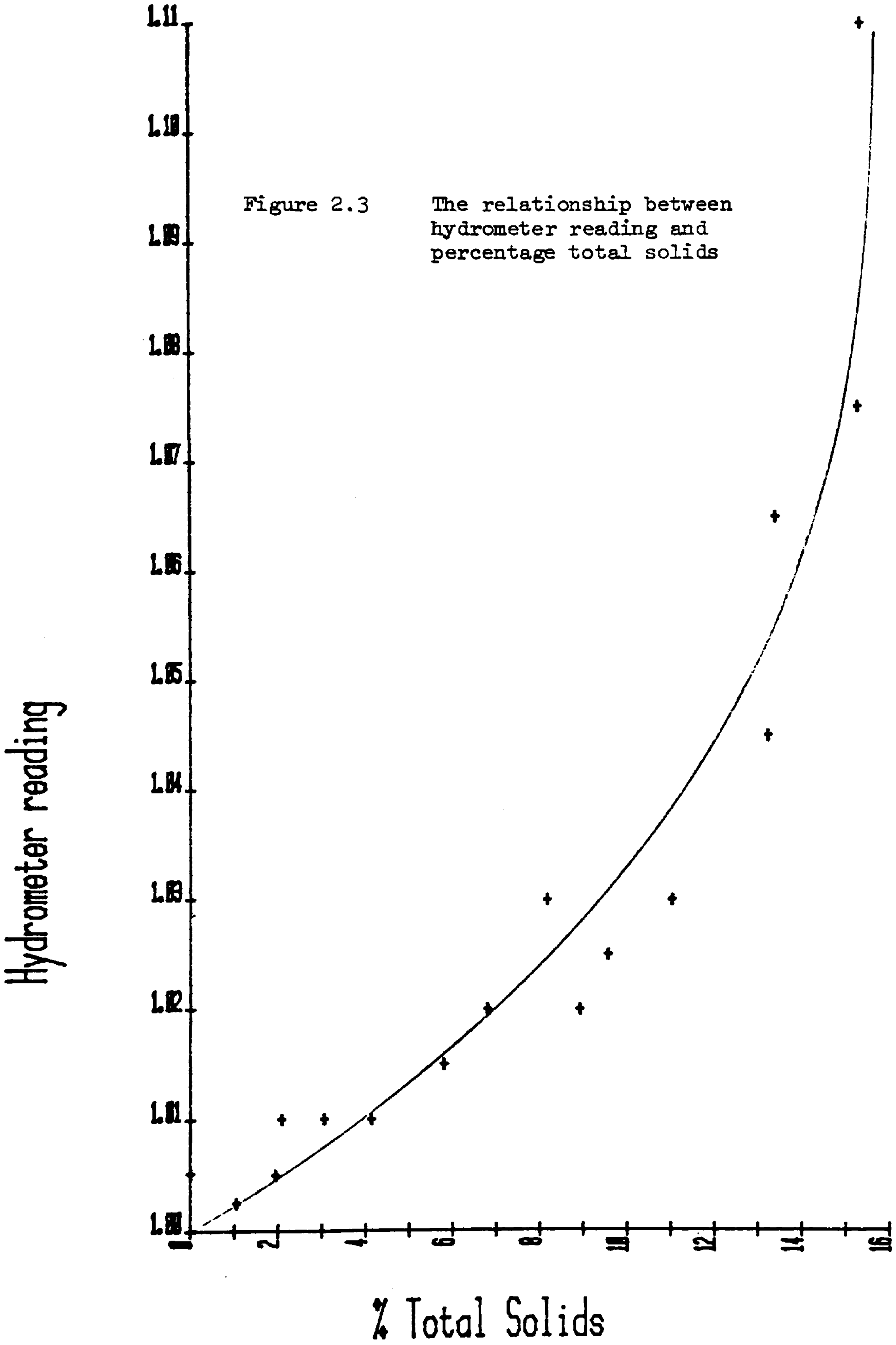


Figure 2.3 The relationship between hydrometer reading and percentage total solids

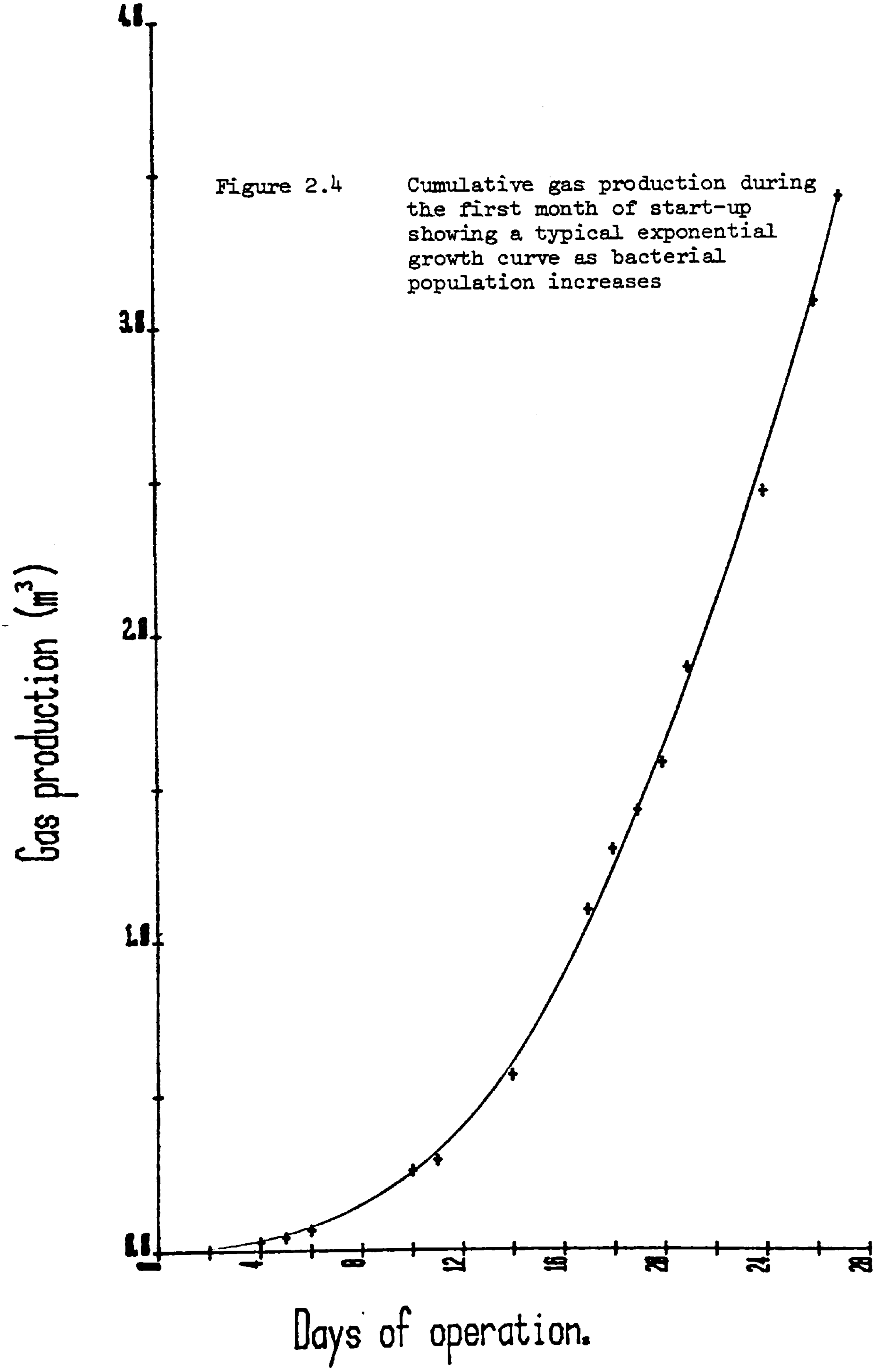


Figure 2.4 Cumulative gas production during the first month of start-up showing a typical exponential growth curve as bacterial population increases

2.3.C Gas Production

The gas production figures from day 50 (May 20th) until the experiment ended are shown in Figure 2.5 together with the volumetric feed loading shown in Figure 2.6. The most noticeable feature of Figure 2.5 is the dramatic reduction in gas produced after the accidental overheating of the digester.

The rise in gas production after day 170 is due to the increased loading as shown in Figure 2.6. The solids percentage of the feed was approximately 4% up to day 90 and 11% after that time.

2.3.D Effect of Overheating

During the night of day 73 the heater control failed and the temperature rose to 58°C. This resulted in an immediate drop in gas production and for two or three days no gas was produced. As the gas volume dropped the proportion of methane dropped also from the 67 - 70% that it had been previously to 22%. The CO_2 proportion rose to 75% and hydrogen was detected (about 2%). The VFA level also rose from the 800 mg/l value to 2000 mg/l. Figures 2.7 and 2.8 show graphically the effect of this temperature rise on the % CH_4, % CO_2 and the VFA level. In order to bring the temperature down quickly after the accident crushed ice was added through the settling tube. This was done in an attempt to reduce the length of time the bacteria would stay at 58°C. The addition of crushed ice added air into the system and Figure 2.6 shows the reduction in % CO_2 from 75% to 12% the remainder being air and a small amount of hydrogen. The corresponding slight levelling off in the rapidly rising VFA curve represents the dilution effect of the ice (Figure 2.8). Very little gas was produced

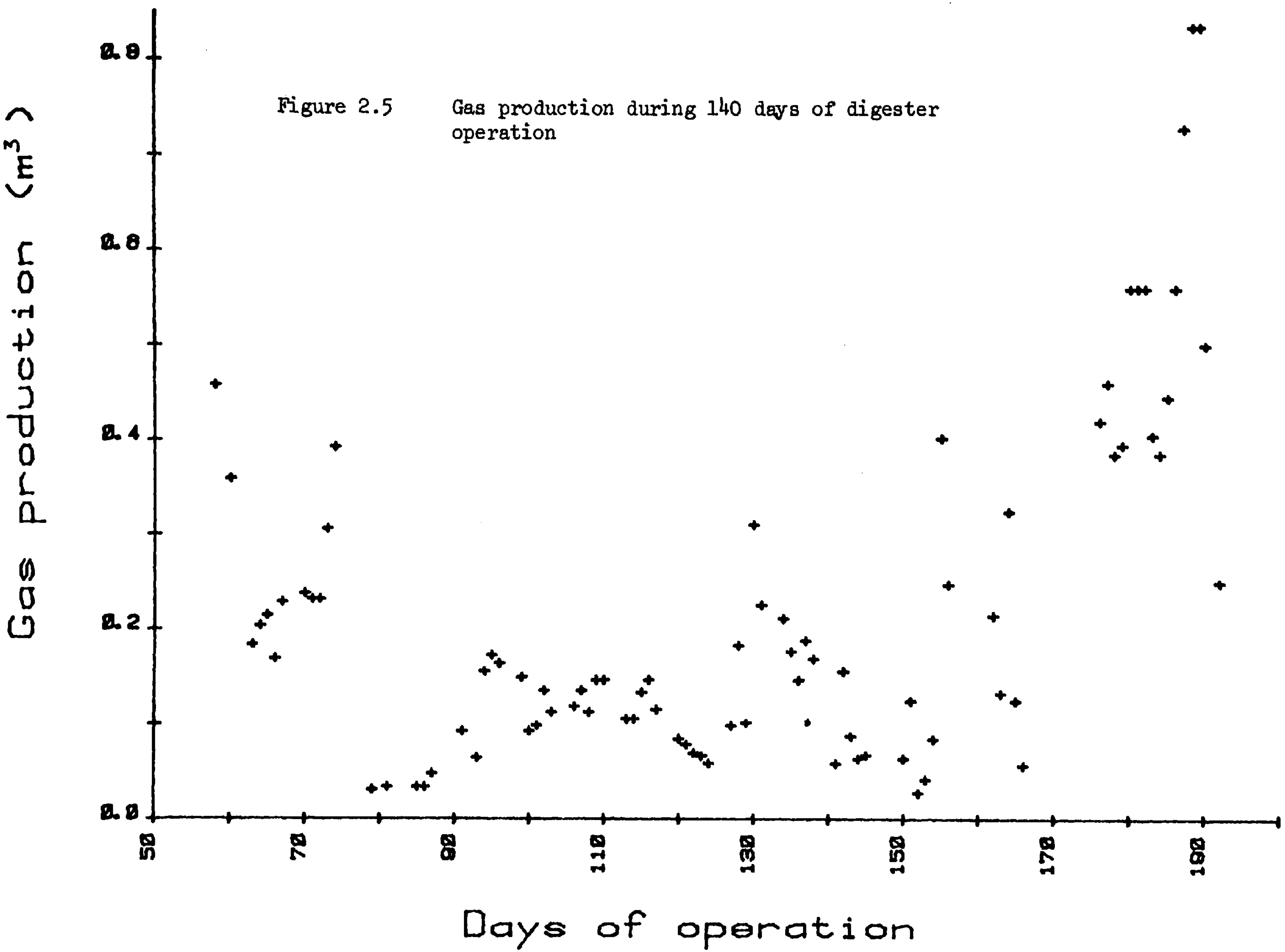


Figure 2.5 Gas production during 140 days of digester operation

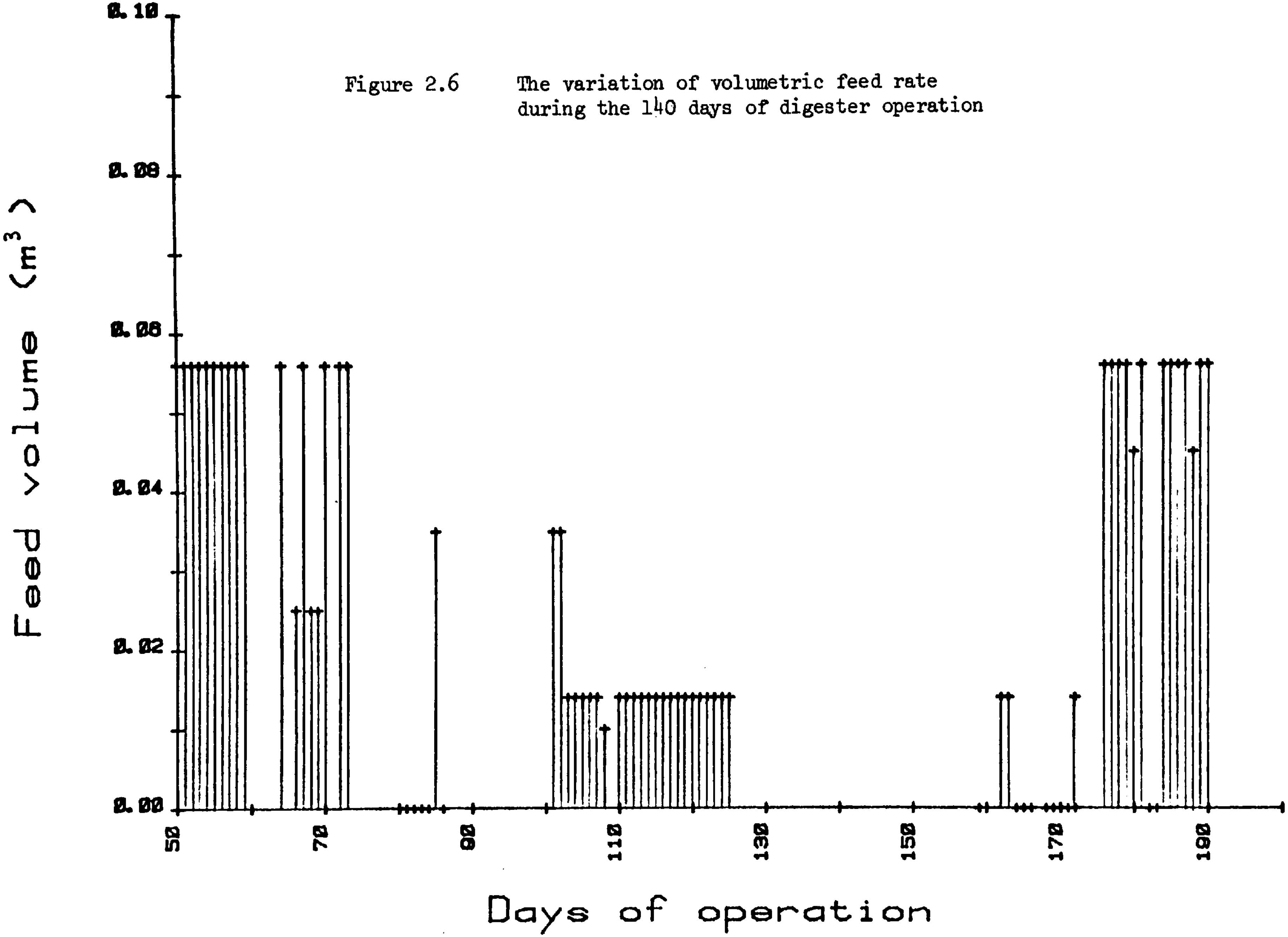


Figure 2.6 The variation of volumetric feed rate during the 140 days of digester operation

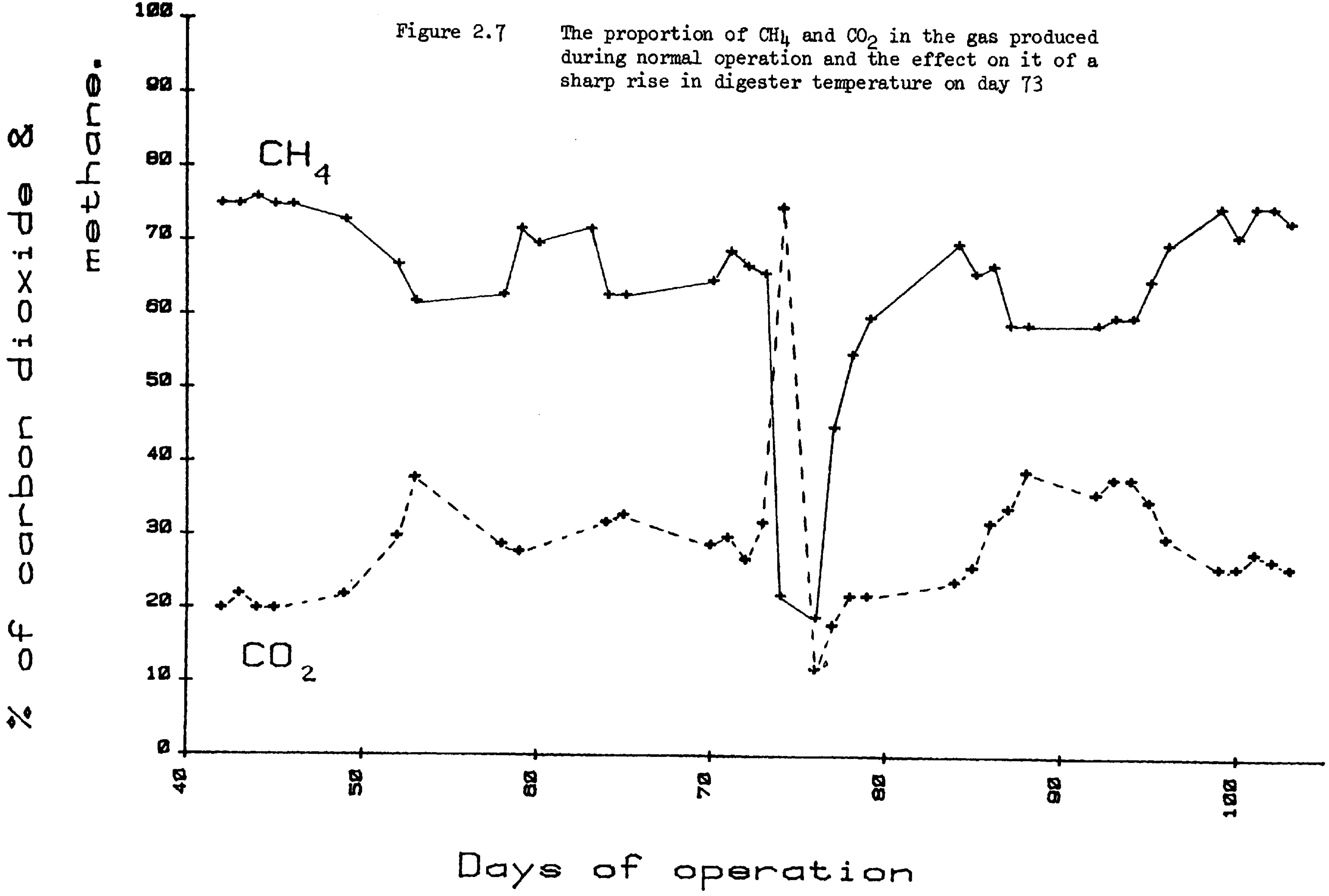
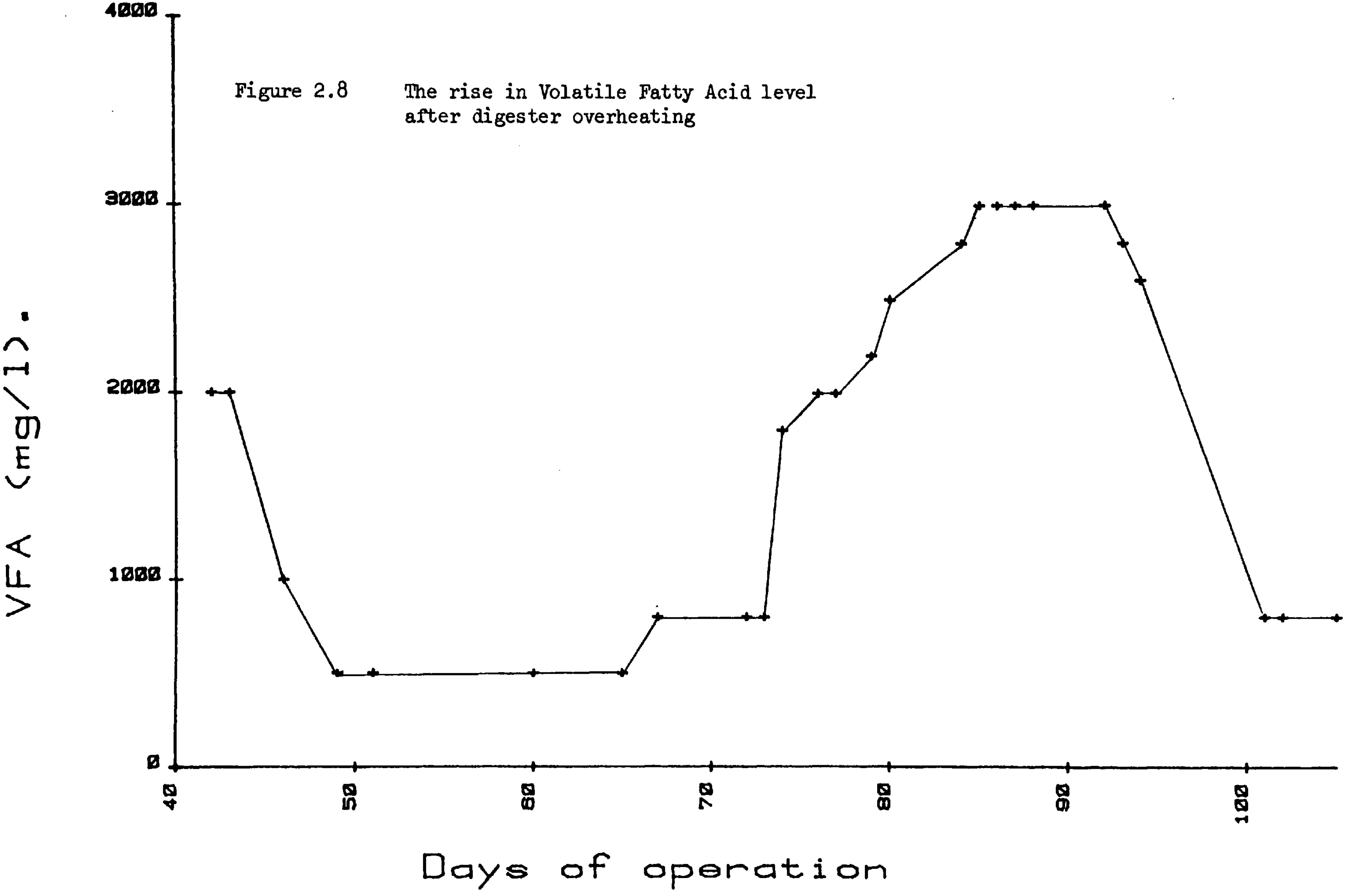


Figure 2.7 The proportion of CH_4 and CO_2 in the gas produced during normal operation and the effect on it of a sharp rise in digester temperature on day 73

Figure 2.8 The rise in Volatile Fatty Acid level after digester overheating



for the next 10 days and the VFA continued to rise reaching 3000 mg/l by day 85. After that the VFA levelled off and began to fall, with a small rise in gas production as it did so. By day 108 the VFA level had fallen to 600 mg/l and feeding was resumed although at a lower level than before.

2.3.E Stable Operation

During the next 60 days the feed was maintained as nearly constant as possible at about 0.014 m^3 per day (an almost 60 day retention time). The solids content at this time was 11% TS of which 20% was volatile solids resulting in a loading of 0.308 kg VS added per day. The gas production averaged 0.14 m^3 which is a gas yield of 0.454 m^3/kg VS added. The methane content fluctuated between 65 - 75% with an average of 70%.

On day 153 the feed rate was increased to give a 24 day retention time. The gas production rose immediately but unfortunately the loading could not be maintained due to blocking of the feed tube, especially at weekends, with the high solids content feed (11% TS). On day 176 the feed was again increased to 0.056 m^3 per day (15 day RT).

This time the full retention time was almost attained before a failure of the heater was discovered on day 190. During this period the gas production reached its maximum value of 0.837 m^3 with an average of about 0.52 m^3 per day. This gave a gas yield of 0.42 m^3/kg VS added. Once again there were times when the feed tube became blocked due to the high solids of the feed material. This problem would be less on a full size unit when the feed hopper would be much larger.

The results from this experiment digesting chicken manure showed that the original design concept was good but trouble with various items of equipment and with blocking of the feed tube meant that the plant needed modification so that the variables affecting the gas production could be examined in more detail.

At the time that the experiment was ended the work came to the notice of Hamworthy Engineering Ltd., Poole, who were manufacturing marine aerobic waste treatment units. They examined the equipment and discussed our objectives for an inexpensive modular construction, high rate energy producing digester and agreed to supply two new pilot plants built to our design in return for the patents and results. This fitted in with their desire to expand their waste treatment product range and to enter the land based market. An agreement with the Polytechnic was subsequently drawn up.

CHAPTER THREE

STUDIES ON THE ANAEROBIC DIGESTION OF SEWAGE SLUDGE

3.1 The Pilot Plants

Chapter 2 described the first rig built to gain experience with pilot plant operation and to try out certain novel ideas. This earlier work came to the notice of Hamworthy Engineering Ltd. who then sponsored the next stage of the research from 1976.

Previous experience had established the desirability of operating two identical rigs simultaneously. Alterations and modifications can be carried out on one rig and its performance evaluated before both are changed. This procedure would ensure minimum delays and time consuming failures.

Accordingly two rigs each of 1 m^3 were designed by D. L. Hawkes and H. R. Horton based on previous experience and were manufactured by Hamworthy Engineering.

The apparatus is shown in Figure 3.1 and consists of three main parts, a feed tank, the digester and an outlet tank. The waste to be treated is deposited into the feed tank, from where it is fed into the digester inlet tube by means of a bucket elevator feed mechanism. This was a modification of the earlier successful design. Within the digester the contents are heated and stirred. The treated waste flows into the outlet tank via the outlet tube.

The biogas about 70% methane, 30% carbon dioxide is given off in the process and goes via a gas meter and pressure regulator to a gas stack.

Plate 2 shows the new pilot plants (a third one was added later) on a specially prepared site at The Polytechnic of Wales. In the background there can be seen a small laboratory for routine tests.

The main features of the new digesters are as follows:

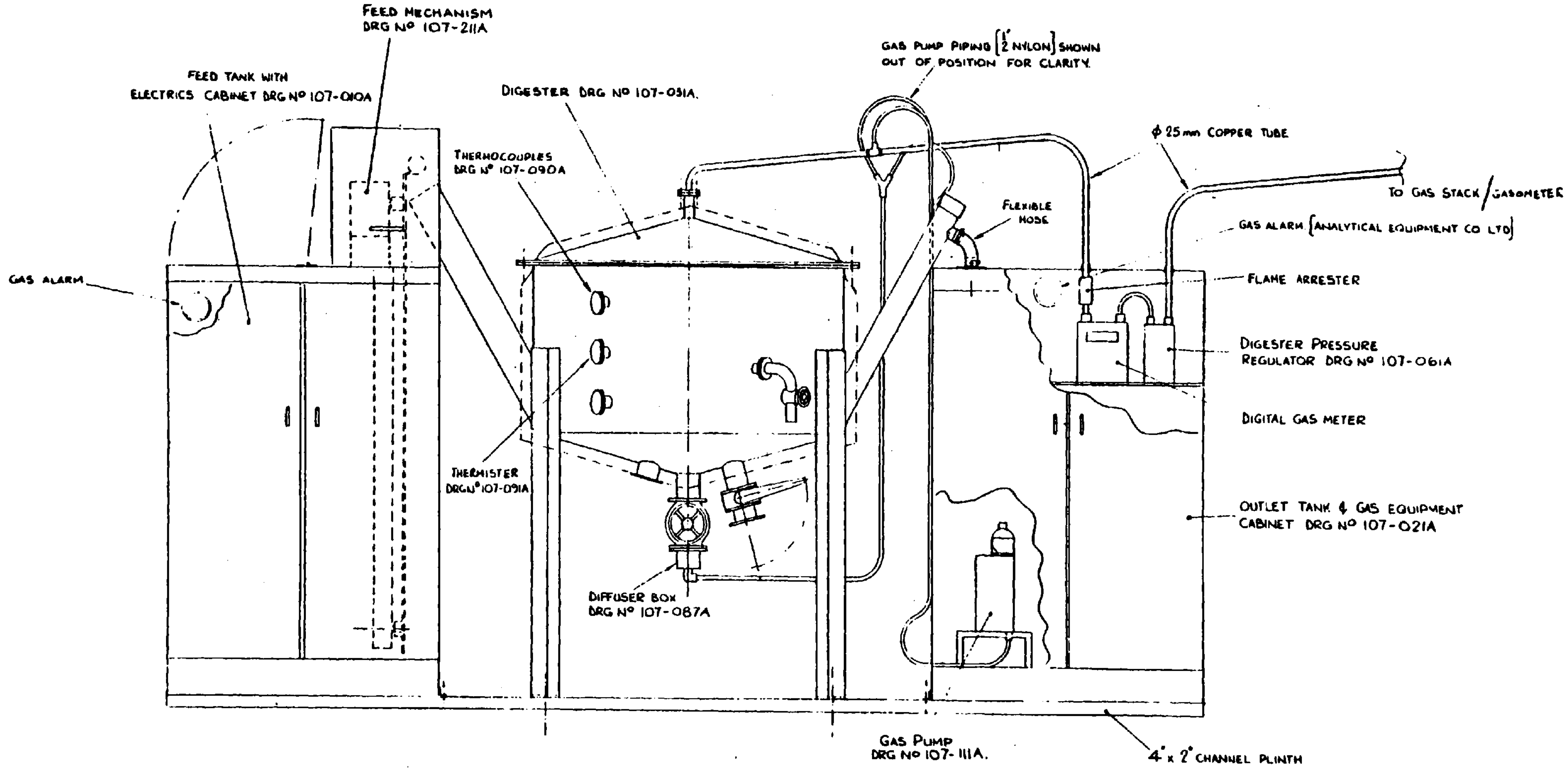


Figure 3.1 The second pilot plant based on modifications to the earlier design

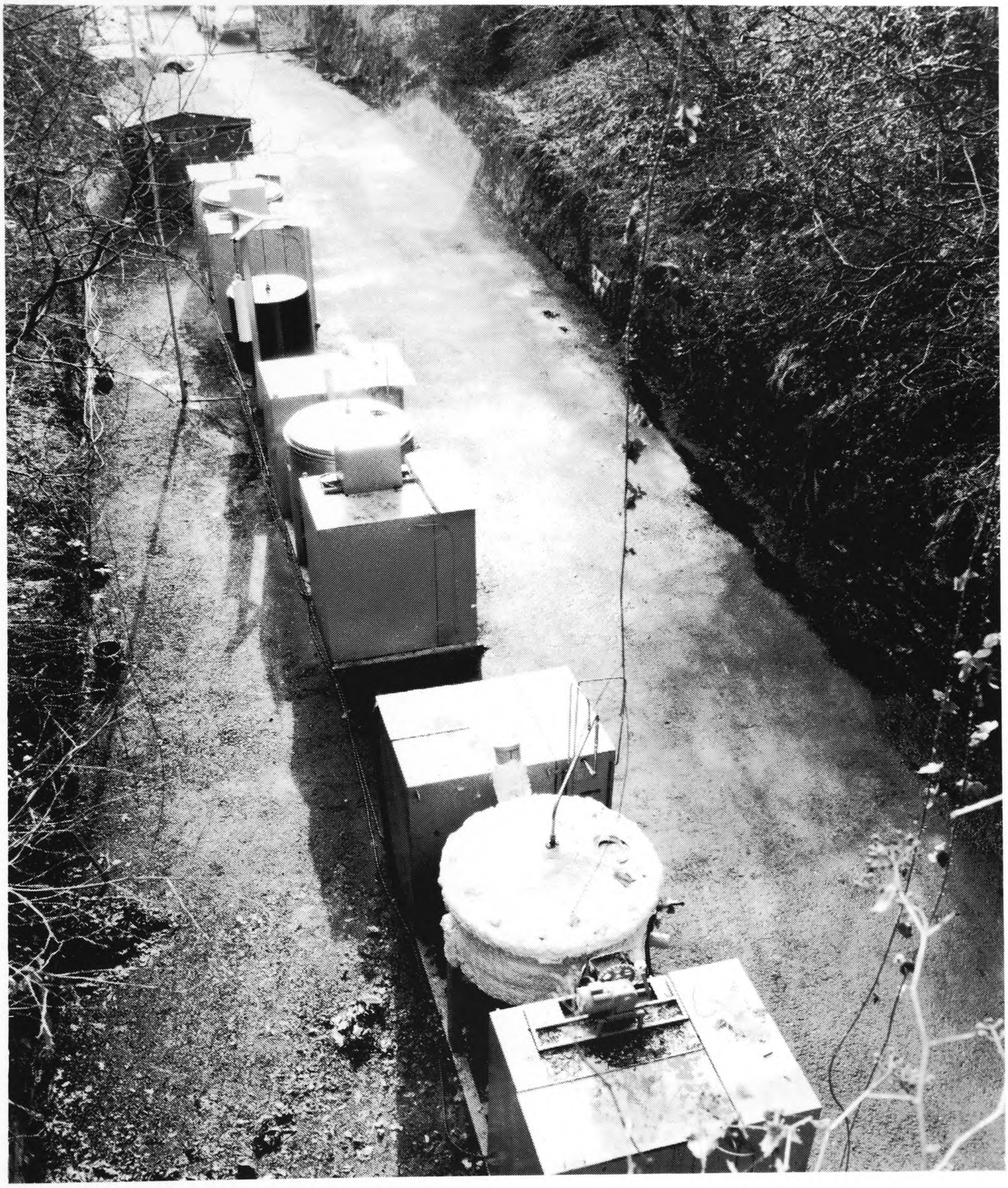


PLATE 2 Pilot plants installed on a specially prepared site at The Polytechnic of Wales

1. The feeding device is adjustable to allow different retention times and to cater for different types of waste. The simple and reliable gravity feed method has advantages over the more usual pumps as it does not rely on any seals or valves and any malfunction is visible.
2. The temperature control is more accurate with a proportional controller circuit and built in safety cutouts.
3. Efficient mixing is obtained by utilizing digester gas recirculation through a centrally located diffuser and using a vessel with the correct geometric proportions. (Horton, R. 1980).
4. An increased bacterial population is encouraged by the method adopted for removing the waste that is by displacement through the settling tube. A proportion of the solids settle back into the digester under gravity allowing a shorter hydraulic retention time for the liquid and thus a smaller digester volume to treat a certain amount of waste. Accumulated sludge can be periodically withdrawn from the valve at the bottom of the digester.
5. The system is safe from pressure build up as both inlet feed tube and outlet tube are open to atmosphere. A workable gas pressure (about 1.5 m bar) is maintained by a predetermined head of water in a pressure regulator.

3.2 The Experimental Programme

3.2.A Installation

The programme of operation was divided into three parts, installation, start-up and operation, the first 6 months being taken up with the installation. This work entailed:

1. Finalising the design and preparing detailed working drawings.
2. Clearing the site. The area where the new pilot plants are operating was originally an old railway cutting; undergrowth, and debris were removed from approximately 460 m^2 and 3 m high fences were constructed in accordance with local safety requirements. The nature of the feed material necessitated this isolated site, the previous pilot plant having been inappropriately sited amongst Polytechnic buildings.
3. Water, electricity and telephone had to be provided which entailed a 300 m long trench being excavated.
4. A laboratory was built and fitted out to enable routine tests to be carried out on site. The basic wood framed shed was 3 m x 4 m with a dividing wall making two rooms, the larger of which was fitted out with laboratory benches, water, electricity and telephone. The smaller room 3 m x 1 m was equipped as a small maintenance workshop. The laboratory facilities included the necessary equipment for VFA analysis using a colorimetric method with standard Lovibond Discs. A pH meter EIL model 7010 and a C.S.T. apparatus Type 130 supplied by Triton Electronics together with a 3 channel chart recorder model CR 503 X (J.J. Instruments Ltd.) were also installed initially. Other equipment added later included a 2 channel Servoscribe 2s chart recorder, bench centrifuge, Hach manometric B.O.D. analyser model 2173, Hitachi microwave oven (for total solids analysis) model MR 6050, and a Carbolite

electric furnace type OAF PIDXIND. A Sartorius top loading balance model 1213 MP was later acquired under an SRC grant to the Department of Science in the Polytechnic.

5. The two pilot plants were assembled and installed on concrete bases.
6. The digesters were lagged with 50 mm glass wool covered with aluminium skin.
7. Initial testing was carried out using water to check the heating, feeding and gas recirculation devices. Several small modifications had to be carried out at this stage.

3.2.B Start-up

The second stage which lasted almost 3 months involved start-up. Starter culture was obtained (November 23rd, 1976) from the Abergavenny sewage works to seed the digester. Unfortunately this later proved to be from a failing digester with a very high VFA (2400 mg/l) where the pH had been adjusted to 7.5 by a large addition of lime just before delivery to us. In an endeavour to make up lost time one of the rigs was emptied and refilled with a new seed from a digester at Avonmouth sewage works (December 22nd, 1976) (pH 7, VFA $<$ 400 mg/l) and the other was allowed to recover naturally to evaluate the recovery characteristics.

Meeting with the Welsh National Water Development Authority which had previously taken place resulted in the choice of a site from which sewage sludge could be regularly obtained. The site chosen was Wenvoe Sewage Treatment Works, South Glamorgan which serves a small rural population. The sewage has very low trade waste additions and is consequently low in heavy metals or other potentially toxic material. The site was also typical of the size which would be suitable for the installation of a digester, that is, serving a population of between 1000 - 2000.

Samples were arranged to be taken from the settling tank in order to obtain a reasonable high solids material. The first delivery was made on 25th November.

It was arranged that the Department of Microbiology, University College Cardiff, would undertake analysis of total and volatile solids, B.O.D., C.O.D. and pathogen reduction on samples sent to them.

Six months later due to the inconvenience of this the total and volatile solids analysis was carried out on site. Routine daily measurements at the Polytechnic included VFA, gas volume, gas composition, Capillary Suction Time, temperature, pH and power consumption.

3.3 Analytical Techniques

3.3.A pH

The pH of the digester contents were determined routinely by the glass electrode method as described in Analysis of Raw Potable and Waste Waters (HMSO 1972). An EIL laboratory pH meter model 7010 was used with a combination electrode (cat. No. 1160 - 200). The normal limits of accuracy reported for this method are ± 2% f.s.d.

3.3.B Volatile Fatty Acids

During the process of anaerobic digestion significant concentrations of the salts of the lower (volatile) fatty acids are formed. These are converted eventually to methane and carbon dioxide. Any disruption in this bacterial process is usually indicated by a sudden rise in the concentration of volatile acids. Frequent checks on this concentration are therefore made when monitoring the process.

There are a number of methods which can be used but the most common one is a colorimetric chemical method. This was the method chosen because of the rapidity of the determination (less than 25 minutes) and the low cost using a Lovibond Comparator and standard Disc 3/62 (obtainable from Lovibond Tintometer Ltd., Salisbury, U.K.). The other factor is that the method can be easily learnt.

The suspended matter was removed by sedimentation using a bench centrifuge. Later the method adopted was filtration using a funnel and filter paper Whatman grade No. 1.

The sample of clarified liquor was then treated with ethylene glycol in the presence of sulphuric acid. This converts carboxylic acids such as fatty acids and their salts to esters which are in turn converted to hydroxamic acids by reaction with hydroxylamine (Montgomery et al 1962). The colour of the complexes formed by reaction of the hydroxamic acids with ferric chloride is a measure of the hydroxamic acid concentration and thus also of the original organic acid concentration. The method used for estimating this colour was to compare it with a permanent glass colour standard Lovibond Disc.

The accuracy using a Disc rather than a spectrophotometer is lower (± 100 mg/l) but since the method was only being used to monitor the process and to detect large sudden changes this method was quite adequate.

The technique used was as follows: 0.5 ml of the clarified liquor was put into a 12.5 x 1.5 cm test tube. Into a similar tube 0.5 ml of distilled water was measured to provide a blank. To both tubes were added 1.7 ml of acidic ethylene glycol from a burette and the contents mixed thoroughly. The acidic ethylene glycol was previously prepared, fresh daily, by mixing 30 ml of ethylene glycol with 4 ml of diluted sulphuric acid (50% water). The tubes were then heated in boiling water for 3 minutes followed by immediate cooling. Hydroxylamine reagent was then made up by adding 20 ml of a solution of 180 g of sodium hydroxide made up to 1 litre with distilled water, to 5 ml of hydroxyammonium sulphate solution (10% W.V. in distilled water). Acidic ferric chloride was prepared by dissolving 20 g of ferric chloride hexahydrate in 500 ml of distilled water together with 40 ml of the diluted sulphuric acid. 10 ml of this acidic ferric chloride solution was then put into each of a pair of 25 ml volumetric flasks and the solutions from the test tubes added using distilled water to rinse out the last traces from the tubes into the flasks. Distilled water was used to make up the volume to the 25 ml mark. The flasks were thoroughly shaken and afterward left for 5 minutes with the stoppers removed to allow the evolved gases to escape. The sample solution was then transferred to a 25 mm comparator cell which was placed in the right-hand compartment of the special purpose Lovibond Comparator. An identical cell was filled with the solution from the blank determination and placed in the left-hand compartment. The colour of the sample solution was then compared with the Lovibond permanent glass colour standards in the disc, illuminating the comparator by holding it up to the north daylight.

3.3.C Total Solids

The total solids concentration was determined in accordance with the procedures described in Analysis of Raw Potable and Waste Waters (HMSO 1972). Approximately 25 g of sample were weighed into a tared dish and evaporated nearly to dryness over a water bath. The drying was completed in an oven at 105°C for approximately one hour. The sample was then cooled in a dessicator and weighed. The total solids content (as a percentage of wet sludge) is given by:-

$$\frac{\text{weight of sludge remaining after drying} \times 100}{\text{weight of sample taken}}$$

This procedure takes about 12 hours to complete and in an effort to decrease this experiments were performed using a microwave oven to dry the sample. This procedure has recently been used successfully by the Welsh National Water Development Authority.

The equipment used was a Hitachi microwave oven model MR 6050 with defrost mode. The method involves taking the sample, about 25 ml, weighing into a dry high sided 250 ml glass beaker and using the microwave oven on the defrost mode. Complete drying takes less than 1 hour with this method. Some spluttering occurs but a 250 ml high sided beaker ensures that none of the sample is lost. After drying the sample is weighed again to determine the weight loss. Before the procedure was adopted for routine use the accuracy was checked on duplicate samples with the more conventional method. No measurable difference in total solids was observable with the two methods. The weighing was performed on a top loading Sartorius balance model 1213 MP.

Care must be observed when taking samples of the sludges for total solids determination by any method so that the sample is entirely representative of the whole. This is potentially the largest source of error.

3.3.D Volatile Solids

Volatile residue was determined on the dried solids obtained from the above analysis. With the first method of total solids determination the drying is carried out in a dish used for the evaporation and suitable for ignition. The second method uses a glass beaker for the drying process and so a sample must be transferred to a ceramic dish before volatilising. The sample after weighing is ignited in an electric muffle furnace at 600°C for half an hour. The furnace used was a Carbolite electric furnace type OAF - PIDXIND. The loss on ignition (volatile matter) as a percentage of dried solids is given by:-

$$\frac{\text{weight lost during ignition} \times 100}{\text{weight remaining after drying}}$$

3.3.E Gas Analysis

The digester gas was sampled daily throughout the experiment and analysed for percentage methane and carbon dioxide. The determination was by gas-liquid chromatography using a Perkin Elmer apparatus model 452 used solely for gas analysis.

A 2 m long x 2 mm inside diameter stainless steel column packed with Porapak T 100 - 120 mesh packing medium was used to separate methane, CO_2 and hydrogen, and these were detected using a thermistor detector. The column was housed in a constant temperature oven operated at 60°C. The inert carrier gas was nitrogen which was BOC ordinary grade without purification. The flow rate was 10 cm^3/min. The system was standardised using high purity CO_2 and CH_4. A calibration curve of gas percentages versus peak heights on the chromatograms was prepared periodically.

Gas samples were collected daily using a 10 ml syringe (Gillette Scimitor Disposable) fitted with a nylon 3 way valve. This enabled the syringe to be flushed out easily with the gas and then sealed until analysis, usually not longer than half an hour later.

The gas sampling port on the digester was a hypodermic needle, plugged when not in use, permanently inserted in the gas line up stream of the gas meter.

3.3.F Capillary Suction Time

The measurement of capillary suction time (CST) was carried out daily not only to determine the filterability of the digester sludge but also as experiment to find if there was a direct relationship between CST and VFA as reported by Al-Rawi (1978).

The measurement of CST is very rapid less than 5 minutes and is a semi-skilled operation. The instrument, shown in plate 3, was a Type 130 CST apparatus obtainable from Triton Electronics Ltd., Dunmow, Essex. This was also the source of the special CST filter papers used.

3.3.G Gas Production Rate

The normal method for measuring gas produced, a gas meter, is not very suitable for obtaining a measurement of the rate of gas production especially at night or at weekends since it involves taking a number of readings at regular time intervals. In order to investigate the rate of gas production in relation to the feed or mixing a Water Research Centre Gas Meter of the type shown diagramatically in Figure 3.2 was purchased. This is a displacement meter with an oscillating gas collector, each oscillation representing a certain volume of gas passing through it.

Magnets are incorporated which cause reed switches to open and close. Thus each volume of gas passing through the meter gives an electric impluse which normally operates a counter as shown in

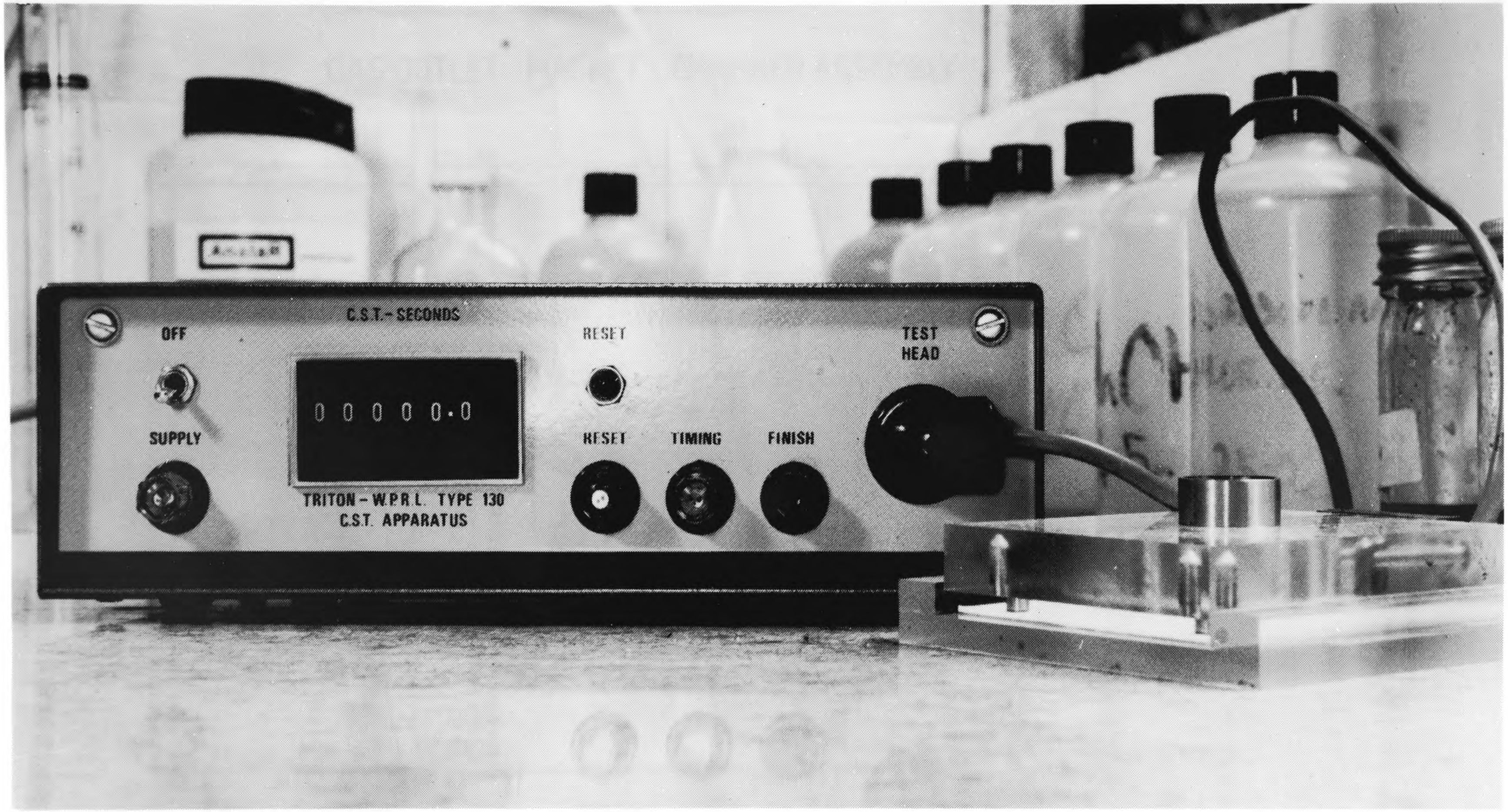


PLATE 3 C.S.T. apparatus, Type 130 Triton Electronics Ltd.

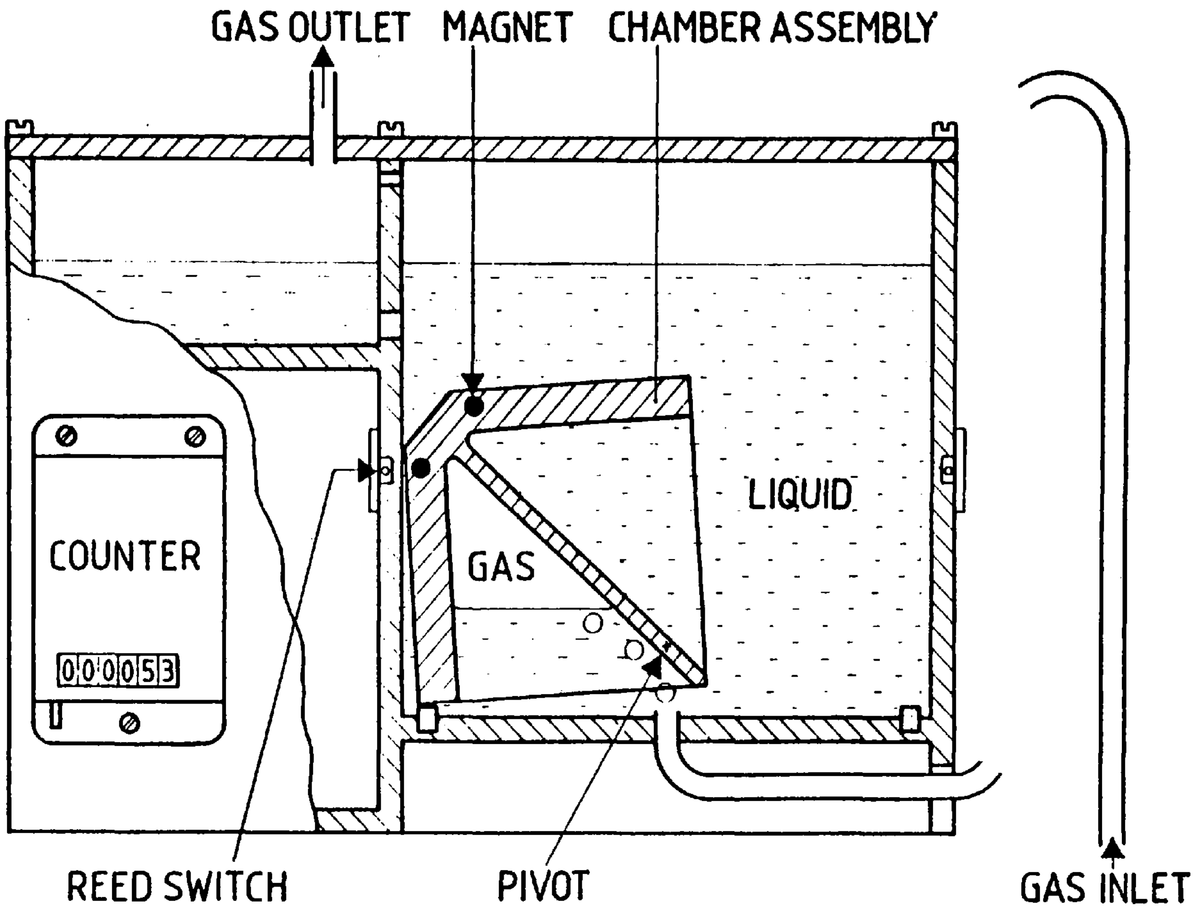


Figure 3.2 Apparatus for the measurement and continuous recording of low flow rates of gas

Figure 3.2. The apparatus was modified so that the impulse generated formed the input to a chart recorder. The apparatus is fully described in a Water Research Centre technical report No. TM 104. It is obtainable from Bird and Tole Ltd., High Wycombe, Bucks.

3.3.H Biological Oxygen Demand

Biological Oxygen Demand (BOD) is used to measure the quantity of oxygen required during stabilization of decomposable organic matter by aerobic biochemical action.

The BOD is one of the basic analytical procedures used for organic pollution measurement. The apparatus was a Hach Manometric BOD Apparatus Model 2173. A measured sample of the effluent is placed in one of the bottles on the apparatus. The bottle is connected to a closed end mercury manometer. Above the sample in the bottle is a quantity of air which contains oxygen. Over a period of time bacteria in the sample utilize oxygen to oxidise organic matter present in the sample thus consuming the dissolved oxygen. The result is a drop in air pressure in the bottle which is registered on the mercury manometer and read directly as mg/l BOD. During the test period usually 5 days the sample is constantly agitated by a magnetic stirring bar which is rotated by a pulley system connected to a motor. Each sample bottle cap contains a small cup into which can be introduced a few drops of potassium hydroxide solution to absorb the carbon dioxide produced by the degradation of the organic matter. If this is not done a positive pressure would result causing an error in the reading.

The Hach BOD Apparatus is simple to use and since a physical change is observed chemical laboratory analysis is not required for the BOD readings.

3.4 Results and Discussion

Both digesters were filled with a bacterial seed sludge from a digester at Abergavenny on November 23rd, 1976 (day 1). The pH was 7.5 although the VFA level was 2400 mg/l and the total solids content 2.5%. The temperature was brought to the operating conditions of 35°C ± 2° which was maintained throughout the experiment. Because of the very high VFA it was decided immediately to obtain a new seed material for one of the digesters this time from a working digester at Avonmouth Sewage Works. During the time that this took to organise and have delivered the VFA continued to fall. Figure 3.3 shows the drop in VFA during the first 30 days of operation of N°2 digester. The other digester responded in the same way but was refilled with the new seed on day 28.

3.4.A Feed Solids

A feed slurry was obtained from Wenvoe Sewage Works with a solids content of only 0.25% and was fed to digester N°2 from day 60 onwards. Until this time a number of minor modifications and problems with gas leaks prevented operation. Both digesters were fed by means of the bucket elevator device semi-continuously (10 mins/hr) for seven days a week to give a retention time of 15 days. Unfortunately the feed total solids varied widely with each new supply (from 3.3% TS to 0.04% TS a 75 : 1 variation), resulting in difficulties in maintaining a constant loading. Also there were problems with sludge lifting in the inlet holding tank and a number of methods to obtain a more stable feed rate were tried. Altogether six different methods were tried out in an attempt to keep the feed homogeneous in the inlet feed tank between deliveries. These methods included various propellers and

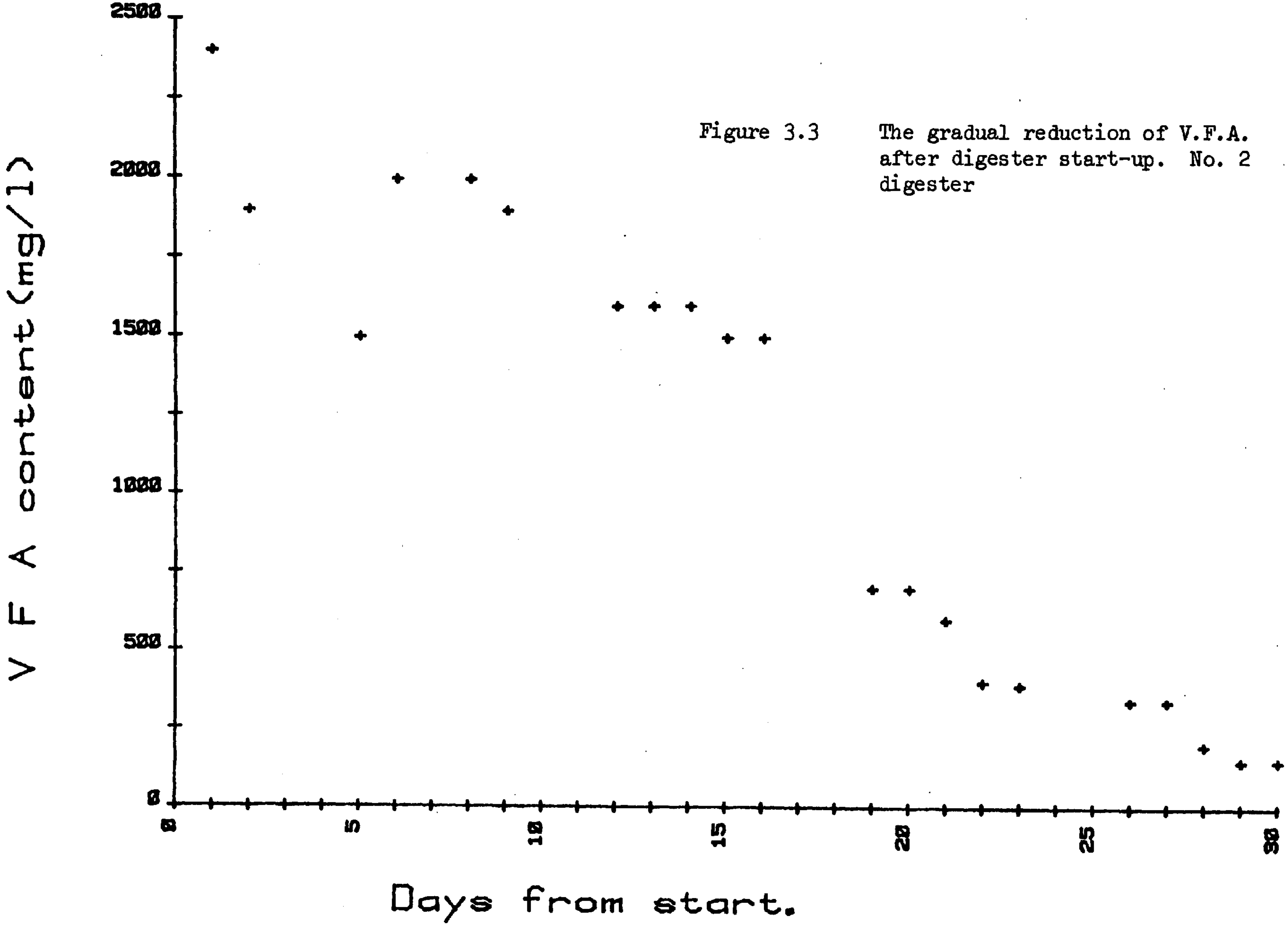


Figure 3.3 The gradual reduction of V.F.A. after digester start-up. No. 2 digester

paddles which tended to soon become ineffective due to the rags and long fibrous material present in the sludge. These rapidly built up around the shafts.

The eventual solution proved to be air agitation using a small rotary compressor bubbling air into the feed tank for 5 minutes every 1½ hours. This prevented stratification and gave a much more consistent feed. This experimentation took until 17th May (day 175) each of the devices used having to be built, installed and evaluated in turn. The air agitation gave consistent results as can be seen from Table 3.1 and was subsequently used on both rigs.

Table 3.1 Results of air agitation showing total solids readings of feed throughout a day (N°2 digester)

Time		% TS of Feed
1030 (am)		2.79
1100		2.88
1130		2.41
1200		2.86
1230 (pm)		3.01
1300		2.66
1330		2.52
1400		2.80
1430		2.44
1500		2.67
1530		2.43
1600		2.71
	mean	2.68

s.d. 0.197

Table 3.1 shows a series of readings taken at half hour intervals throughout the day showing the feed total solids varying from 3.01 to 2.41%, a variation of 1.25 : 1 which was considered satisfactory.

The variation in feed solids with each delivery remained however and since each tanker load lasted only 2 to 3 weeks the overall result was fluctuation in feed solids with an average value throughout the 550 days of operation (370 days for N°2 digester) of 2.25%. The actual values are shown on Figures 3.4 and 3.5. Repeated requests were made to the Water Authority to provide more consistent sludge but without success. Occasionally a high feed solids was delivered, for example day 349 or a very low solids, day 463 (see Figure 3.4). Table 3.2 shows the average total solids in each feed delivery throughout the period of operation.

3.4.B Sampling

The sampling method was used for all total and volatile solids determinations and for VFA, BOD, etc. was as follows: For the feed a sample was obtained directly from the cups delivering to the feed tube, approximately 0.75 l was taken from which the determinations were made. From the digester a sample was taken from the sampling port situated at approximately one half tank depth. The sample was always taken whilst mixing the digester, about 2 l being first run off to clear the sampling tube before the ½ litre sample of slurry was withdrawn. The feed sample was collected as it overflowed from the outlet tube.

3.4.C Retention Time

The method for determining the retention time was at first based on the delivery rate of the cups on the bucket elevator and the timing

Figure 3.4 The variation of feed total solids during the period of No. 1 digester operation

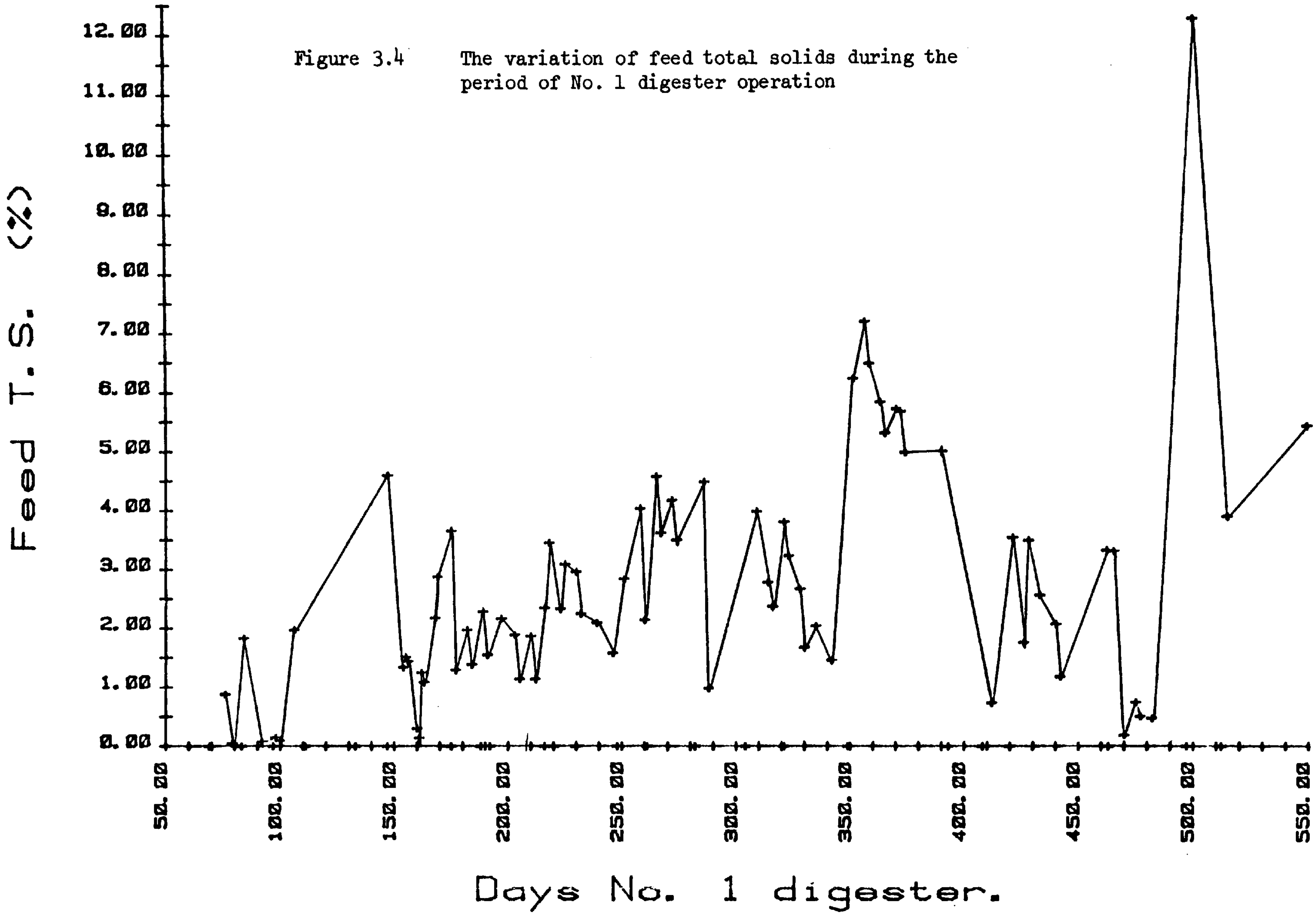


Figure 3.5 The variation of feed total solids during the period of No. 2 digester operation

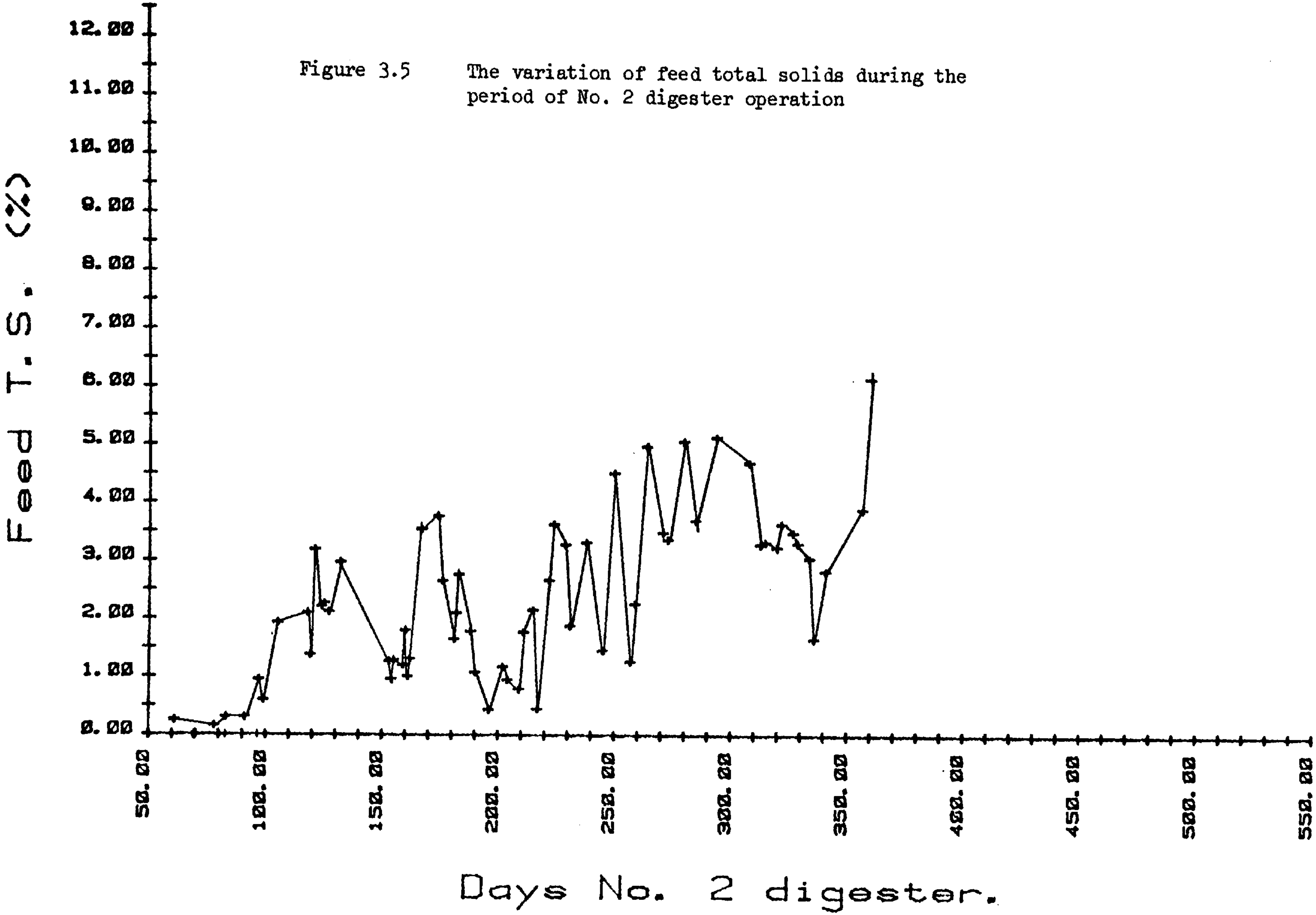


Table 3.2 **Average total solids in each feed delivery showing variation**

Feed Delivery Day	Average Total Solids in Feed %
30	0.25
69	0.10
83	0.63
97	0.74
111	2.17
133	3.78
147	1.44
175	2.36
188	1.67
192	1.35
216	2.10
220	2.94
230	2.36
248	2.85
261	4.10
282	3.58
304	3.41
321	2.78
349	5.76
393	0.74
408	0.74
420	2.41
463	1.05
497	NA
512	4.67
	Average 2.25% . s.d. = 1.46

period. Due however to the nature of the sewage sludge used (it contained rags and other fibrous material) this method was found to be unreliable, since sometimes some of the cups would block; a dipstick in the feed tank each day was found to be a better method. By this means, what had been put into the digester from the feed tank each day could be measured and the retention time worked out.

3.4.D Capillary Suction Time and Relationship to VFA

Of considerable importance in the treatment of sewage sludges is the ability to dewater them, accordingly routine analysis of this parameter was undertaken. The Capillary Suction Time (CST in seconds) is the reciprocal of the specific filterability and is measured by means of a standard instrument involving a filtration device and automatic time recording unit (Baskerville et al 1968), see Section 3.3.F. The sample to be measured is placed in a short tube on a standard CST filter paper resting on a perspex block. The block contains sensing elements which enable the movement of the water front across the filter paper to be timed. The shorter the time recorded for the water front to pass the two probes the easier is the sludge to dewater. It has been suggested (Al-Rawi 1978) that there may be a relationship between Volatile Fatty Acids and CST and therefore it was felt that the measurement of CST (which takes only a few minutes) could be used instead of VFA as an indicator of digester performance. Since the CST determination involves a standard relatively low cost instrument (≏ £100. 1978) and is a semi-skilled technique that can be readily learnt, both VFA and CST measurements were made on samples from both digesters about 3 times each week. The results of this exercise are shown in Figure 3.6. Although there is reported to be a relationship between CST and VFA, (Al-Rawi 1978), that is as VFA increases

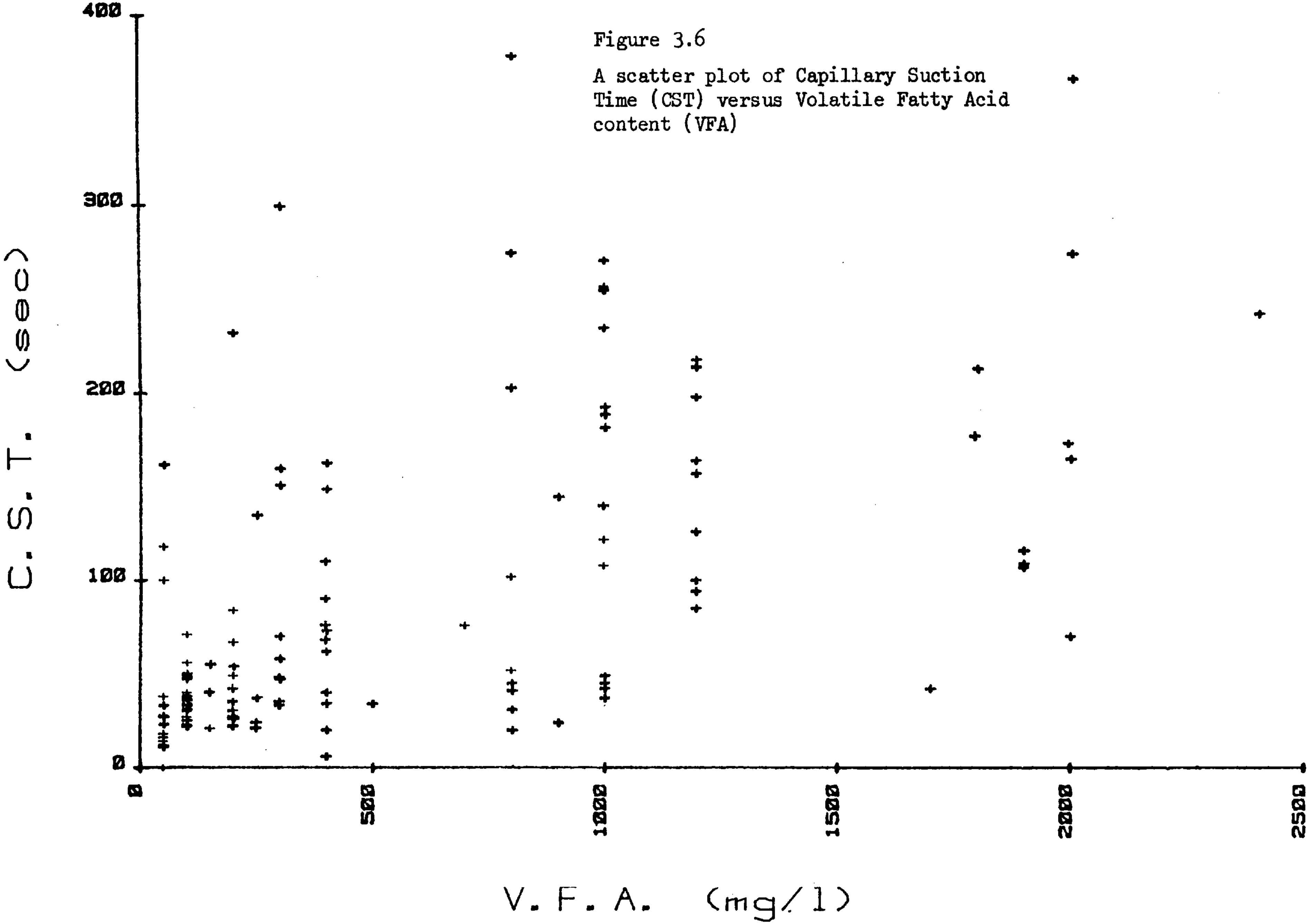


Figure 3.6

A scatter plot of Capillary Suction Time (CST) versus Volatile Fatty Acid content (VFA) the average value for CST also increases, the results of this experiment do not support this conclusion and are not definite enough to be able to use CST to predict VFA levels and hence digester performance.

3.4.E Solids Retention

The design of the pilot plant digester incorporated a sloping outlet settling tube in order to attempt to retain some of the solid particles and hence bacteria which were attached to them. Measurements of the total solids of the digester contents and of the effluent overflowing from the settling tube were made regularly to determine the effectiveness of this method of solids retention.

The results are summarised in Figures 3.7 and 3.8. Figure 3.7 shows the percentage reduction in total solids between the digester contents and the effluent overflowing from the settling tube in N°1 digester throughout the experiment, Figure 3.8 shows the results for N°2. The results for N°2 digester show that there is a greater than 80% reduction in total solids that is more than 80% of the total solids in the digester contents remain and do not leave in the effluent from the top of the settling tube. The solids thus captured were subsequently either solubilised, digested or remained in the digester from where they were periodically (once every 3 to 4 months) removed from the bottom. Unfortunately due to the large fluctuations in solids of the feed and effluent it was not possible to carry out an accurate materials balance. Occasionally solids tended to float in the settling tube and the percentage reduction would then appear as a negative value. These were expressed for convenience as a zero point in Figures 3.7 and 3.8.

N°1 digester settling tube did not perform as well as N°2 with

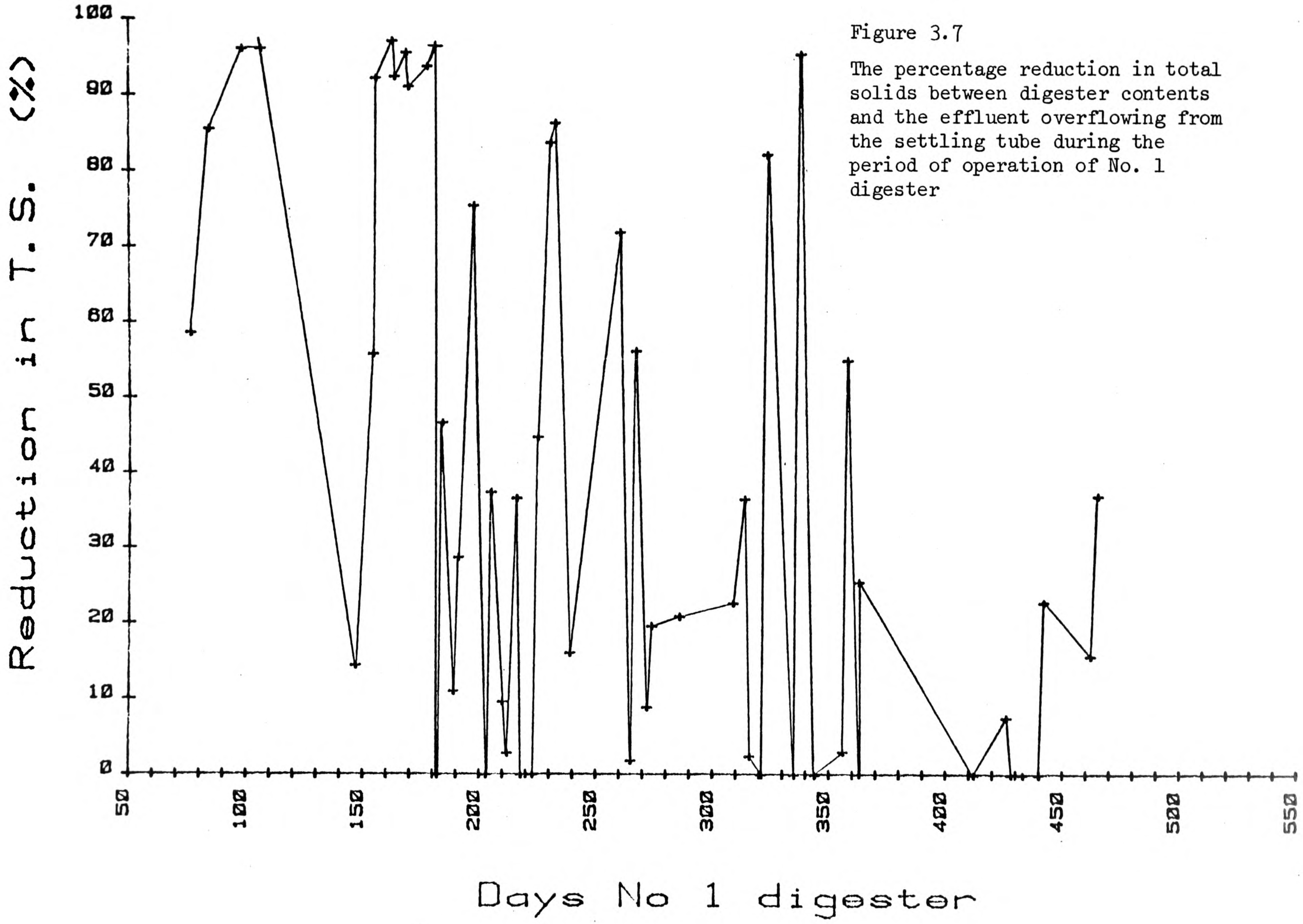


Figure 3.7

The percentage reduction in total solids between digester contents and the effluent overflowing from the settling tube during the period of operation of No. 1 digester

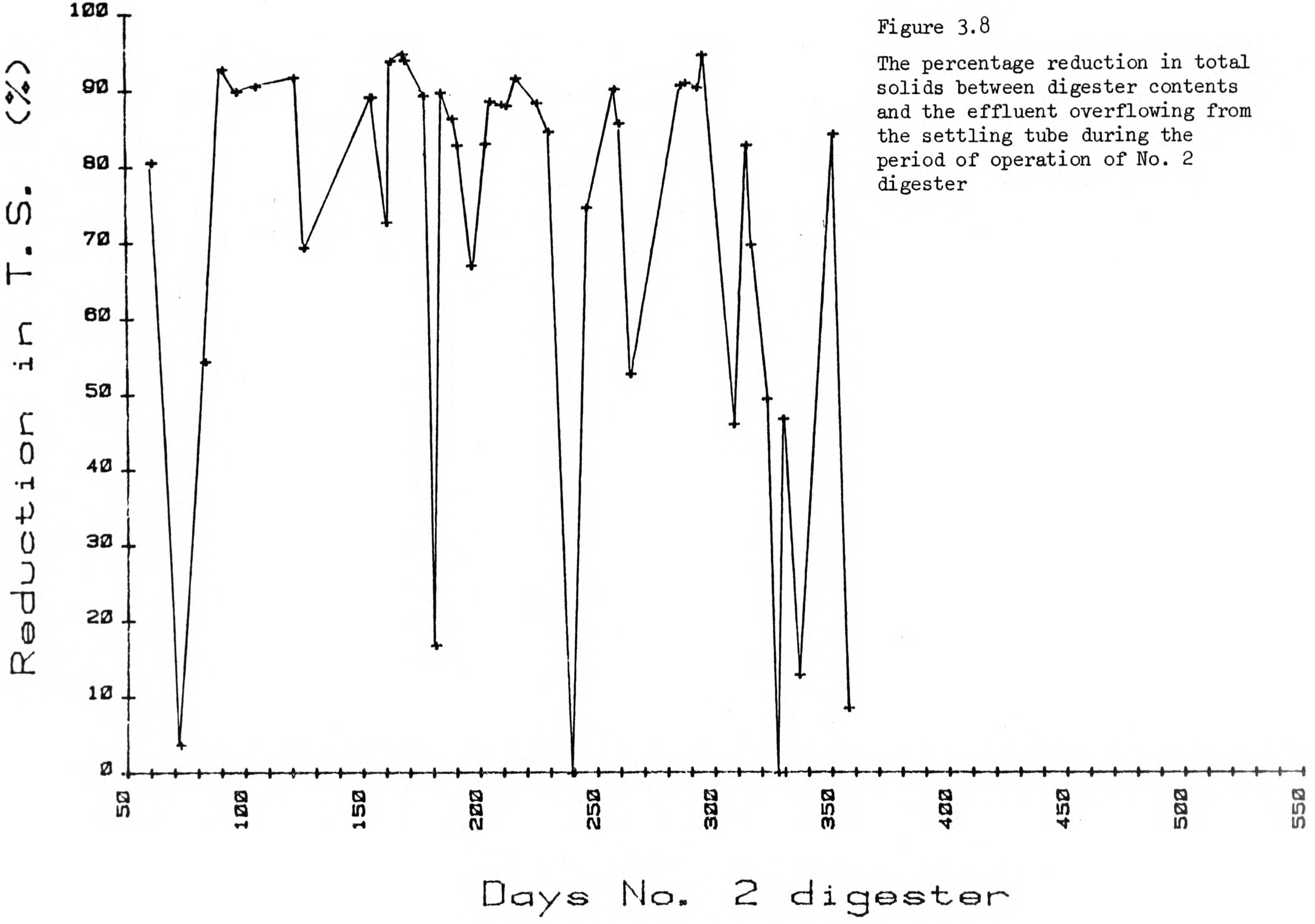


Figure 3.8

The percentage reduction in total solids between digester contents and the effluent overflowing from the settling tube during the period of operation of No. 2 digester an average of only 34% reduction in total solids. More sludge lift took place in this tube despite the fact that both digesters were operated as far as was possible in an identical manner using the same sludge. One factor which was different however was the initial seed, N^{o}1 from Avonmouth and N^{o}2 from Abergavenny Sewage Works.

A different population of bacteria could have resulted although this is doubtful since the gas production from both digesters was similar. The other more likely explanation is that the mixing was less vigorous in N^{o}2 digester than in N^{o}1.

Both were mixed by gas recirculation using double acting reciprocating gas pumps designed by Horton and Hawkes (Stafford et al 1980) delivering 70 l/min. Because of lack of development and the need for continuous service there were numerous breakdowns and a third pump was used whenever this occurred. Therefore since there was a continual changing of pumps on both digesters any variation in the flow rate between the three pumps was ironed out during the 1½ years of operation.

The electrical immersion heater on N^{o}2 digester failed (day 355) and was subsequently found to be coated with baked-on sludge (about 25 mm thick) which had caused overheating. This together with a scum which built up in the digester (neither of which occurred on N^{o}1 unit) also suggests lack of adequate mixing in N^{o}2 which was probably caused by a partially blocked diffuser.

3.4.F Gas Production

Gas production throughout the period fluctuated considerably due mainly to the lack of a consistent feed. The data for volume of gas produced during the period of the test is summarised in Figures 3.9 and 3.10. Figure 3.9 shows a break in the gas production graph between

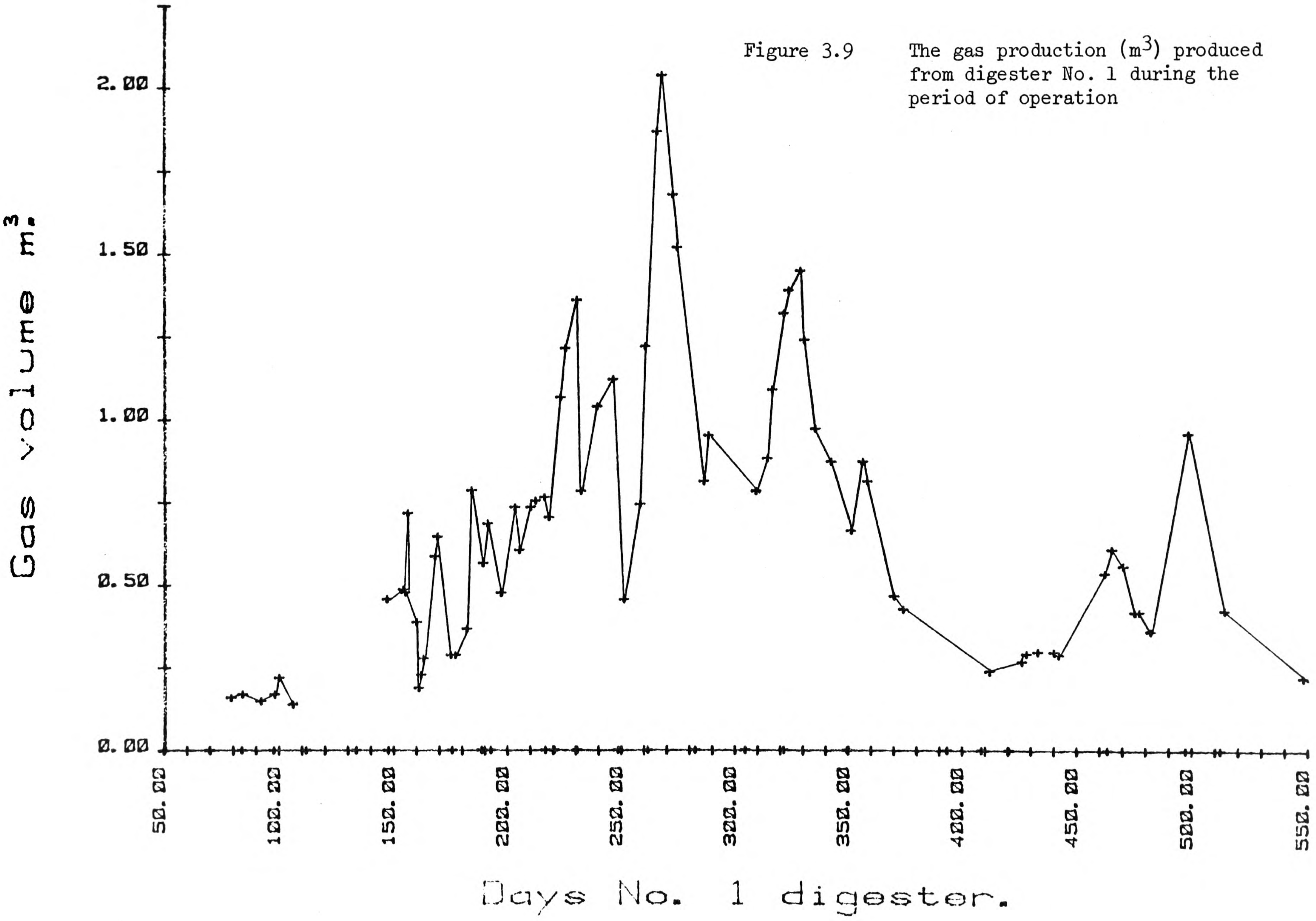


Figure 3.9 The gas production (m^3) produced from digester No. 1 during the period of operation

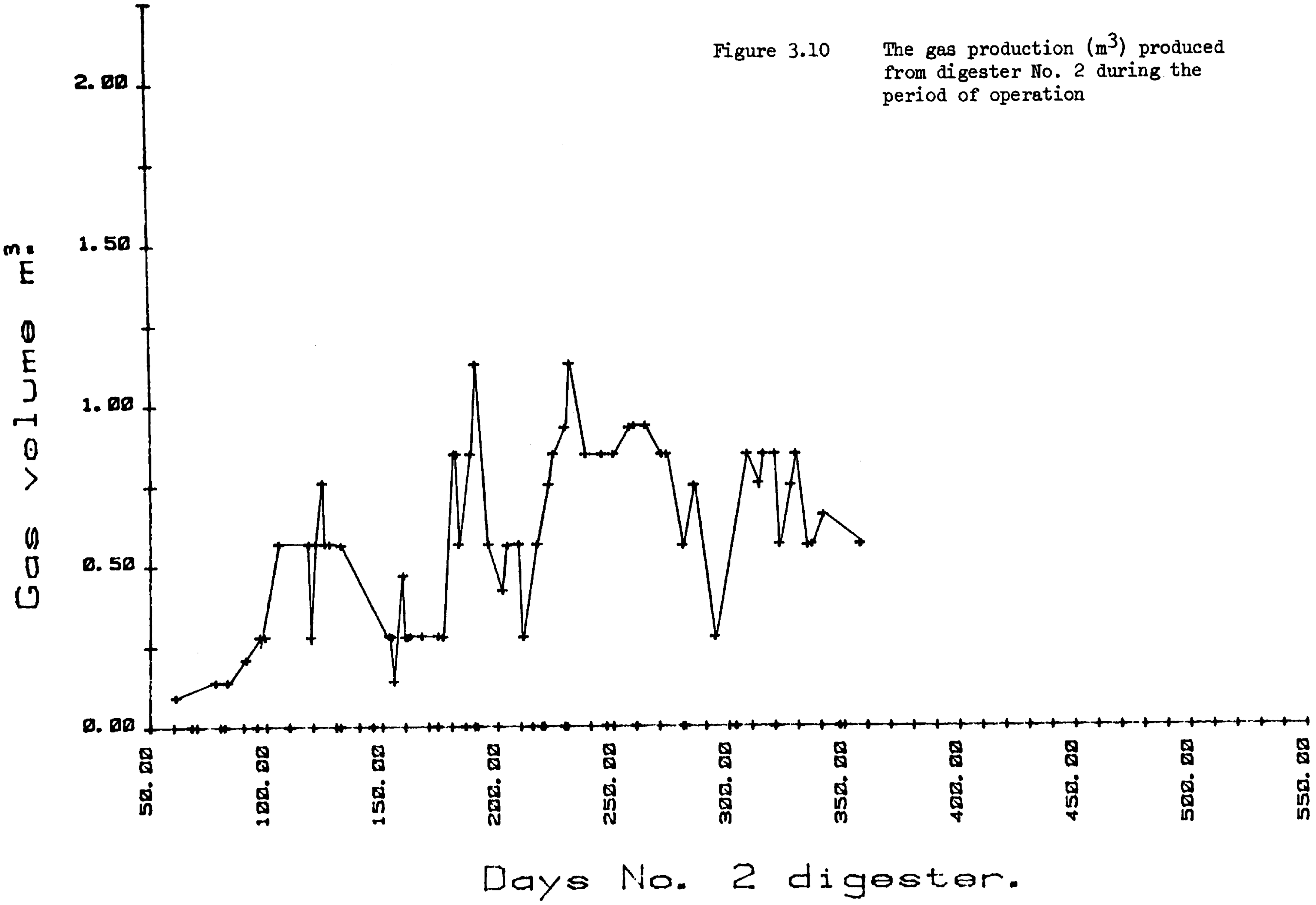


Figure 3.10 The gas production (m^3) produced from digester No. 2 during the period of operation

15th March (day 112) and 13th April (day 141). This was due to a gas leak which proved difficult to locate and repair. However apart from this and other occasional gas leaks from the pump pipework the two pilot plants were relatively free from this problem.

The highest gas production recorded during the test was on N°1 digester when the volume reached over 2 m^3 per day, this was during a delivery of sludge which averaged 4.1% TS (the overall average was 2.25%).

The gas volume was monitored each day using a Parkinson Cowan dry bellows gas meter of the type used in a domestic gas supply. This method proved very satisfactory and was an inexpensive and reliable way of measuring the flow.

The gas composition was also analysed daily, except weekends, using a Perkin Elmer gas liquid chromatograph fitted with a stainless steel column packed with Porapack T and operated at 60°C (see Section 3.3.E). We were grateful for the expert technical assistance of Mr. H. Hopkins, Department of Science, who provided these analyses.

The gas composition for digester N°1 is shown in Figure 3.11 and as can be seen it proved to be consistently high in methane with the range of between 65% and 75%. The methane content was similar for N°2 digester, and overall for both of them the average content was 70% CH_4 giving a gas with a calorific value of approximately 26 MJ/m^3.

On day 111 there was trouble with the gas pump on N°1 digester which broke down. This coincided with a new supply of feed material which meant that the methane proportion dropped to 43% and the carbon dioxide rose to 52%. The VFA also rose to 1100 mg/l by day 113. The pump was repaired on day 115 but since air was suspected to have

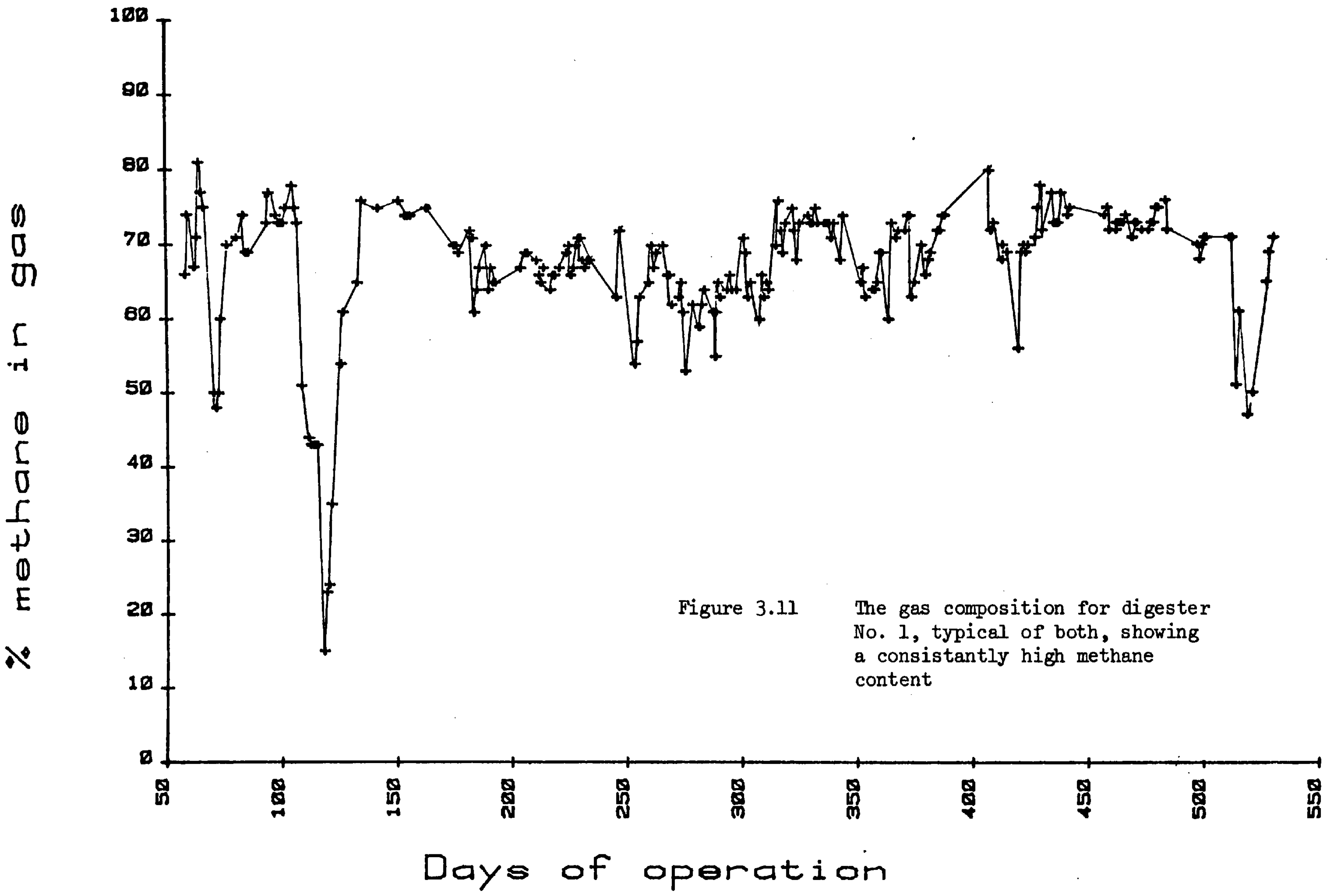


Figure 3.11 The gas composition for digester No. 1, typical of both, showing a consistantly high methane content

entered the digester the system was purged with car exhaust gas prior to reconnecting the repaired gas pump. This brought the CH_4 reading down to 15% with a CO_2 of 24% the remainder being mostly exhaust gases. The system recovered quickly however and by day 126 the CH_4 content was 61% and the CO_2 39%.

Since the volume of gas produced per day is dependent upon the feed solids a better indication of the performance of a digester than volume or gas composition is the gas yield. That is the volume of gas produced per mass of volatile solids added.

3.4.G Gas Production in Relation to Mixing Frequency

The W.R.C. gas meter described in Section 3.3.G was used to investigate the gas production during periods of mixing and feeding. This was in an endeavour to determine whether or not gas production was affected by different frequencies of mixing. A 3 channel chart recorder, J.J. Instruments model CR 305X, was used. One channel was connected to respond to the feed motor registering the periods during which the digester was being fed. A second channel was used to monitor the gas pump and record the periods for mixing. The third channel was connected to the gas meter. Each time the gas meter collecting chamber filled with gas the reed switch was operated causing a blip on the chart paper. Each blip corresponded to 147 ml of gas having passed through the meter.

A number of tests were conducted with the digester on the same feed routine but with different mixing. Although there was generally more gas produced whilst mixing was in progress this was found to be a temporary increase with a corresponding fall when mixing ceased. Figure 3.12 is typical of the results obtained and shows the gas

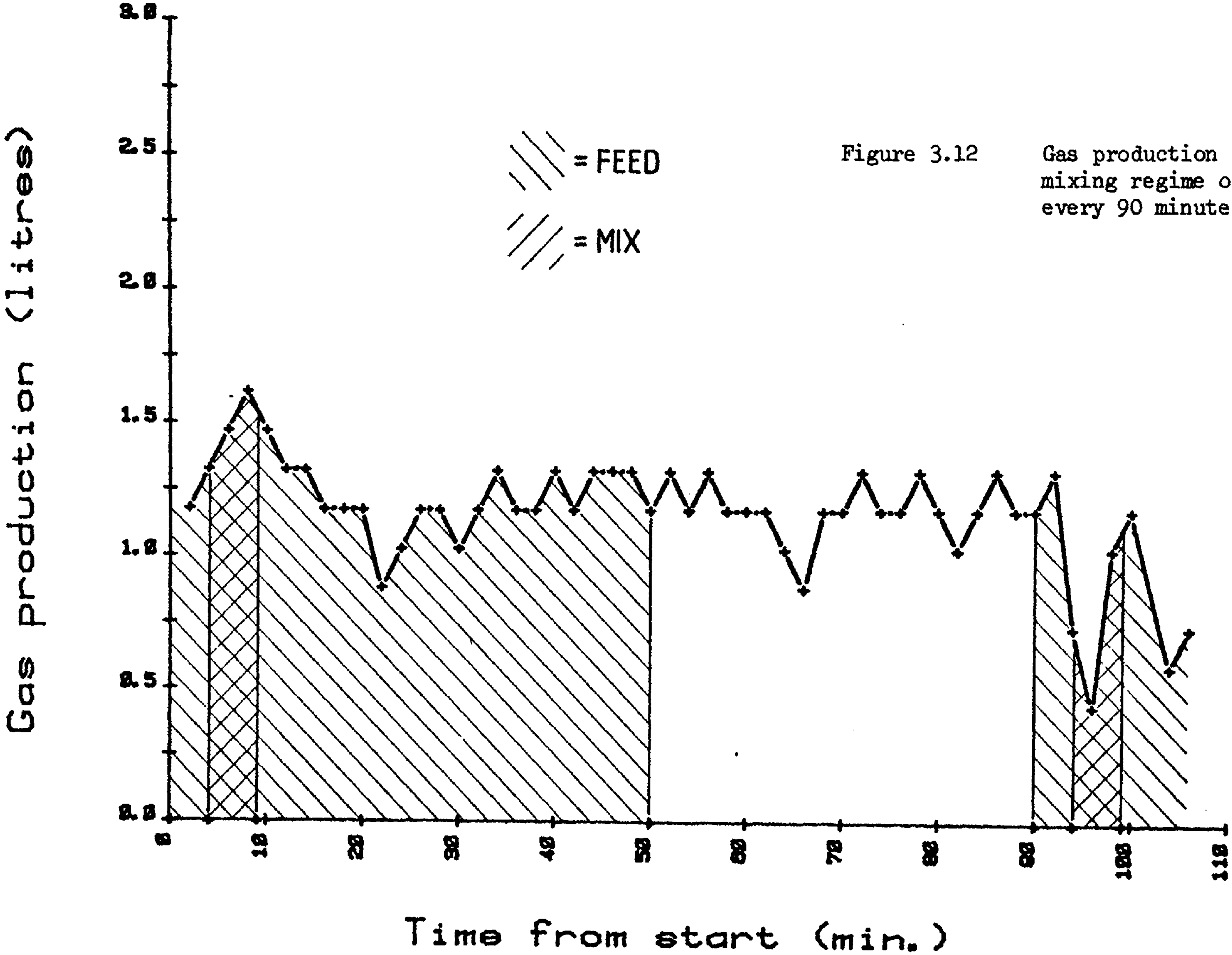


Figure 3.12 Gas production during a mixing regime of 5 minutes every 90 minutes

production in litres per 2 minute accounting period recorded on 7/7/1977 when the timing cycle for the digester feed was 50 minutes every 1½ hours.

The mixing routine was for 5 minutes every 1½ hours as shown in the figure. The average rate of gas production was 1.17 l per 2 minutes. Figure 3.13 is for the same circumstances except with a mixing regime of 5 minutes every 20 minutes. The variation in rate of gas production is greater although the overall average value is again 1.17 l. This comparison test was repeated on a number of occasions with similar results. These indicated that gas mixing frequency made no difference to the total volume of gas produced. The test should have been compared with no mixing whatsoever.

This was not attempted during this experimental period because of the possibility of a build-up occurring on the digester heating tube, with subsequent overheating, when there was no agitation for a long period. Because of other experimental work also being carried out it was necessary to avoid this possibility of damaging the heating tubes.

3.4.H Gas Yield

The gas yield is the volume of gas produced per mass of volatile matter added (m^3/kg VS added).

Figures 3.14 and 3.15 show the gas yield as a function of retention time for digesters 1 and 2 respectively. The figures show similar trends and Figure 3.16 is a summary of results from both digesters. These data show a wide variation in gas yield for given retention times which was undoubtedly caused by changes in the quality, age and composition, of the sludge fed to the digesters.

The summary of the gas production data and loading rates for both

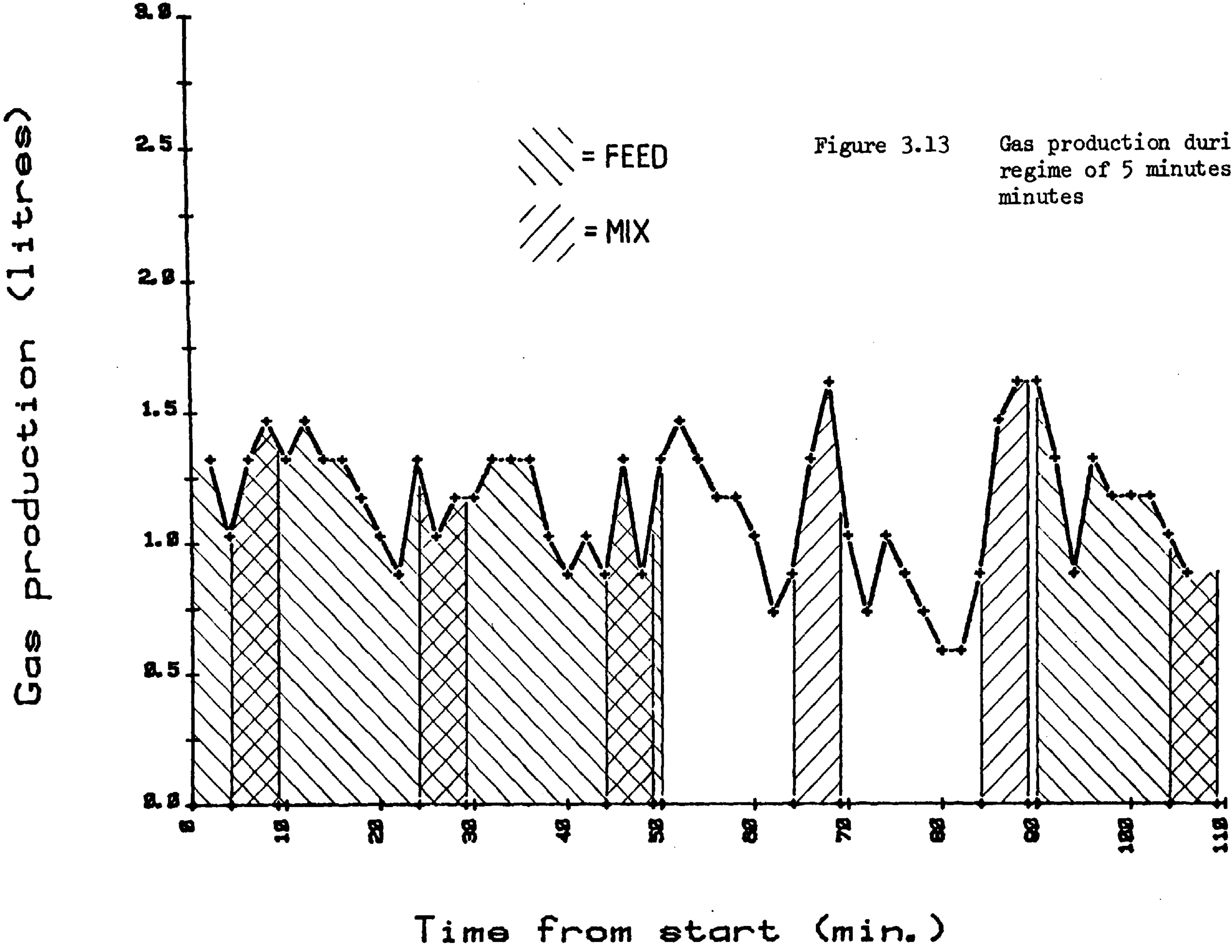
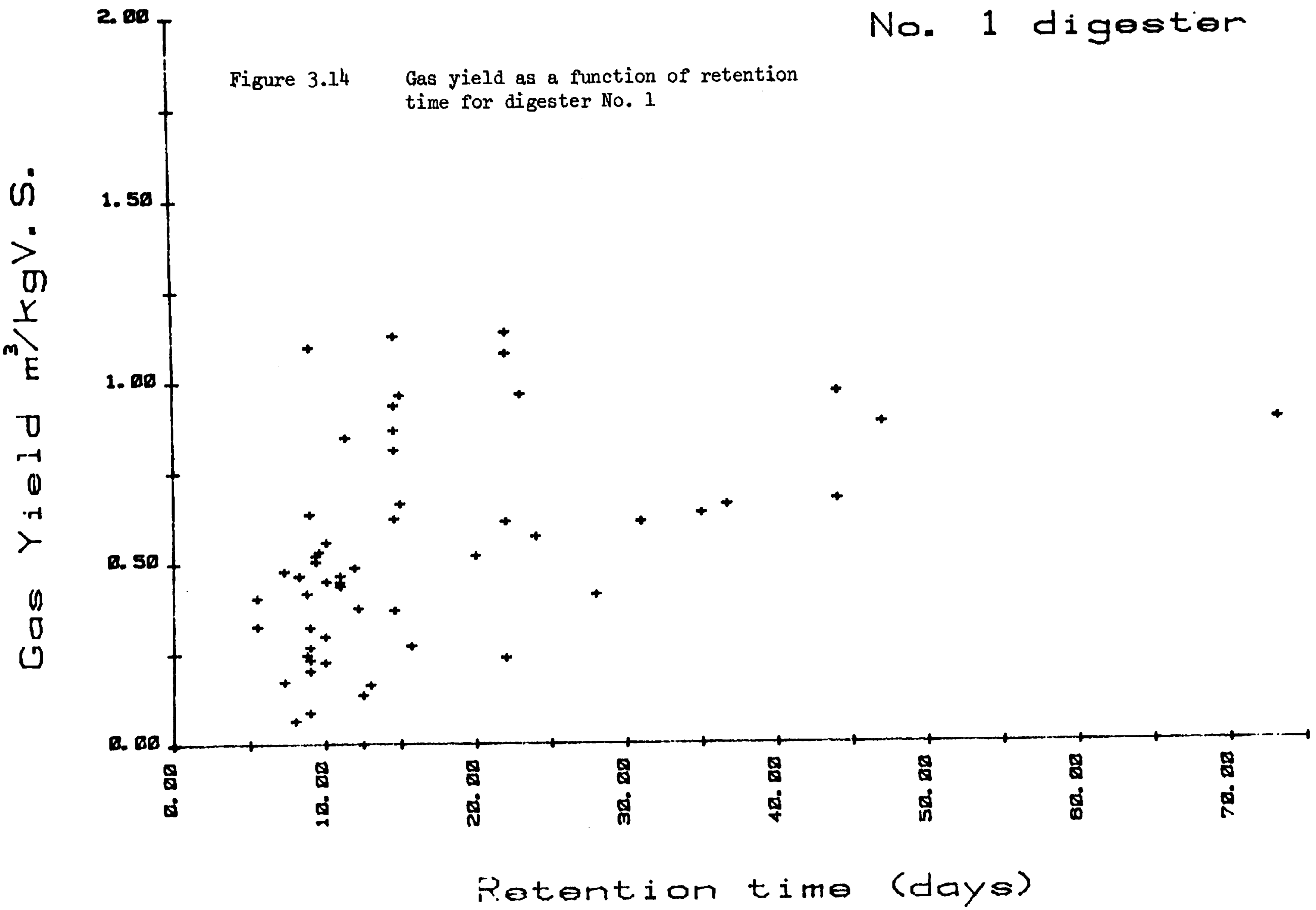


Figure 3.13 Gas production during a mixing regime of 5 minutes every 20 minutes

Figure 3.14 Gas yield as a function of retention time for digester No. 1



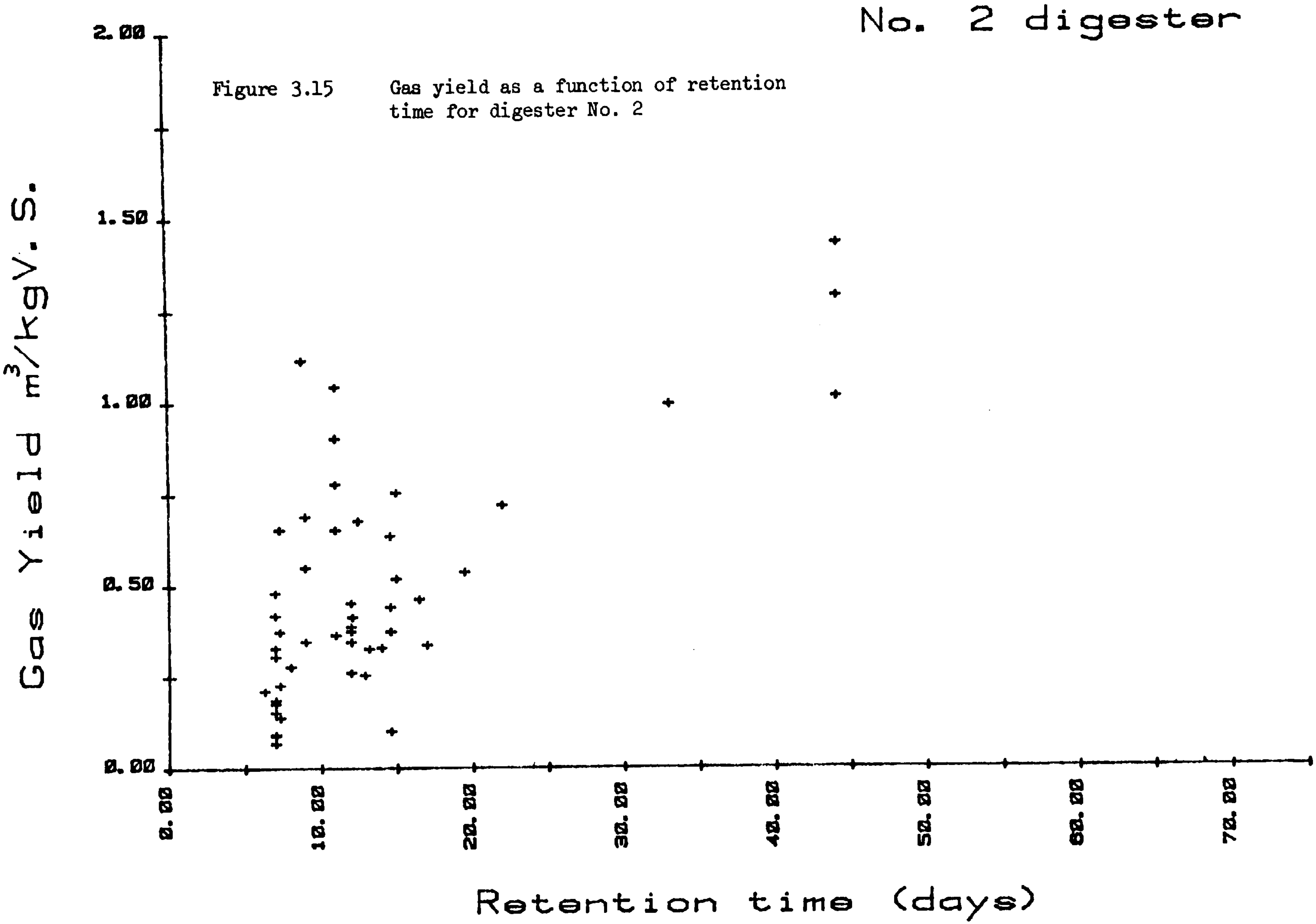


Figure 3.15 Gas yield as a function of retention time for digester No. 2

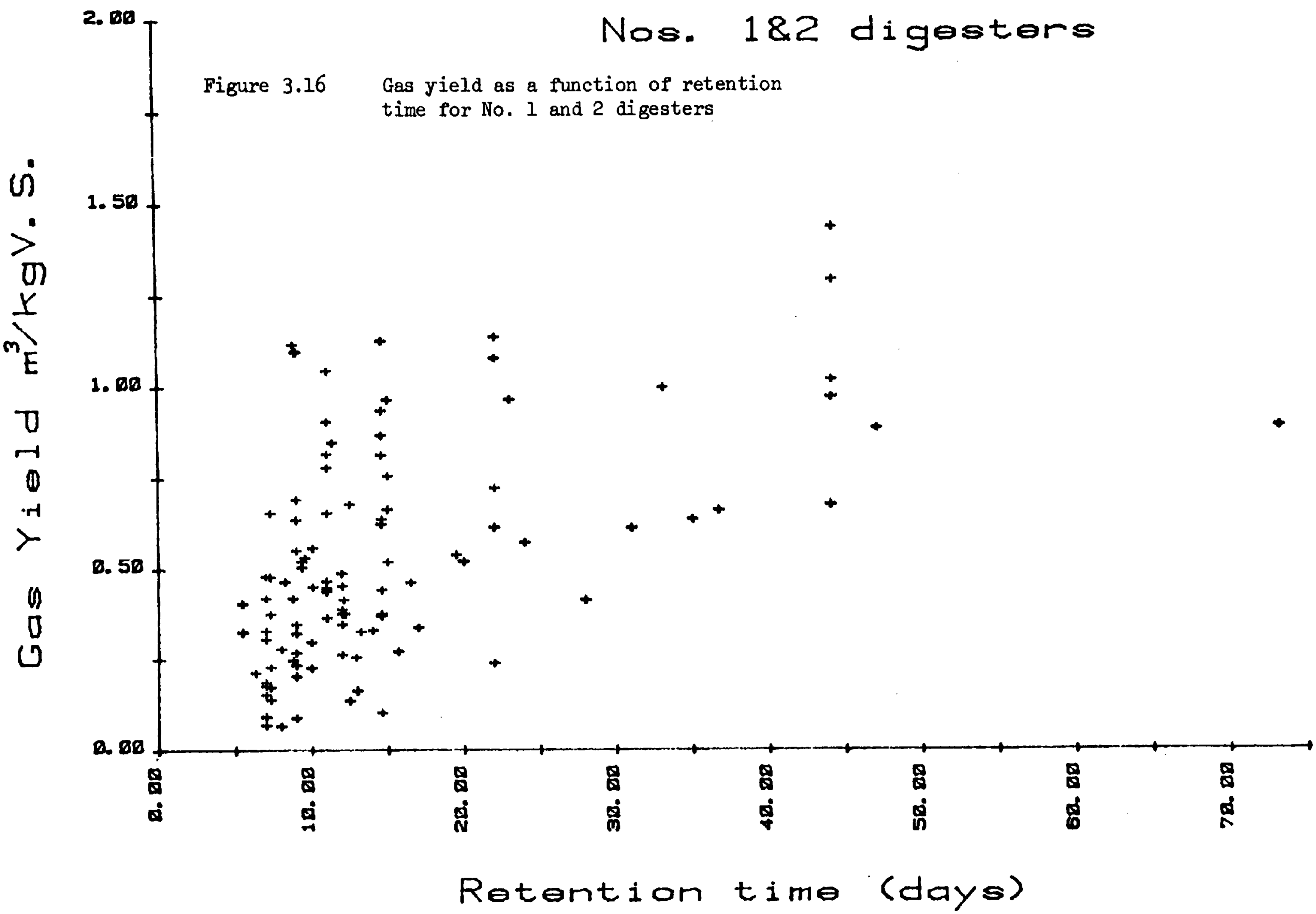


Figure 3.16 Gas yield as a function of retention time for No. 1 and 2 digesters

TABLE 3.3 Gas production data for No. 1 digester, using sewage sludge

	Day	Gas m^3	Feed		RT	Loading Rate kg VS/m^3/day	Gas Yield m^3/kg VS added	Code
			TS	VS				
NF 69	50							
NF 83	79	0.158	0.044	100	20	0.022	7.182	C
	84	0.169	1.830	85	12.5	1.244	0.136	
NF 97	92	0.153	0.074	91	9	0.075	2.040	C
	98	0.167	0.150	91	9	0.152	1.099	
NF 111	100	0.223	0.094	(91)	9	0.095	2.347	B
NF 133	106	0.141	1.972	88	8	2.169	0.065	
NF147	147	0.458	4.602	79	13	2.797	0.164	
	154	0.489	1.340	86	11	1.047	0.467	
	155	0.475	1.510	79	11	1.084	0.438	
	156	0.721	1.440	(79)	11	1.034	0.697	B
	160	0.396	0.299	59	10	0.176	2.250	C
	161	0.186	0.140	93	10	0.130	1.430	C
	162	0.226	1.250	80	10	1.000	0.226	
	163	0.275	1.087	85	10	0.924	0.298	
	168	0.586	2.180	75	9	1.817	0.323	
	169	0.651	2.880	76	9	2.432	0.268	
NF 175	175	0.288	3.658	80	9	3.251	0.088	
	177	0.288	0.295	86	9	1.237	0.233	
	182	0.365	1.976	82	9	1.800	0.203	
NF 188	184	0.792	1.385	81	9	1.246	0.636	
	189	0.566	2.290	89	22	0.920	0.615	

NF 192	191	0.690	1.547	86	22	0.605	1.140	
	197	0.481	2.172	85	(20)	0.923	0.521	
	203	0.736	1.887	88	15	1.107	0.665	
	205	0.606	1.145	86	14.6	0.674	0.937	
	210	0.744	1.870	81	22	0.688	1.081	
	212	0.761	1.143	86	14.6	0.673	1.130	
NF 216	216	0.767	2.353	80	11	1.711	0.448	
NF 220	218	0.708	3.460	73	8.8	2.870	0.247	
	223	1.075	2.339	83	9.4	2.065	0.521	
	225	1.223	3.102	83	8.8	2.926	0.418	
NF 230	230	1.368	2.970	82	8.3	2.934	0.466	
	232	0.792	2.258	82	14.6	1.268	0.624	
	239	1.047	2.100	84	5.5	3.207	0.326	
NF 248	246	1.132	1.580	84	22	0.603	1.877	C
	251	0.462	2.850	82	31	0.754	0.613	
	258	0.754	4.050	70	8.3	3.415	0.221	C
NF 261	260	1.228	2.150	87	7.3	2.562	0.479	
	265	1.877	4.590	74	10.1	3.363	0.558	
	267	2.052	3.630	77	5.5	5.082	0.404	
	272	1.688	4.190	75	9.4	3.343	0.505	
NF 282	274	1.528	3.510	78	14.6	1.875	0.815	
	286	0.821	4.500	77	7.3	4.746	0.173	
NF 304	288	0.962	0.990	77	11	0.692	1.390	C
	309	0.792	4.000	78	14.6	2.136	0.371	
	314	0.886	2.790	78	12	1.813	0.489	
	316	1.104	2.380	78	14.6	1.271	0.869	
NF 321	321	1.330	3.816	(78)	10.1	2.947	0.451	

	323	1.401	3.245	(78)	9.6	2.637	0.531	
	328	1.457	2.678	73	11.4	1.715	0.849	
	330	1.245	1.678	(74)	17	0.721	1.726	C
	335	0.976	2.050	74	15	1.011	0.966	
NF 349	342	0.877	1.460	74	23.5	0.460	1.907	C
	351	0.671	6.254	(70)	44	0.994	0.675	
	356	0.877	7.219	(70)	15.7	3.218	0.272	
	358	0.821	6.508	(70)	36.7	1.241	0.661	
	370	0.473	5.740	77	330	0.133	3.556	F
FW 393	374	0.425	(5.0)	(70)	73	0.479	0.887	
EA 408	412	0.238	0.737	77	23	0.246	0.967	
EA 420	426	0.266	1.765	80	47	0.300	0.886	
	428	0.294	3.502	77	22	1.226	0.239	
	433	0.303	2.569	80	28	0.734	0.413	
	440	0.299	2.080	79	35	0.469	0.637	
	442	0.289	1.186	79	12.2	0.768	0.376	
EA 463	462	0.538	3.334	73	44	0.553	0.972	
	465	0.611	3.324	77	24	1.066	0.573	
	470	0.555	0.189	74	14.6	0.108	5.106	C
	475	0.416	0.747	85	17	0.374	1.114	C
	477	0.419	0.508	84	22	0.194	2.161	C
FW 497	482	0.362	0.475	84	12.7	0.314	1.152	C
NF 512	498	0.962	12.300	70	44	1.957	0.492	C
	514	0.425	3.904	80	17	1.837	0.231	C
	548	0.221	5.430	77	8.8	4.751	0.047	C
	550							

CODES

A	Gas volume is unreasonably low.
B	Gas volume is unreasonably high.
C	Recent change in TS feed, unreliable reading.
D	Mechanical problems, unreliable readings.
E	Gas leaks subsequently found, unreliable readings for gas volume therefore.
F	R.T. just drastically changed, unreliable reading for gas yield therefore.
NF	New feed.
FW	Feed watered down.
EA	Effluent added.

TABLE 3.4 Gas production data for No. 2 digester, using sewage sludge

	Day	Gas	Feed		R.T.	Loading Rate	Gas Yield	Code
		m^3	% TS	% VS	Days	kg VS/m^3/day	m^3/kg VS added	
	50							
NF 68	61	0.094	0.249	(75)	15	0.125	0.757	
NF 82	78	0.142	0.155	96	11	0.135	1.046	
	83	0.142	0.306	85	12.5	0.208	0.679	
NF 96	91	0.212	0.304	91	9	0.307	0.691	
	97	0.263	0.950	77	9	0.8128	0.348	
	99	0.283	0.600	(77)	9	0.5133	0.551	
NF 110	105	0.566	1.930	84	8	2.026	0.279	
	118	0.566	2.100	86	12	1.505	0.376	
	119	0.283	1.380	64	12	0.736	0.385	A
	121	0.566	3.190	81	12	2.153	0.263	
	124	0.755	2.210	79	12	1.455	0.519	B
	125	0.566	2.270	77	12	1.457	0.389	
	127	0.566	2.120	(77)	15	1.088	0.520	
NF 132	132	0.566	2.970	83	14	1.761	0.331	
NF 146	153	0.283	1.270	77	12	0.815	0.347	
	154	0.283	0.960	78	12	0.624	0.454	
	155	0.142	1.290	(78)	12	0.839	0.168	A
	159	0.472	1.200	74	10	0.888	0.531	B
	160	0.283	1.800	72	7	1.851	0.153	
	161	0.283	1.010	75	7	1.082	0.306	
	162	0.283	1.310	81	7	1.516	0.187	
	167	0.283	3.540	62	7	3.135	0.090	

NF 174	174	0.283	3.770	77	7	4.147	0.068	
	176	0.283	2.650	79	7	3.028	0.093	
	181	0.849	1.650	86	7	2.027	0.419	
	182	0.849	2.100	(86)	7	2.579	0.329	
NF 186	183	0.566	2.760	81	7	3.194	0.177	
	188	0.849	1.780	80	11	1.295	0.655	
NF 191	190	1.132	1.080	81	11	0.795	1.423	B
	196	0.569	0.440	91	8.8	0.455	1.119	
	202	0.425	1.170	83	7	0.883	0.481	
	204	0.566	0.950	84	11	0.725	0.780	
	209	0.566	0.790	87	11	0.625	0.906	
	211	0.283	1.770	84	7.3	2.037	0.139	
NF 215	215	0.472	2.150	78	16.5	1.016	0.464	
NF 219	217	0.566	0.450	86	(15)	0.258	2.195	C
	222	0.755	2.670	85	11	2.063	0.366	
	224	0.849	3.630	77	14.6	1.914	0.443	
NF 229	229	0.934	3.280	83	12.1	2.249	0.415	
	231	1.132	1.880	81	11	1.384	0.818	B
	238	0.849	3.320	76	6.3	4.005	0.212	
NF 247	245	0.849	1.460	85	22	0.564	1.505	C
	250	0.849	4.520	71	66	0.486	1.746	D
	257	0.934	1.270	82	7.3	1.427	0.655	
NF 260	259	(0.940)	2.260	81	7.3	2.508	0.375	
	264	(0.940)	4.980	78	13.2	2.867	0.328	
	271	0.849	3.490	(78)	7.3	3.729	0.228	
	273	0.849	3.370	79	44	0.605	1.403	E
NF 281	280	0.566	5.070	(79)	00	-	-	

	285	0.753	3.700	(79)	14.6	2.002	0.376	
NF 303	294	0.283	5.140	(79)	14.6	2.781	0.102	
	308	0.849	4.700	78	44	0.833	1.019	
	313	0.755	3.290	78	44	0.583	1.294	
	315	0.849	3.330	78	44	0.590	1.438	
NF 320	320	0.849	3.240	(78)	22	1.149	0.739	E
	322	0.566	3.640	(78)	17	1.670	0.339	
	327	0.753	3.490	78	19.5	1.396	0.539	
	329	0.849	3.310	(78)	22	1.174	0.723	
	334	0.566	3.050	78	22	1.081	0.523	E
	336	0.566	1.660	(78)	14.6	0.887	0.638	
NF 348	341	0.659	2.830	77	33	0.660	0.999	
	357	0.566	3.900	73	12.9	2.207	0.256	
	550							

CODES

A	Gas volume is unreasonably low.
B	Gas volume is unreasonably high.
C	Recent change in T.S. feed, unreliable reading.
D	Mechanical problems, unreliable reading.
E	Gas leak subsequently found, unreliable reading for gas volume.
F	R.T. just drastically changed, unreliable reading for gas yield.
NF	New feed

reactors are given in tables 3.3 and 3.4.

These tables include all the data for which both gas volumes, feed solids and retention time were known, and whilst the digesters were functioning correctly. Code letters in the final column specify data which for various reasons was considered unreliable and therefore was not included in the graphs. As can be seen from the tables, one potentially large source of error was in the calculation of gas yields for periods in which one retention time at least had not been completed. This is particularly noticeable on the longer retention times when circumstances such as a mechanical breakdown or a change of feed sometimes forced a change in retention before even one retention period had been achieved.

Figure 3.17 is a plot of gas yield expressed as a function of loading rate and this suggests that for an increased loading rate (kg VS added/m^3 digester/day) there is a decrease in the gas yield. For an infinitely long retention time the loading rate is zero and so the point at which a curve through these points cuts the y axis would correspond to the value of gas yield at an infinitely long retention time, that is, the ultimate gas yield for this feed material.

Although there is a wide scatter in the data an attempt was made to estimate this ultimate gas yield by plotting the log of the gas yield against loading rate. The best fit straight line is shown in Figure 3.18 for N^{o}2 digester and resulted in gas yield axis intercept of 1.017, that is the ultimate gas yield for this material is 1.017 m^3/kg VS added.

This is theoretically possible since 1 kg of fatty acid could produce 1.4 m^3 of gas (see chapter 1.2.A).

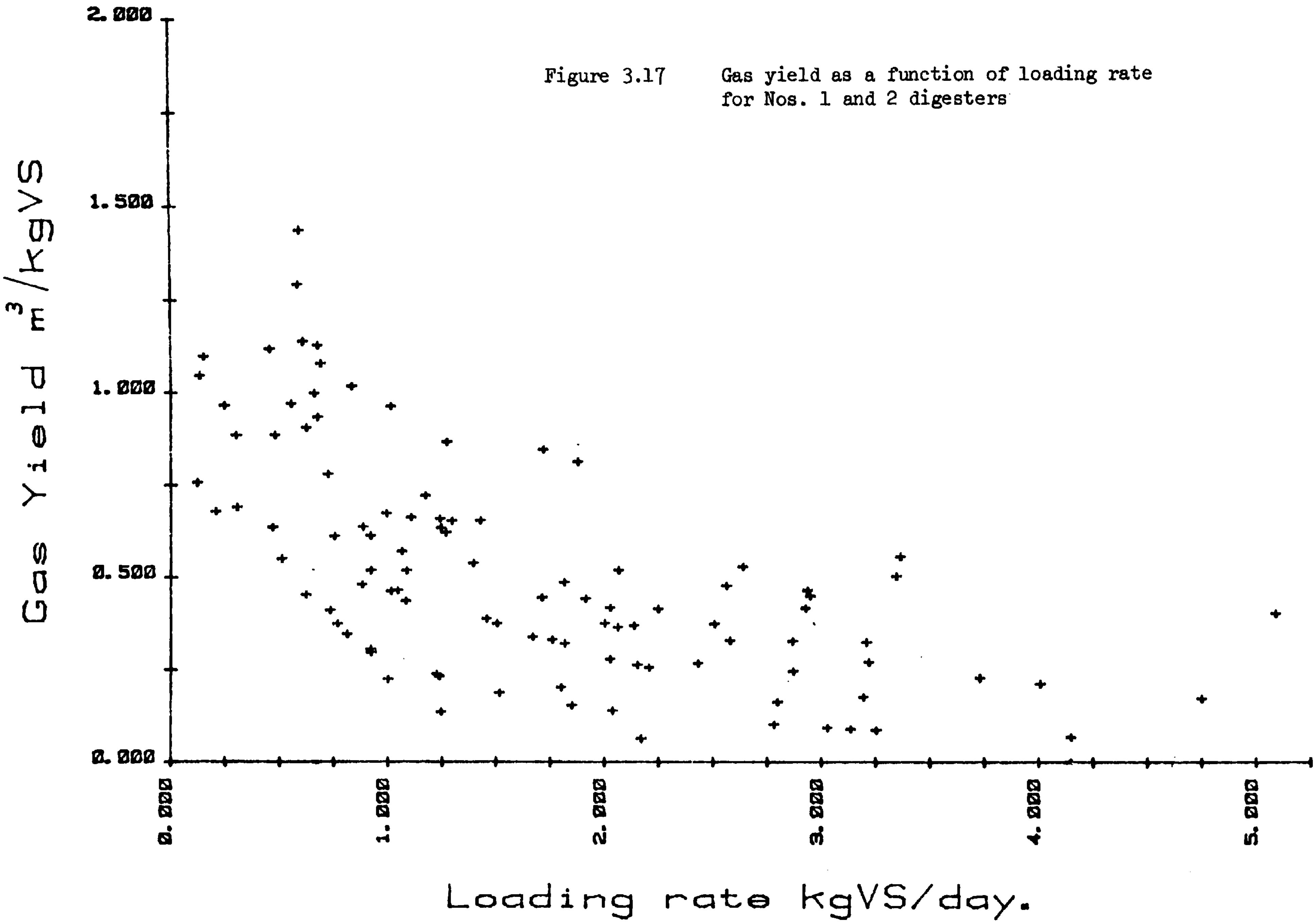


Figure 3.17 Gas yield as a function of loading rate for Nos. 1 and 2 digesters

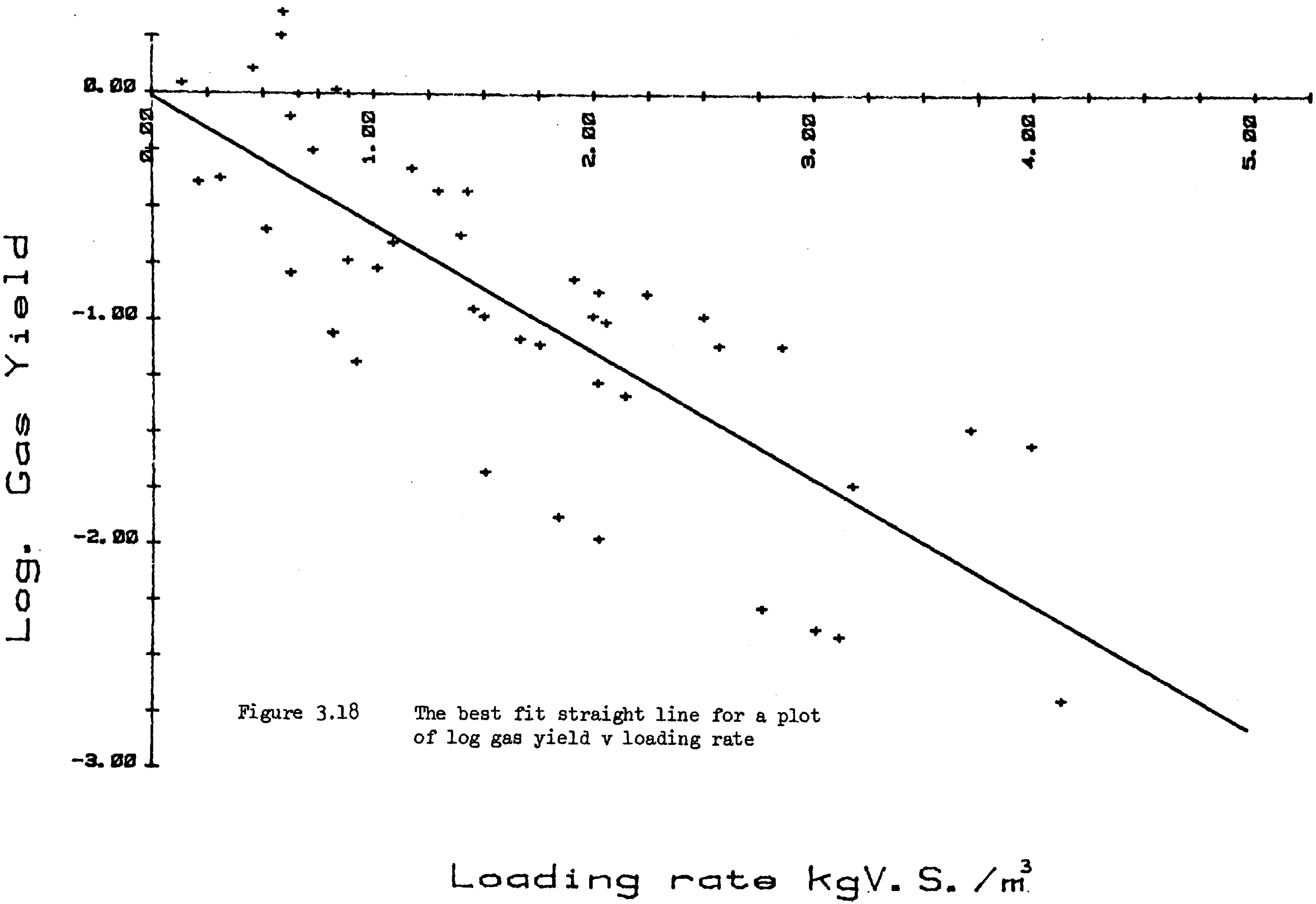


Figure 3.18 The best fit straight line for a plot of log gas yield v loading rate

The correlation coefficient, the quantity which indicates the overall goodness of fit of the regression line, for the results from digester No. 2 is - 0.798 and for the combined results of both 1 and 2 digesters is - 0.634.

The implication of the gas yield versus loading rate relationship being non-linear is that if the relationship were known more accurately it could be used in digester design to optimise for maximum gas production using a simple computer model. It was decided to investigate this relationship, and its incorporation into a computer model.

CHAPTER FOUR

THE RELATIONSHIP BETWEEN LOADING RATE AND GAS YIELD

4.1 Introduction

It is believed that for some wastes, for example pig slurry, the gas yield increases to a maximum at a particular retention time, say ten days, and thereafter even with an increased retention time the gas yield remains constant (Hobson 1978). Expressed on a gas yield : retention time graph this would appear as in Figure 4.1.

In this figure the horizontal part of the graph 2 - 1 would appear as a horizontal line, A - B, on the gas yield : loading rate graph in Figure 4.2. The sloping line 1 - 0 in Figure 4.1 represents the line B - C on the gas yield : loading rate graph.

The line B - C must approach zero gas yield when the loading rate is very high. The point A represents an infinitely long retention time for any particular feed solids. Point B represents the ten day retention time shown in Figure 4.1 as point 1.

Where this is an accurate representation of the situation it implies that all of the potentially biodegradable material is being used up by the bacteria within ten days. This also implies that for a continuously loaded digester operating on a ten day retention time, if the feed were suddenly stopped then the gas production would decrease until after a further ten days no more gas would be produced. This situation is shown diagramatically in Figure 4.3. The implications of this for the design of digesters is that for maximum net gas production and minimum digester cost, the digester should be run at a ten day retention time. This is exemplified by the following example.

Assume that a digester is utilising pig waste with a daily feed of 18 tonnes at 4% solids of which 70% is volatile; this amount of waste would be produced by about 2000 pigs. As can be seen from the previous

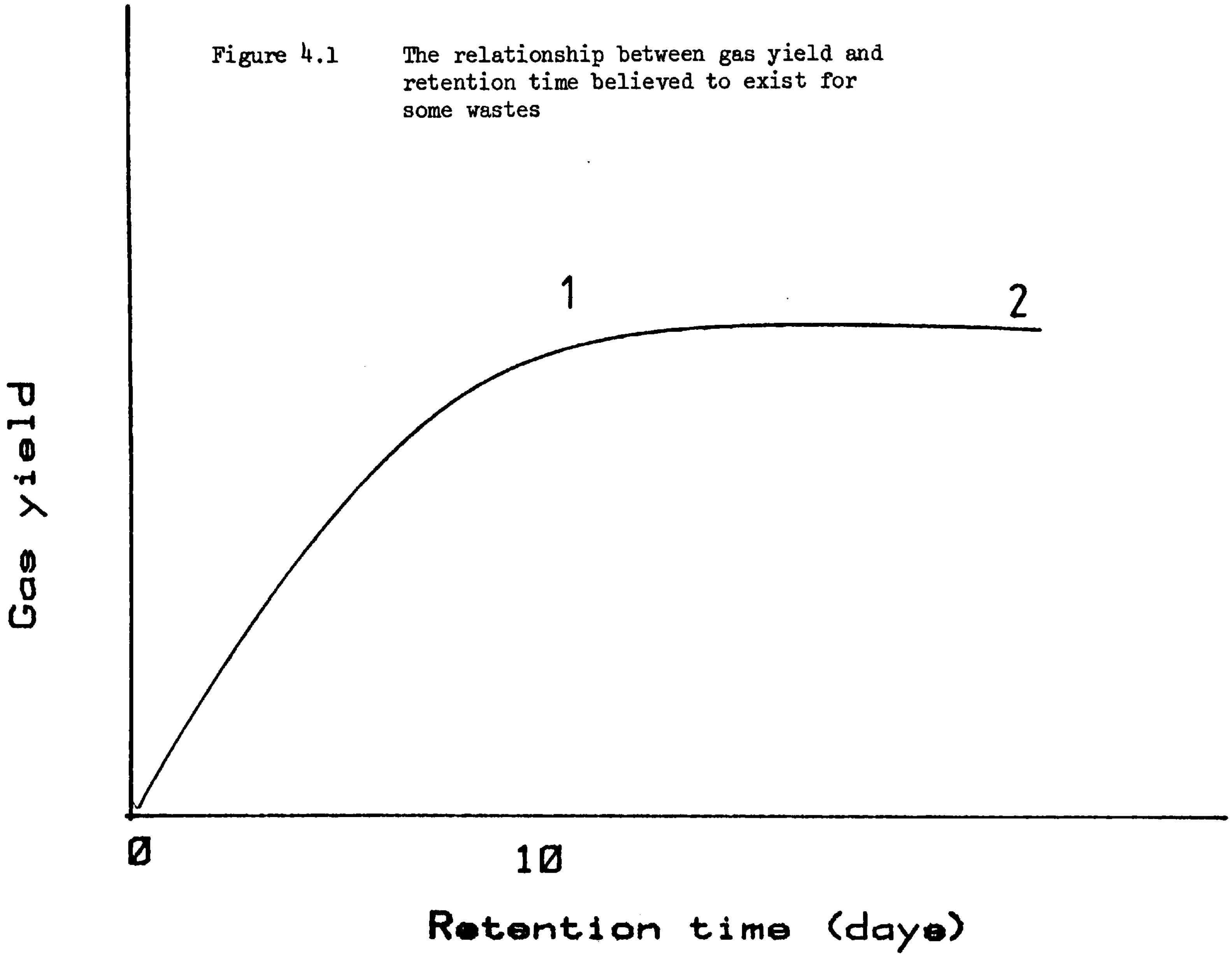


Figure 4.1 The relationship between gas yield and retention time believed to exist for some wastes

Figure 4.2 The same information as for Figure 4.1 plotted as a graph of gas yield versus loading rate

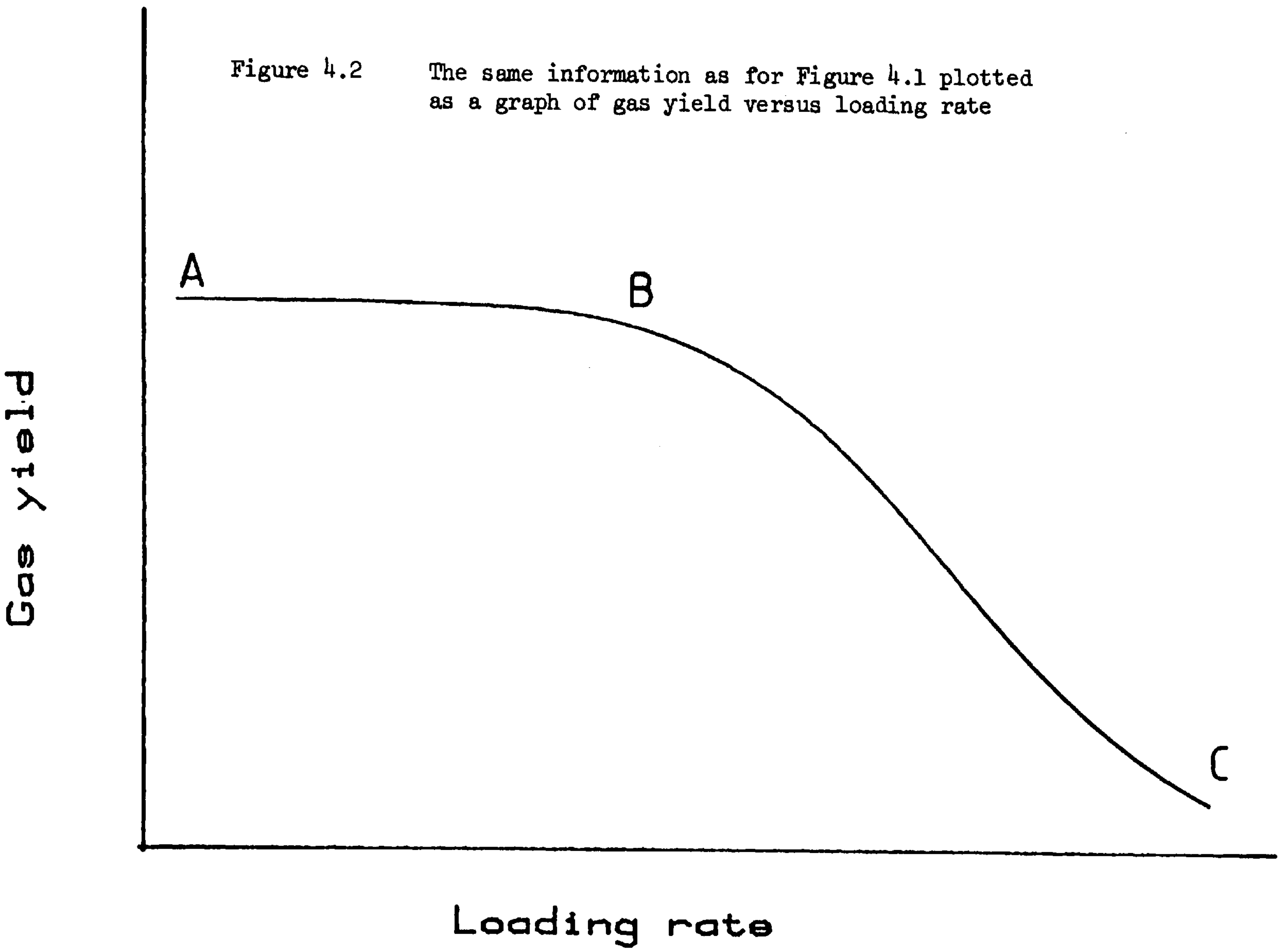
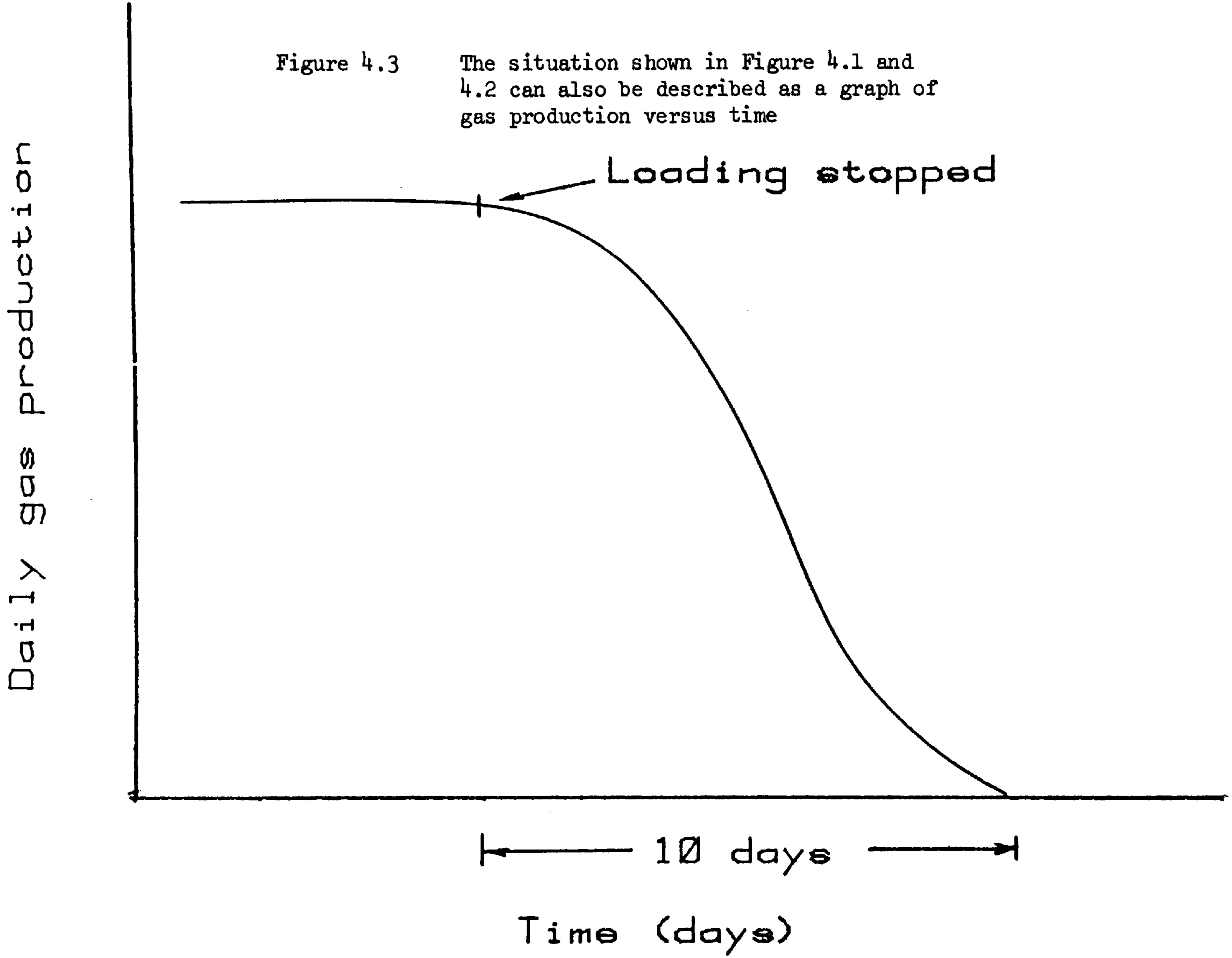


Figure 4.3 The situation shown in Figure 4.1 and 4.2 can also be described as a graph of gas production versus time



figures if the gas yield were constant above a ten day retention period there is no advantage in keeping the waste in the digester for longer than this. The volume of gas generated is assumed to be 0.4 m^3 per kilogram of volatile solids fed to the digester at a ten day retention time or longer (Hobson 1978). Part of the gas would be used to maintain the digester at its optimum temperature, 35°C. The majority of the energy required for this would be used to heat up the incoming feed and some is needed to make up the losses through the digester walls. In the example chosen it is assumed that the ambient temperature is 10°C and the insulation of the digester is sufficient to give an overall U factor of 0.78 and 0.64 watts per square metre °K for the walls and roof respectively (about 50 mm mineral wool or equivalent protected by weathersealed skin).

There will be an increase in heat losses through the digester surface as the design capacity is increased to give a longer retention time whilst still treating the same volume of waste but the energy necessary to heat the influent would be constant since the amount of waste is the same, at eighteen tonnes per day. Assuming these conditions, and a boiler efficiency of 60%, the net energy produced from such a digester at various retention times may be calculated. The results are shown in Figure 4.4.

This shows clearly that above a ten day retention time the net energy produced would get less and there would be therefore no advantage in having a longer retention period.

4.2 Sewage Sludge

Whilst Figure 4.1 appears to be the case for certain wastes, other research, including that reported here, shows a relationship between

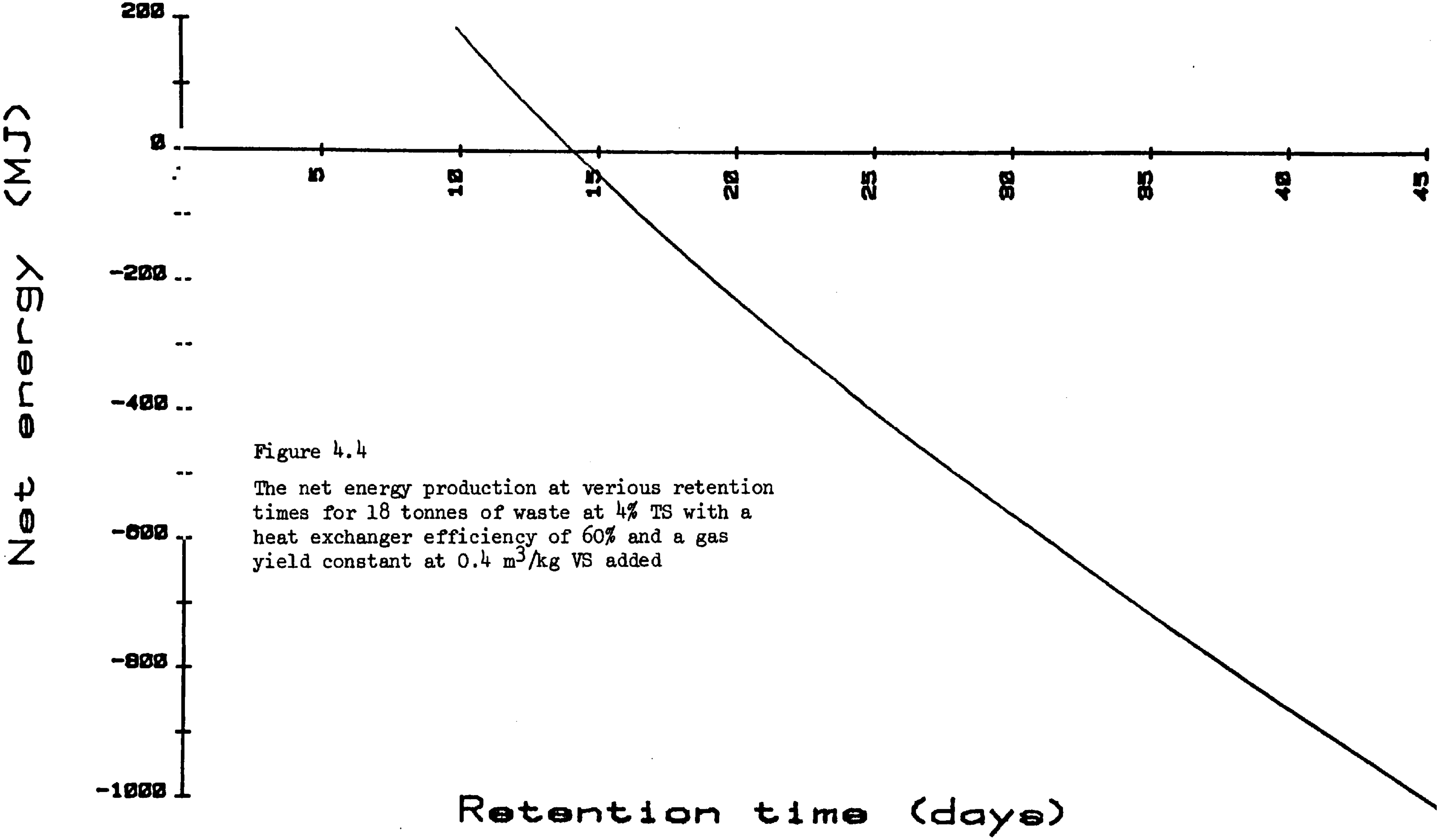


Figure 4.4

The net energy production at verious retention times for 18 tonnes of waste at 4% TS with a heat exchanger efficiency of 60% and a gas yield constant at 0.4 m^3/kg VS added gas yield and loading rate that does not reach a maximum figure at a relatively low retention period and then level off.

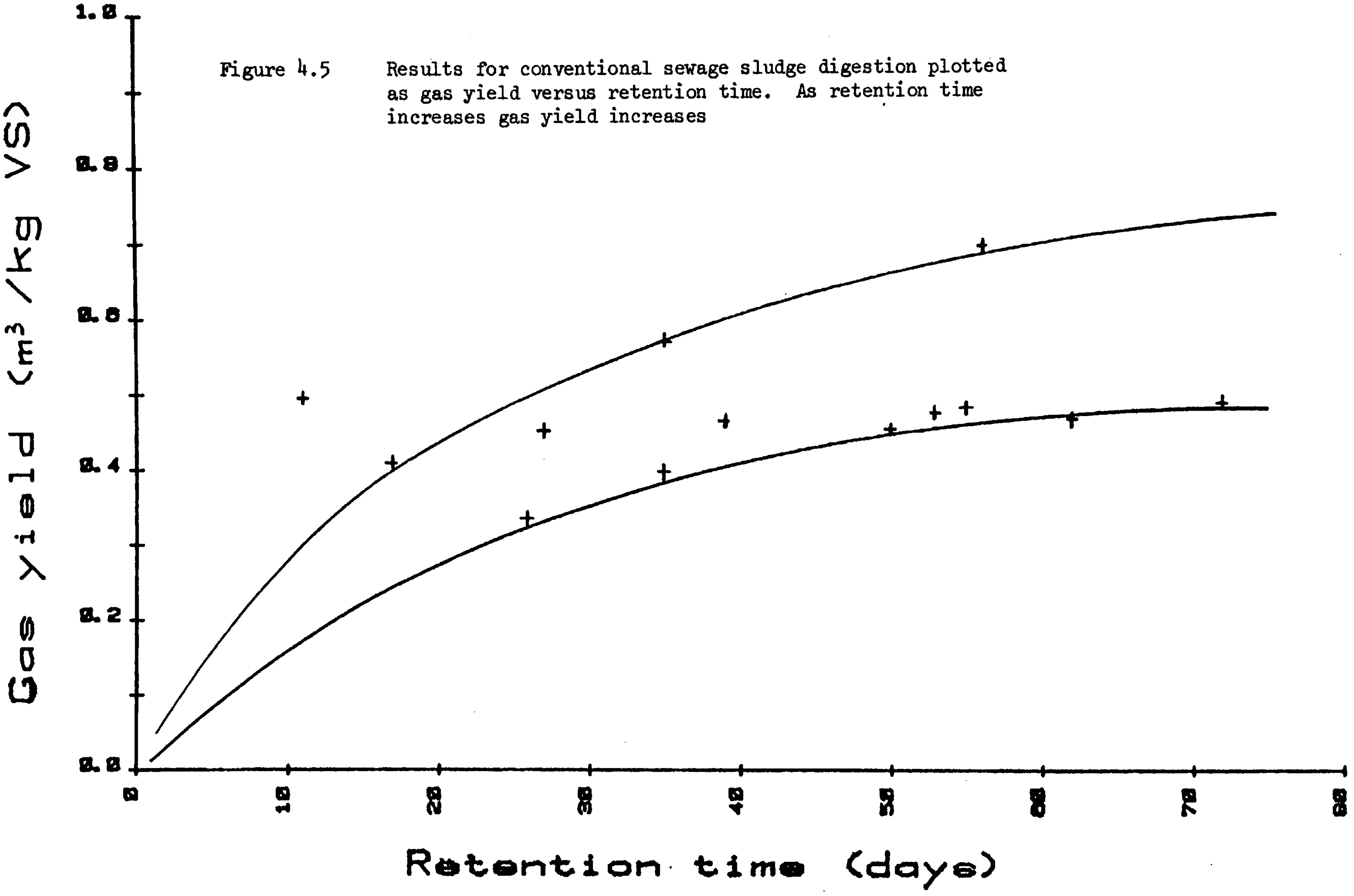
For example an investigation carried out by Rankin (Rankin 1948) on full scale conventional sewage digesters showed results for gas yield that when plotted on a gas yield : retention time graph, Figure 4.5, continue to increase as retention time increases. (All the points except one fall within the band shown.) These results when expressed as a function of loading rate appear as in Figure 4.6.

A likely curve through these points which must approach zero gas yield at infinite loading rate would appear to curl up as the loading rate decreases. The shape of this curve and the rate of increase of the slope influences digester design significantly. By applying this curve to the design of a digester to cater for the sewage treatment needs of a small community (1000 population) it can be seen that in this case the maximum net gas would be produced at a 35 day retention period, see Figure 4.7, providing that the relationship shown in Figures 4.5 and 4.6 apply. (See appendix B for calculation of net energy.)

The results of other experiments on both laboratory scale and full size digesters working at 35°C were examined and appear in Table 4.1

Torpey (1955) working with a pilot scale digester with a sludge volume maintained at 0.169 m^3 (6 ft^3) obtained results as shown in Table 4.1, ref. 1. These results are shown in Figure 4.8 and suggest a relationship between gas yield and loading rate. The temperature was maintained between 33 and 38°C and the feed was poured into the feed well manually every 2 hours throughout the day and night for seven days a week for a total of more than seven months. The digester was run at retention times which varied from 14 days down to 2.6 days at which

Figure 4.5 Results for conventional sewage sludge digestion plotted as gas yield versus retention time. As retention time increases gas yield increases



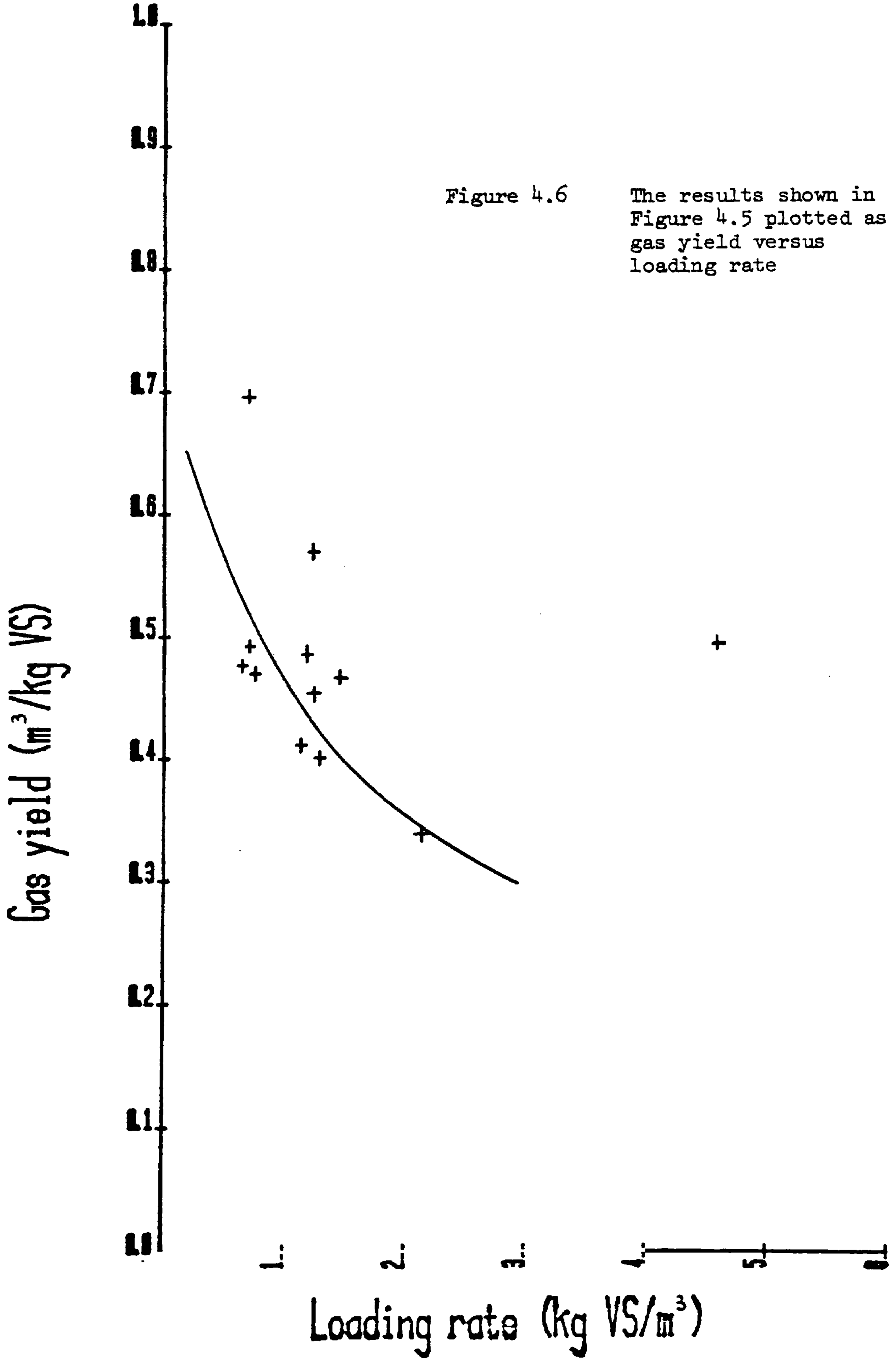


Figure 4.6 The results shown in Figure 4.5 plotted as gas yield versus loading rate

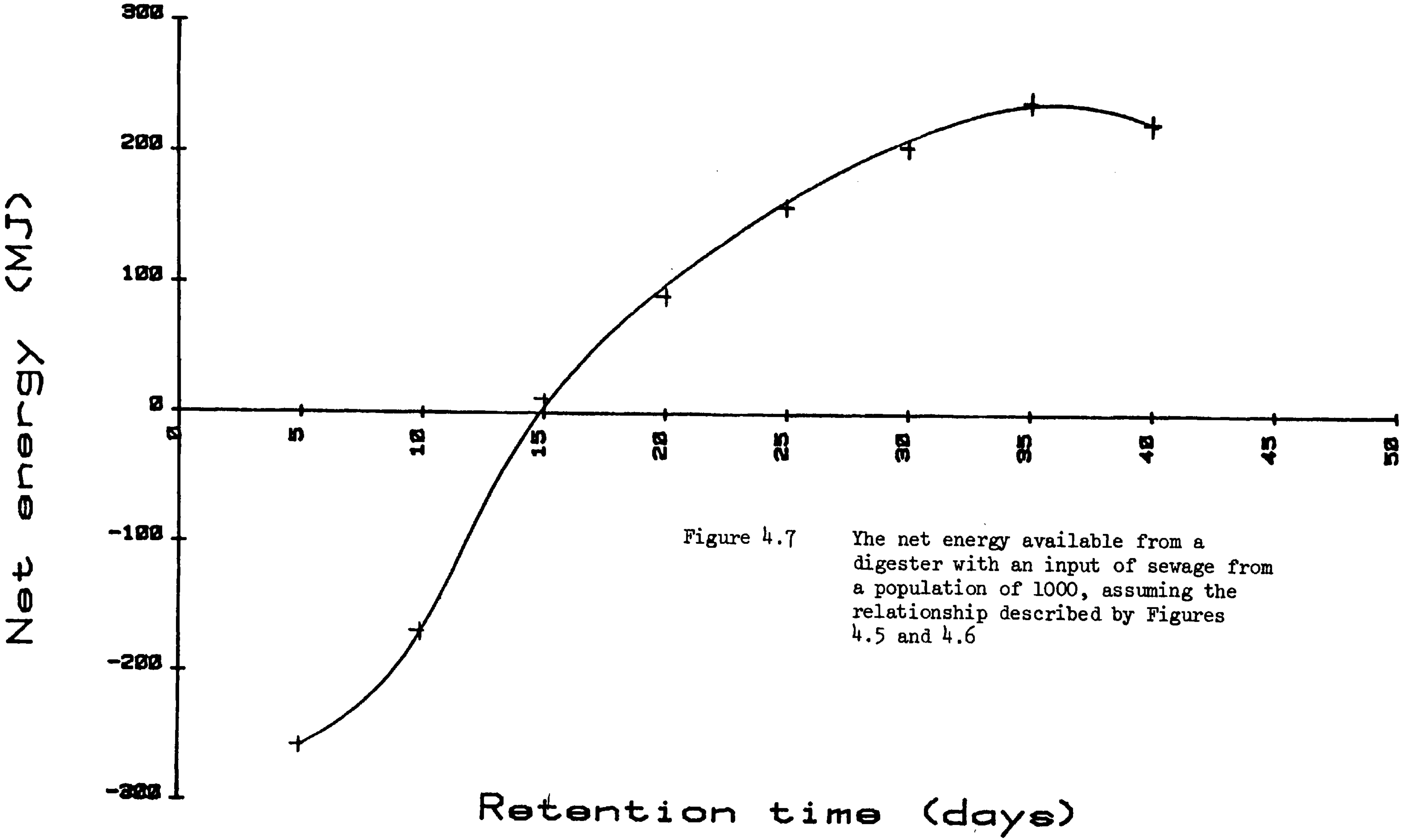


Figure 4.7 Yhe net energy available from a digester with an input of sewage from a population of 1000, assuming the relationship described by Figures 4.5 and 4.6

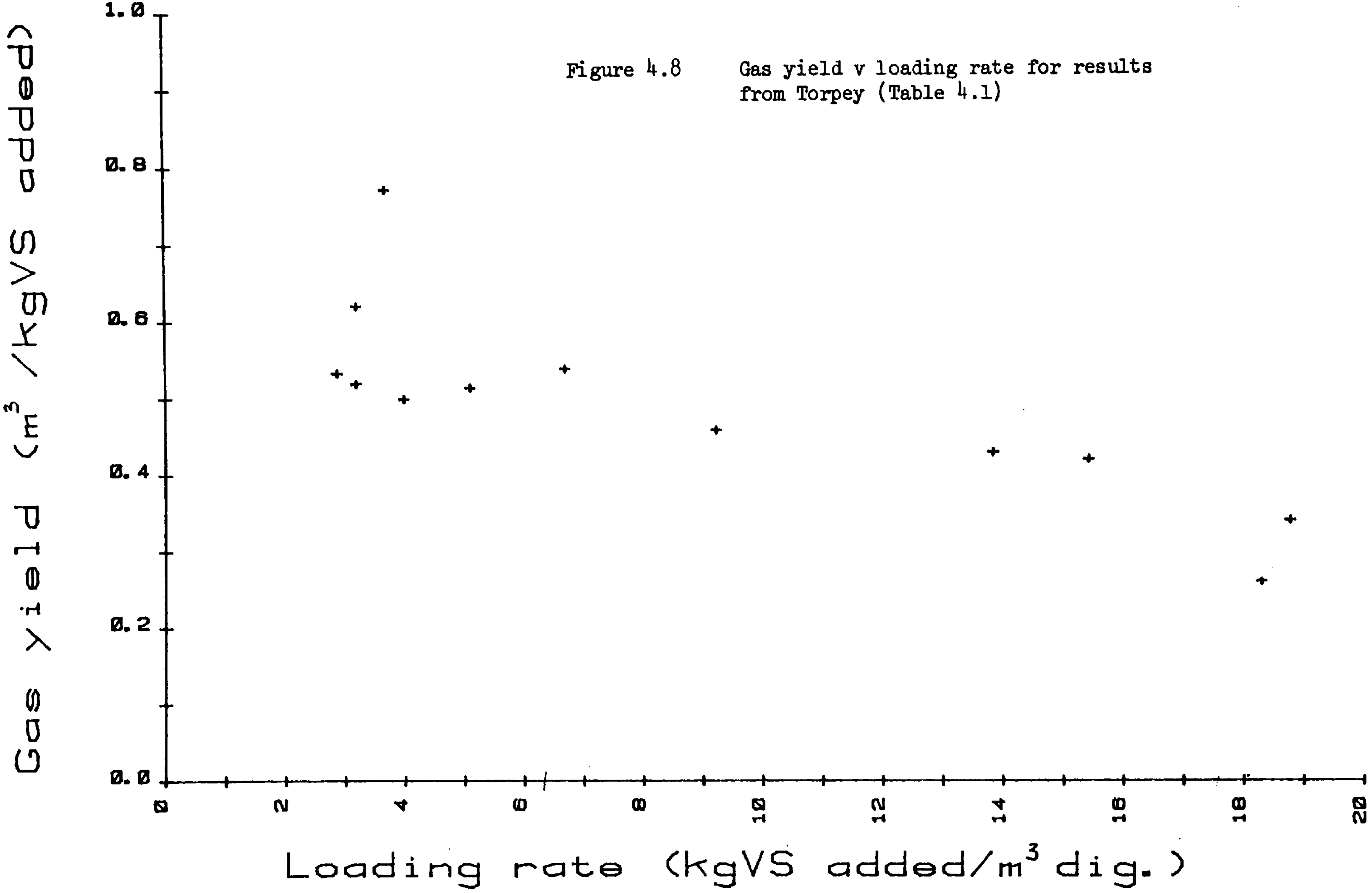


Figure 4.8 Gas yield v loading rate for results from Torpey (Table 4.1)

TABLE 4.1 Results of sewage sludge high rate digestion at 35°C

Type of Digester	Loading Rate kg VS/m^3/day	Gas Yield m^3/kg VS added	R.T. Days	% T.S.	Ref.
Lab scale and pilot plant	3.18	0.622	14	5.8	1
	3.18	0.520	10	4.5	
	3.98	0.500	8.3	4.8	
	5.09	0.515	6.4	4.5	
	6.68	0.540	4.7	4.2	
	9.22	0.460	3.7	4.5	
	13.84	0.430	3.2	5.8	
	15.43	0.420	2.9	5.7	
	18.77	0.340	2.6	6.2	
	18.29	0.260	2.6	5.8	
	3.66	0.774	14.3	6.3	
	2.86	0.534	13.3	5.1	
Lab scale	5.57	0.559	6	3.15	2
	4.13	0.575	8	3.05	
	3.34	0.579	10	2.99	
	2.22	0.600	15	2.92	
	1.59	0.610	20	2.77	
Pilot-plant and full scale	4.31	0.529	10	7.5	3
	3.55	0.611	9.8	5.2	
	4.03	0.580	8.9	5.0	
	4.47	0.559	8.0	6.6	
	3.50	0.458	11.8	6.0	
	4.41	0.537	7.7	5.4	
	4.80	0.544	7.7	6.9	
	5.63	0.490	7.5	6.9	
	5.01	0.616	7.2	6.1	
	4.58	0.641	8.8	5.6	
	2.72	0.446	14.4	6.6	
Lab scale	1.066	0.575	14	2	4
	2.170	0.635	14	4	
	3.286	0.573	14	6	
	4.240	0.672	14	8	
	1.320	0.575	11	2	
	2.700	0.548	11	4	
	4.170	0.527	11	6	
	5.410	0.602	11	8	
	1.790	0.419	8	2	

	3.450	0.539	8	4	
	5.570	0.500	8	6	
	7.525	0.538	8	8	
Lab scale	4.805	0.484	12		5
	3.204	0.459	12		
	1.602	0.398	12		
	4.805	0.388	6		
	3.204	0.388	6		
	1.602	0.283	6		
Full scale	2.563	0.655	17.2	5.7	6
	3.044	0.774	14.5	5.7	
	4.485	0.736	24	13.8	
	5.606	0.686	20	14.4	
	7.048	0.537	15	14.9	
	2.402	0.736	30	9.4	
	4.004	0.735	24	11.1	
	4.485	0.743	24	13.8	
	5.606	0.636	20	14.4	
	3.524	0.736	30	13.8	
	4.645	0.736	24	14.4	
	4.325	0.792	24	14.9	
	2.402	0.724	30	9.4	
	3.202	0.761	30	11.1	
	3.524	0.824	24	13.8	
	4.645	0.636	24	14.4	

Key to references:

1	Torpey - 1955
2	Sawyer and Roy - 1955
3	Morgan - 1954
4	Sawyer and Shmidt - 1955
5	Malina - 1962
6	Albertson - 1961

point the performance deteriorated rapidly. When the tests were repeated on the full size plant digester there was a marked drop in performance compared to that of the pilot plant. This was thought to be due not to any biochemical differences but simply to the fact that in the pilot plants the mixing and temperature were more uniform than in the full scale digester. It was considered that in the full scale unit not all of the volume was utilized effectively since approximately one third of the tank volume was taken up by silt or floating material.

Sawyer and Roy in 1955 used laboratory digesters of 6 litre capacity fitted with gas recirculation for stirring. In these experiments the sludge was fed twice daily after withdrawal of the sludge sample. The digesters were operated at a variety of retention times. It was reported that the gas yield showed no definite relationship with retention time. However if the percentage total and volatile solids content is taken into account to arrive at figures for loading rate then there is a relationship between loading rate and gas yield as can be seen in Table 4.1 (ref. 2); gas yield increases as loading rate decreases.

In Table 4.1 (ref. 3), the first 10 results are for a 10 month long pilot plant operation conducted by Morgan (1954). The plant was just over 5 m^3 capacity (1130 gal.) and stirred by gas recirculation. The digested sludge was withdrawn once daily and the raw sludge was added in two equal increments. The final result was for a full scale unit at the Colombus Ohio sewage treatment plant. The eleven results do not show any clear relationship between loading rate and gas yield.

The next set of results (ref. 4, Table 4.1) were from experiments conducted on laboratory digesters (Sawyer and Schmidt 1955). These were each 9.5 litres capacity and mixing by gas recirculation was abandoned in favour of thorough shaking after each twice daily feeding.

The experiment was carried out for a range of retention times and total solids. For any particular retention time there is an increase in gas yield for an increase in loading rate i.e. an increase in total solids. However for constant total solids there is an increase in gas yield for decreasing loading rate, that is, increasing retention time. The highest gas yield is for the situation with longest retention time and highest total solids whereas the lowest gas yield is for the shortest retention time with the lowest total solids content.

Malina (1962) whose laboratory scale experiments were concerned with investigations into the effects of temperature also showed that if loading rate was kept constant the gas yield increased as retention time increased.

Albertson's study on full scale sewage works (1961) are listed in Table 4.1 (ref. 6) but do not show any clear trends regarding the relationship between gas yield and loading rate. The digesters were full size units from cities throughout the United States,presumably some inhibited by trade wastes and others situated in more rural areas.

The results of these 6 sets of experiments are summarized in Figure 4.8a.

Figure 4.8a does not show any clear relationship between loading rate and gas yield. This is perhaps because there are very few results for loading rates above 5 kg VS added/m^3 digester. However many of the individual sets of results do show a trend that suggests that the lower the loading rate the higher the gas yield.

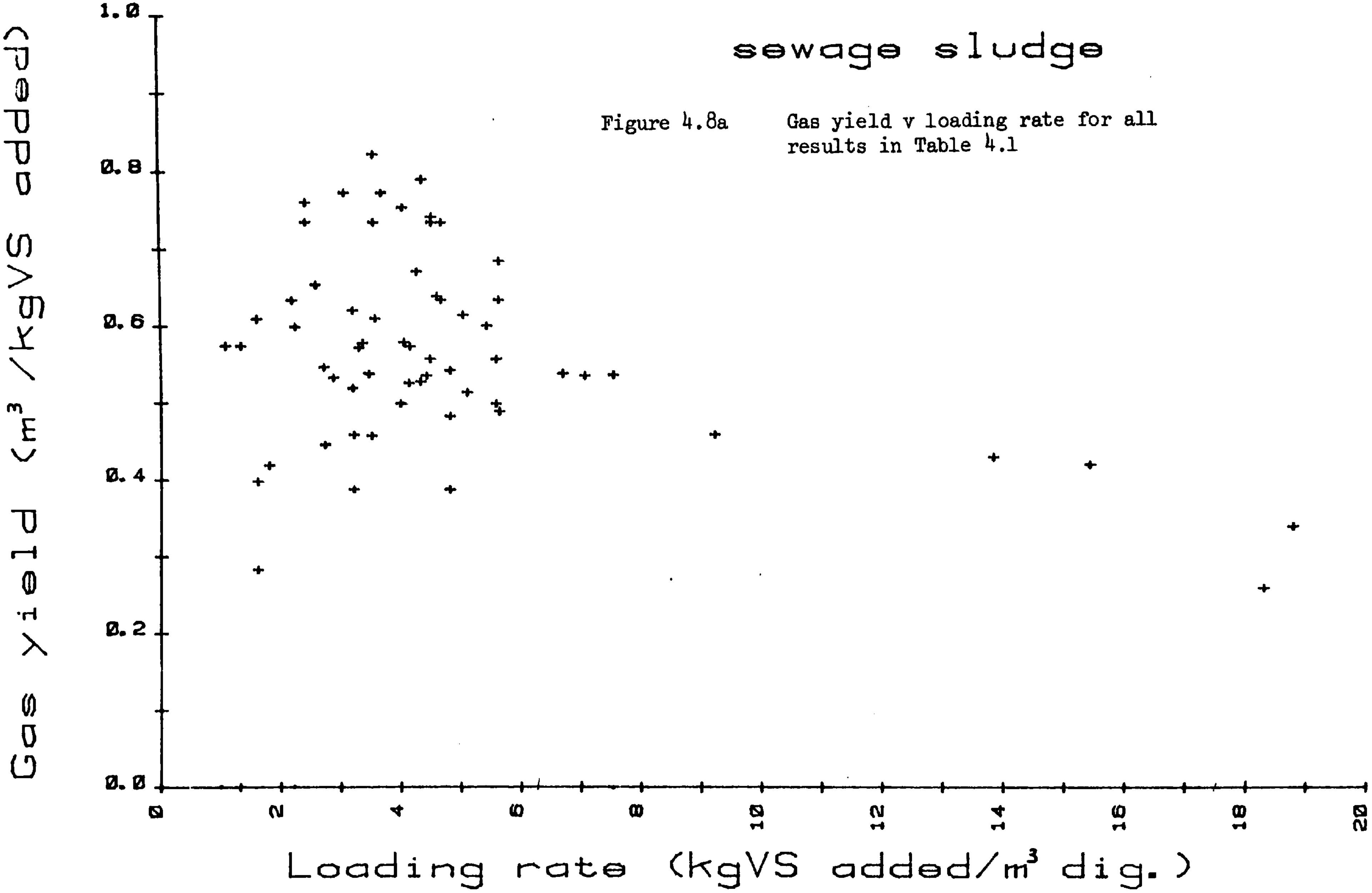


Figure 4.8a Gas yield v loading rate for all results in Table 4.1

4.3 Farm Wastes

4.3.A Cattle

A study on the digestion of cattle manure (Pfeffer and Quindry 1978) estimated that the maximum gas production for the manure used in that experiment was 0.83 m^3/kg VS added if these solids were totally biodegradable. From data in the same paper it was also calculated that the biodegradability of the manure under mesophilic conditions ranged between 30.1% and 48.2% that is between 0.25 and 0.4 m^3/kg VS added. In other words only between 30.1 and 48.2% of the volatile matter could actually be degraded.

Figure 4.9 shows results of work carried out with a 226 m^3 digester at Monroe State Farm, U.S.A., during 1978/79. (Wise et al 1978, 1979.) If a curve is drawn through these points it should cut the 'y' axis below 0.83 m^3/kg VS added, if the cattle manure used at Monroe is similar to that used by Pfeffer and Quindry, and preferably between 0.25 and 0.40, the range indicated in that study. With some manures these values may be higher. Three possible curves A, B and C are shown drawn through these points in Figure 4.10. These 3 curves can be used in prediction of digester performance using a computer model as described in appendix B.

The results of such an exercise using the 3 curves shown and applied to a digester of 18 tonnes per day of cattle manure at 10% T.S. and 60% V.S. are shown graphically in Figure 4.11. The net energy from such a digester is clearly much greater with increased retention time. Even with curve C, the most conservative choice in Figure 4.10, the maximum net energy occurs at around 25 day retention time.

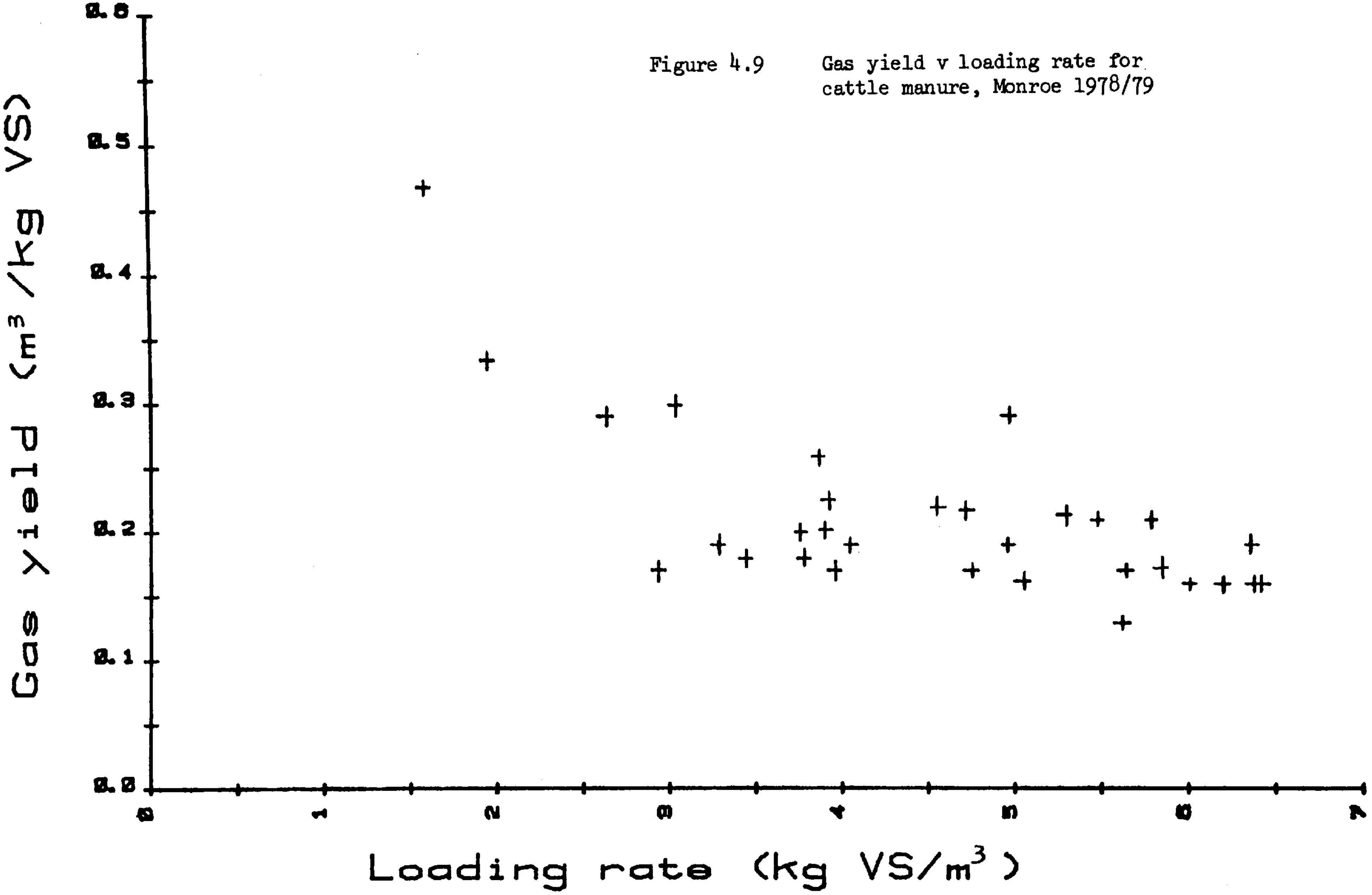


Figure 4.9 Gas yield v loading rate for cattle manure, Monroe 1978/79

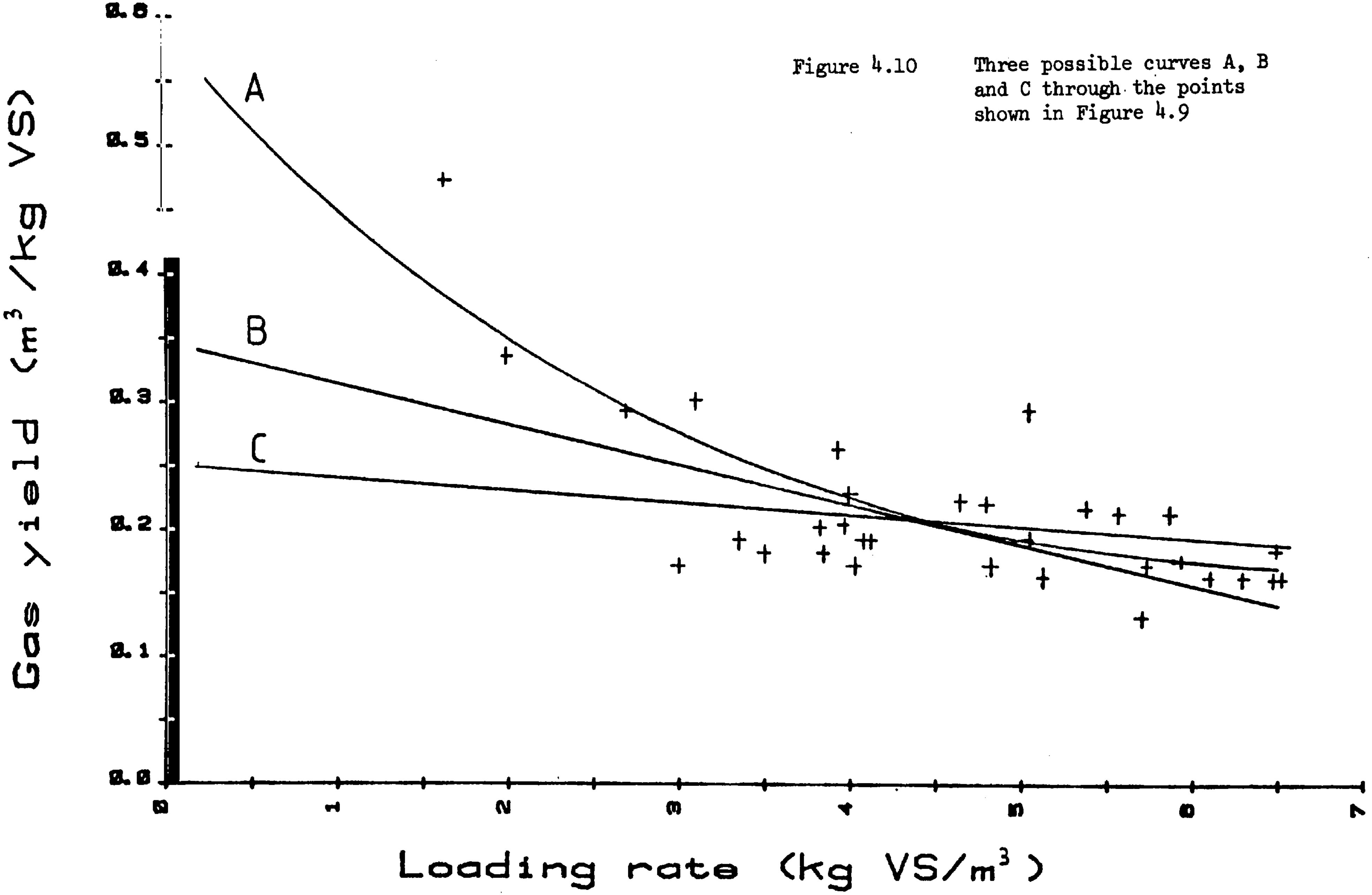


Figure 4.10 Three possible curves A, B and C through the points shown in Figure 4.9

Figure 4.11 The net energy produced using the three curves shown in Figure 4.10 for a digester with an input of 18 tonnes per day of cattle manure

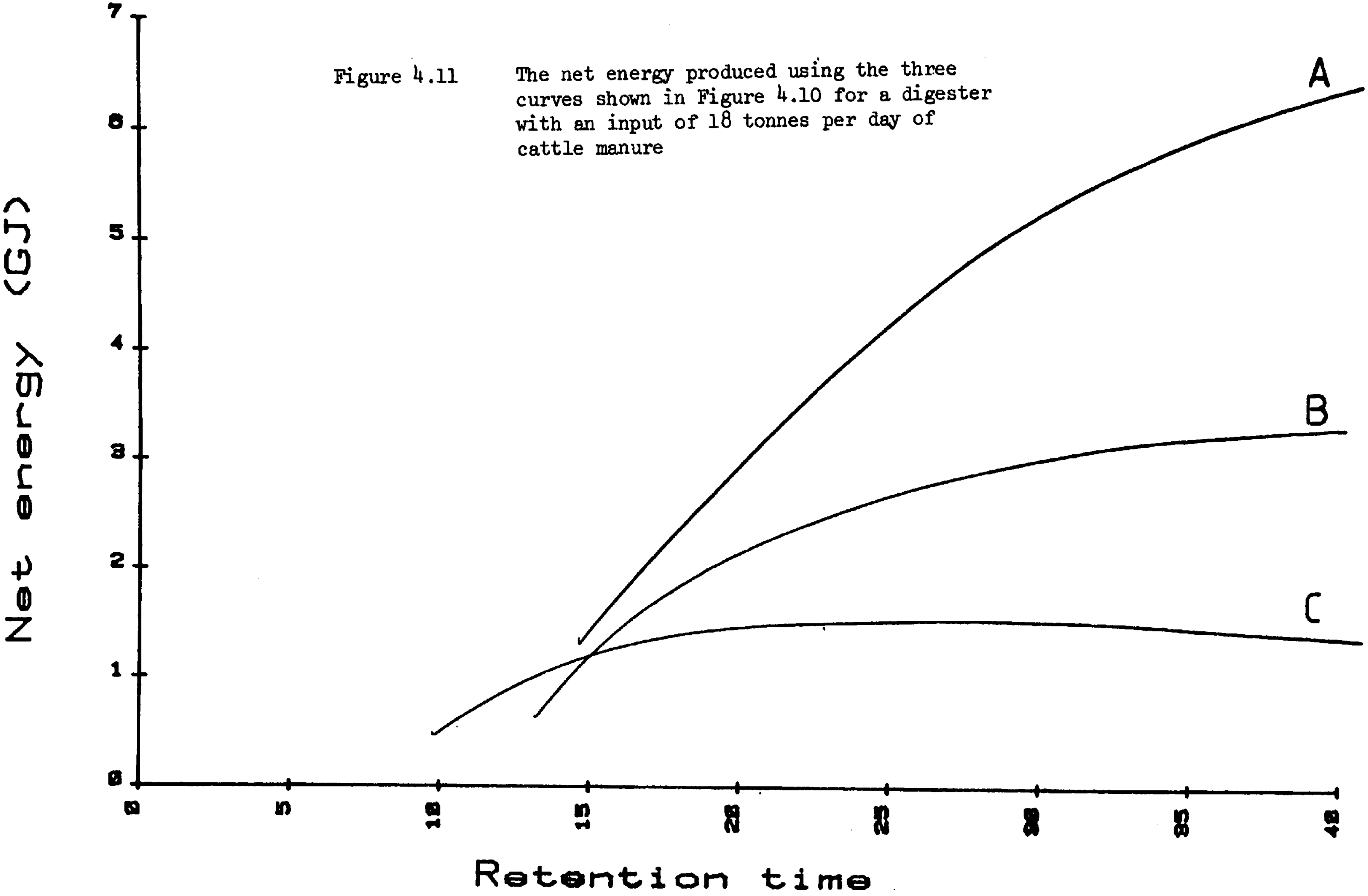


TABLE 4.2 Results of digestion of cattle wastes

Type of Digester	Loading Rate kg VS/m^3/day	Gas Yield m^3/kg VS added	R.T. Days	% T.S.	Ref.
Full scale	6.050	0.210			1
	4.490	0.260			
	6.110	0.200			
	6.210	0.200			
	6.150	0.230			
	6.070	0.200			
	6.370	0.190			
	6.640	0.200			
	4.820	0.260			
Full scale	2.95	0.170			2
	3.97	0.170			
	3.45	0.180			
	3.79	0.180			
	3.30	0.190			
	3.77	0.200			
	4.06	0.190			
	4.97	0.190	15	10	
	4.76	0.170	15	10	
	1.58	0.470			
	5.63	0.130			
	6.02	0.160	12	10	
	6.39	0.160	12	10	
	6.43	0.160	12	10	
	5.49	0.210			
	3.87	0.260			
	6.21	0.160			
	6.07	0.170			
	5.65	0.170			
Full scale	4.97	0.291			3
	5.06	0.162			
	5.79	0.209			Monroe
	5.30	0.214			1979
	4.73	0.218			
	3.91	0.202			
	3.93	0.226			
	3.04	0.299			
	2.64	0.291			
	1.94	0.334			
	4.58	0.201			
	3.63	0.229			

Lab scale	1.75	0.307	20	5	4
	3.50	0.278	10	5	
Lab scale	3.444	0.145	25.3	6.7	5
	1.954	0.156	26.3	4.1	
Lab scale	3.50	0.377	20	10	6
	2.10	0.307	20	6	
	2.80	0.368	20	8	
	1.75	0.270	20	5	
	4.13	0.279	10	5.9	
Full scale	5.03	0.178			7
	5.44	0.182			
	3.97	0.247			
	3.46	0.250			
	1.46	0.486			
	3.76	0.242			
	5.41	0.171			
	4.55	0.262			
	5.71	0.210			
	6.73	0.164			

Key to references:

1	Ashare and Wise - 1978
2	Wise et al - 1978
3	Wise et al - 1979
4	Hobson - 1978
5	Hart - 1963
6	Summers and Bousfield - 1978
7	Wise et al - April 1979

Table 4.2 shows results of 6 different studies on the digestion of cattle manure and these are shown graphically in Figure 4.12.

There are no results yet obtainable at loading rates higher than 7 kg VS added/m^3 digester for mesophilic digestion of cattle slurry. There are a number of experiments conducted at thermophilic temperatures in the higher range which shown a decrease in gas yield with increased loading rate but these have not been included in this work.

The results shown in Figure 4.12 emphasise the curve that was postulated from those shown in Figure 4.9. Apart from the Monroe State Farm study (refs. 1, 2, 3 and 7 in Table 4.2) other results are from laboratory experiments. Hobson (1978) ref. 4 using 150 litre stainless steel digesters with propeller mixing reported an increase in gas yield with decreased loading rate. This was for constant total solids. Ref. 5 in Table 4.2 shows average results for two experiments carried out on very different equipment. These were simple 3.8 litre glass bottles and feeding was carried out twice weekly. In order to feed the digesters the bung had to be removed thus inevitably letting in air. This may well account for the very low gas yield obtained. The digesters were mixed by shaking twice daily and the gas was collected in a floating gas holder.

Summers and Bousfield (1978) using the same equipment as Hobson showed that for a constant retention time (20 days) the gas yield increased as total solids increased and similarly that for a constant total solids feed, 5.9 - 6%, the gas yield was higher for a lower loading rate i.e. a longer retention time.

4.3.B Pigs

Results of work on pig manure digestion shows similar trends to

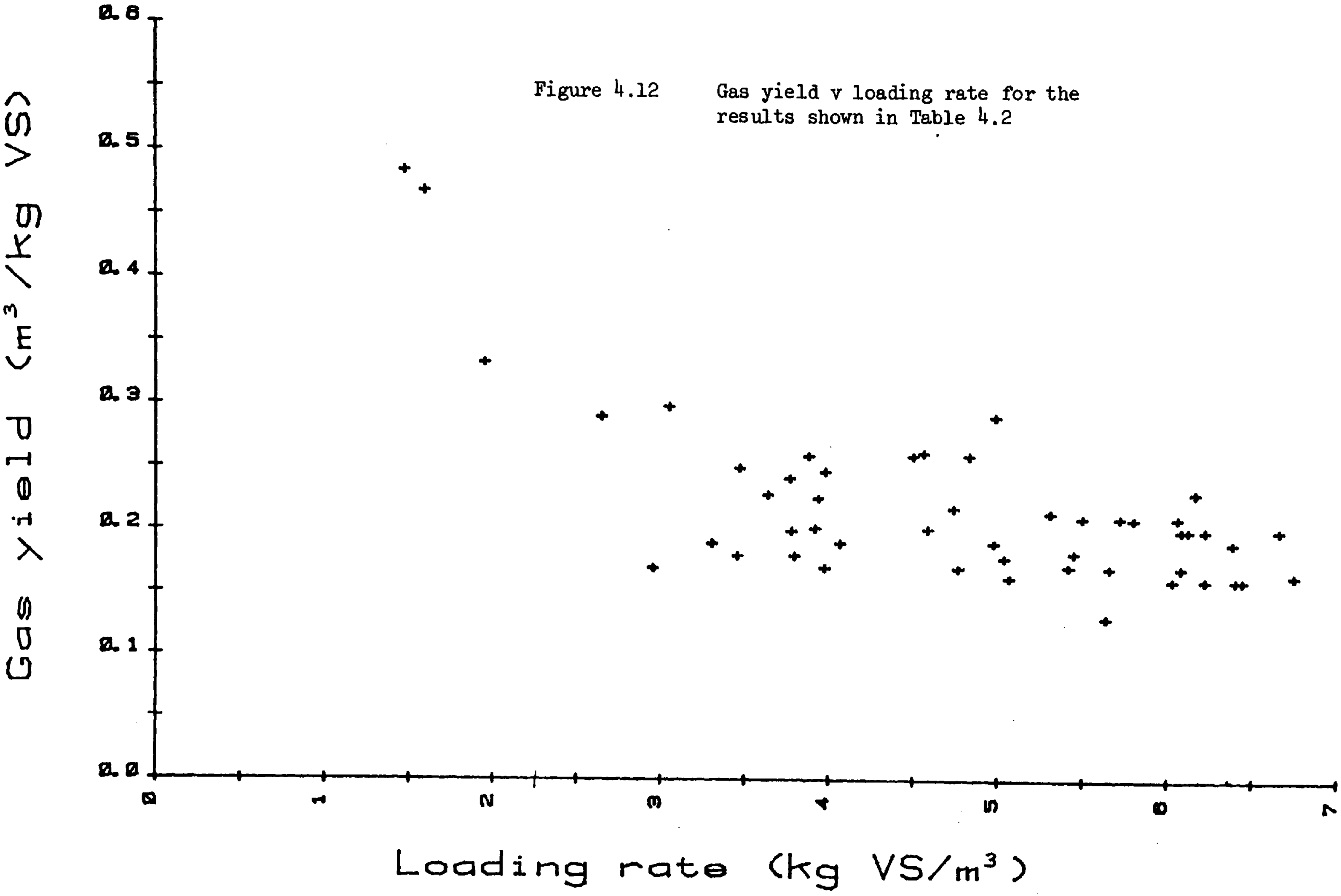


Figure 4.12 Gas yield v loading rate for the results shown in Table 4.2

those for sewage and cattle. For example pilot plant operation at the University of Manitoba (Kroeker et al 1975) gave results on four different digesters working at two loading rates which are summarized in Figure 4.13. It would appear that the slope in this case again indicates the benefits of a longer retention time. This is borne out by the results. These showed that of two digesters operated on the same daily input of identical waste the one running at a 30 day retention time gave a gas yield of around 0.76 m^3/kg VS added.

The digester with the higher loading that is running at 15 day retention time yielded 0.65 m^3/kg VS added. If these results were applied to a digester with an input of eighteen tonnes per day of 4% T.S. pig slurry operated at a 13.5 and 27 day retention time the results would be as shown in Table 4.3.

TABLE 4.3 Net energy is greater at a longer retention time

	Retention Time Days	
	13.5	27
Gross gas (m^3)	328	383
Net energy at 0°C (MJ)	3308	4267
Net energy at 10°C (MJ)	4796	5894

These computations for net energy production are given for ambient and incoming waste temperatures of 0°C and of 10°C for comparison. Once again the indication is that an increased retention time would give a higher net energy production.

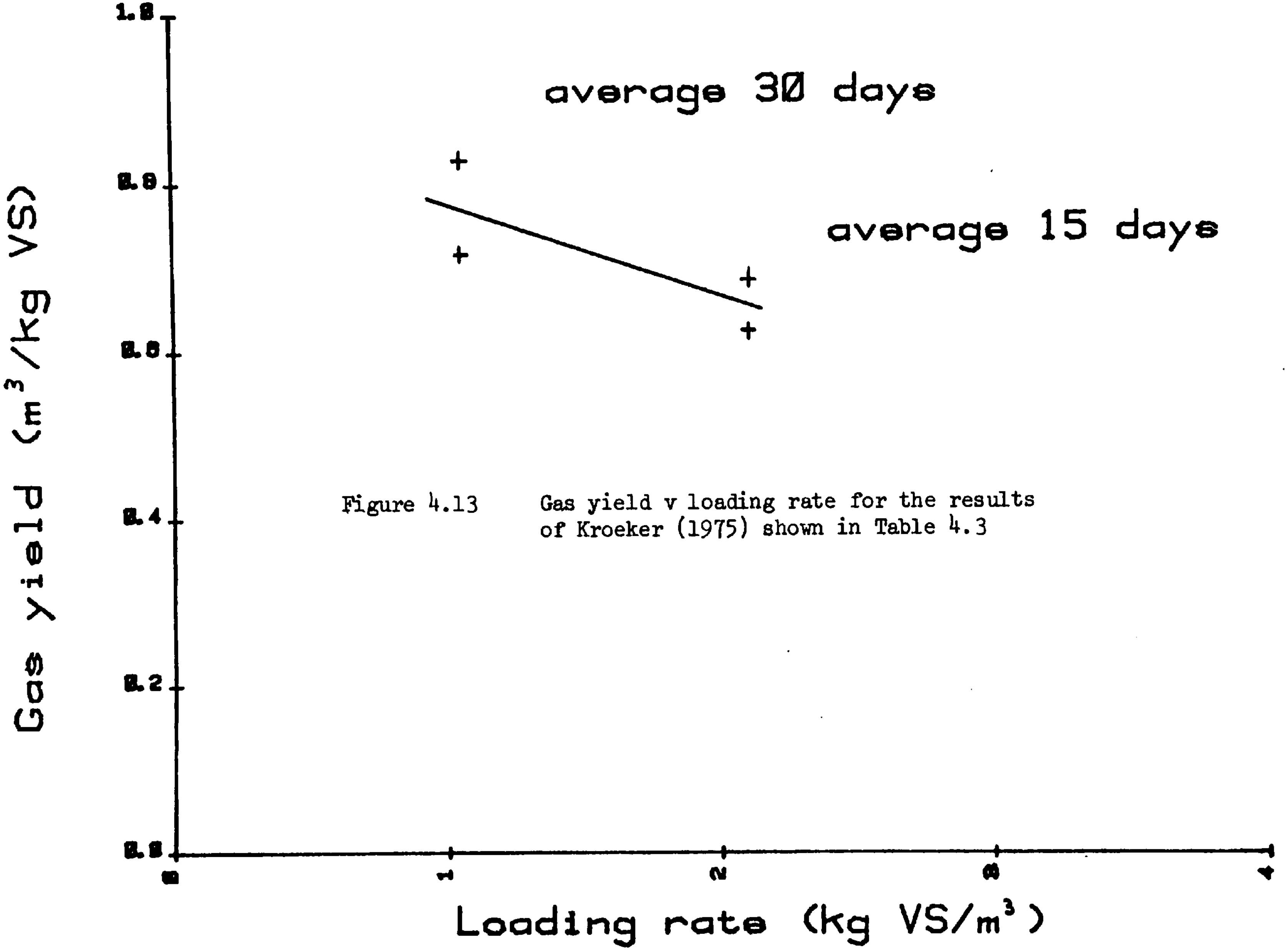


Figure 4.13 Gas yield v loading rate for the results of Kroeker (1975) shown in Table 4.3

TABLE 4.4 Results of digestion of pig slurry

Type of Digester	Loading Rate kg VS/m^3/day	Gas Yield m^3/kg VS added	R.T.	% T.S.	Ref.
Lab (61) pilot plant scale (2401)	2.4	0.271	15	5	1
	3.6	0.198	10	5	
	2.7	0.332	20	7.5	
	2.7	0.3	20	7.5	
	3.4	0.274	16	7.5	
	4.3	0.24	12.5	7.5	
	5.4	0.24	10	7.5	
	4.1	0.273	20	11.25	
	5.4	0.268	15	11.25	
	8.1	0.066	10	11.25	
	1.4	0.3	40	7.5	
	3.6	0.286	15	7.5	
	4.5	0.262	12	7.5	
Pilot scale	2.1	0.680	15		2
	2.1	0.620	15		
	1.05	0.820	30		
	1.05	0.710	30		
Lab scale	2.409	0.410	10	3.3	3
	3.860	0.389	7	3.7	
	5.402	0.328	5	3.7	
	8.516	0.232	3	3.5	
Lab scale	0.961	0.243	19		4
	1.602	0.283	14		
	2.243	0.294	14		
	2.883	0.235	14		
	3.204	0.246	14		
	3.204	0.291	19		
	2.883	0.305	14		
	2.243	0.327	14		
	1.602	0.279	14		
	0.961	0.298	14		
Lab scale	1.922	0.256	10		5
	1.922	0.404	15		
	3.844	0.404	10		
	3.844	0.425	15		

Lab scale	4.900	0.428	10	6
	6.999	0.405	7	
	9.800	0.342	5	
	16.33	0.242	3	

Key to references:

1 Van Velson - 1977

2 Kroeker et al - 1975

3 Summers and Bousfield

4 Hobson and Shaw - 1972

5 Gramms et al - 1971

6 Hobson - 1978

Other results for the digestion of pig slurry show similar trends although there are considerable variations in the yields of gas obtainable probably due to the difference in pig feed between experiments.

Table 4.4 summarized the data obtained from 6 different studies. These results are presented graphically in Figure 4.14.

4.3.C Poultry

A similar graph can be drawn for poultry manure (Hart 1963) (Athonison 1974) (Summers and Bousfield 1978) (Gramms et al 1971) (Hawkes et al 1976). A table of data is shown, Table 4.5 and is presented graphically in Figure 4.15. This graph shows most clearly of all a relationship between gas yield and loading rate. Some of the results are for very low loading rates with a consequently high gas yield. No work has been reported for high loading rates, above about 5 kg VS added/m^3 digester. This is perhaps because of the high ammonia content of chicken manure which is known to be toxic to the digestion process at levels above about 1500 mg/l (McCarty Part III 1964).

4.3.D Wheat Straw

The digestion of wheat straw (Wise et al 1979) although giving lower gas yields shows a similar trend that is increasing gas yield albeit rather small with decreasing loading rate. The values are given in Table 4.6 and graphically in Figure 4.16.

4.4 Conclusion

There is a tendency to operate modern anaerobic digesters at very high loading rates since this results in smaller and less costly units to treat the same volume of waste. These results however suggest that at least for certain wastes there should be a reappraisal of this trend

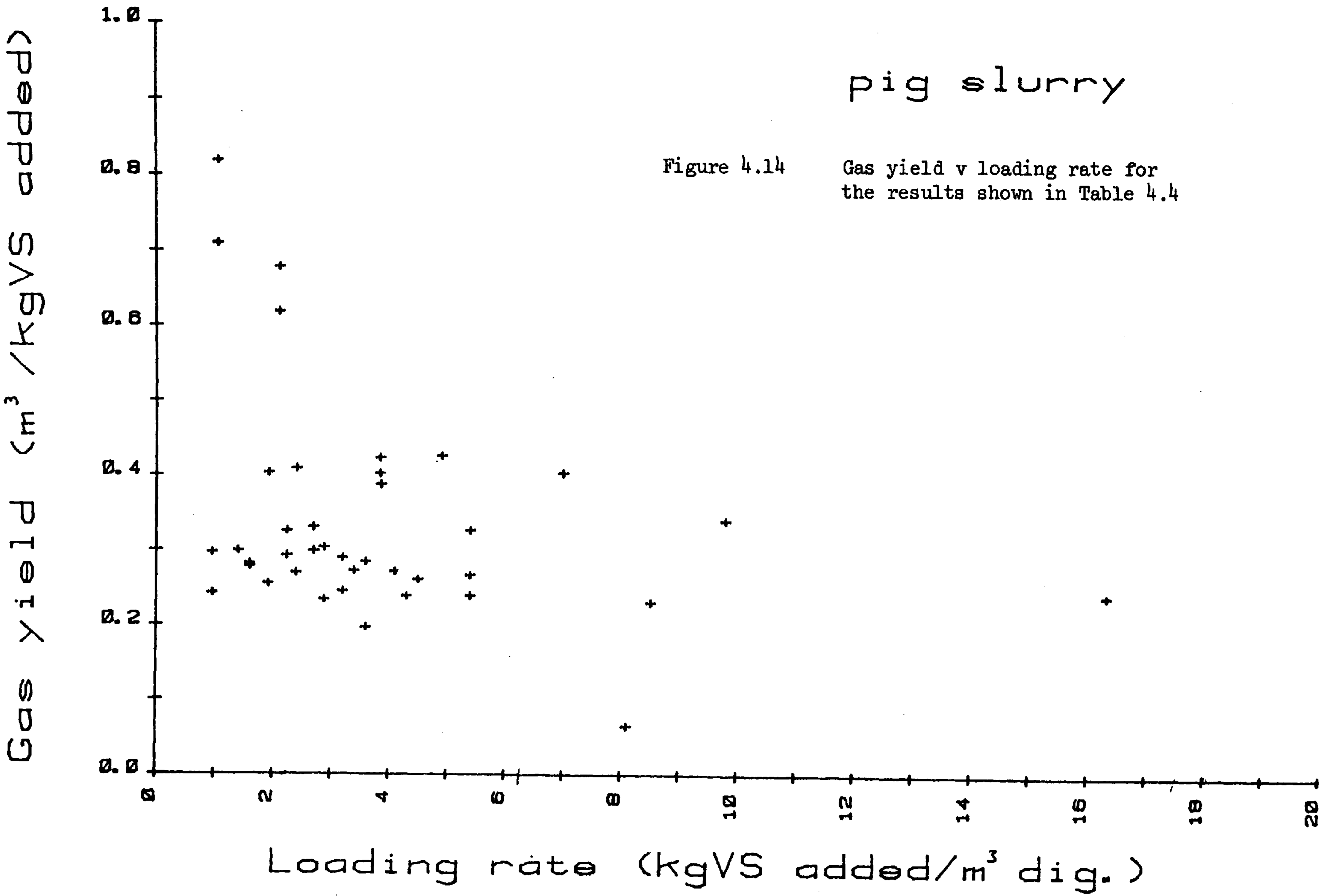


Figure 4.14 Gas yield v loading rate for the results shown in Table 4.4

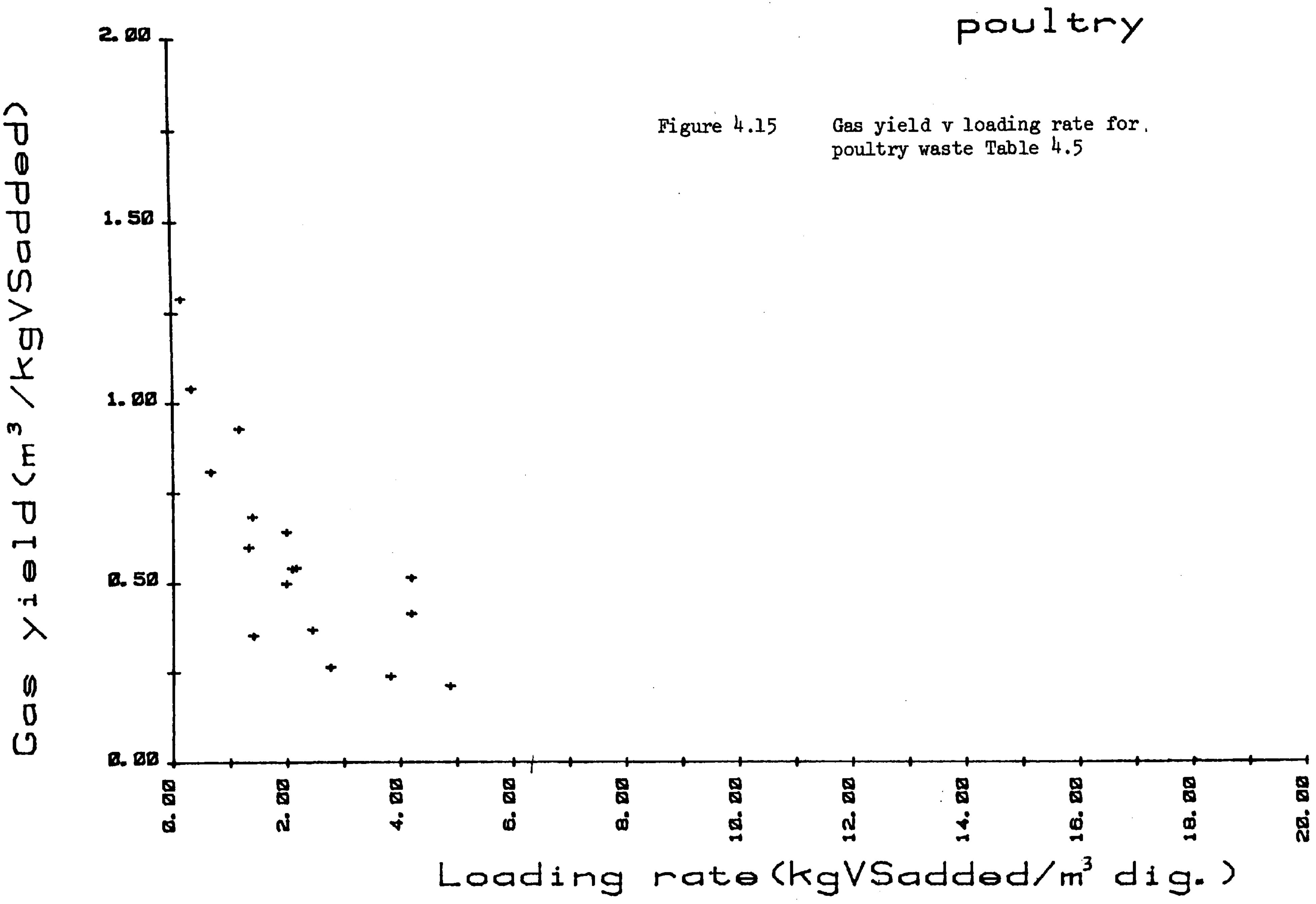


Figure 4.15 Gas yield v loading rate for poultry waste Table 4.5

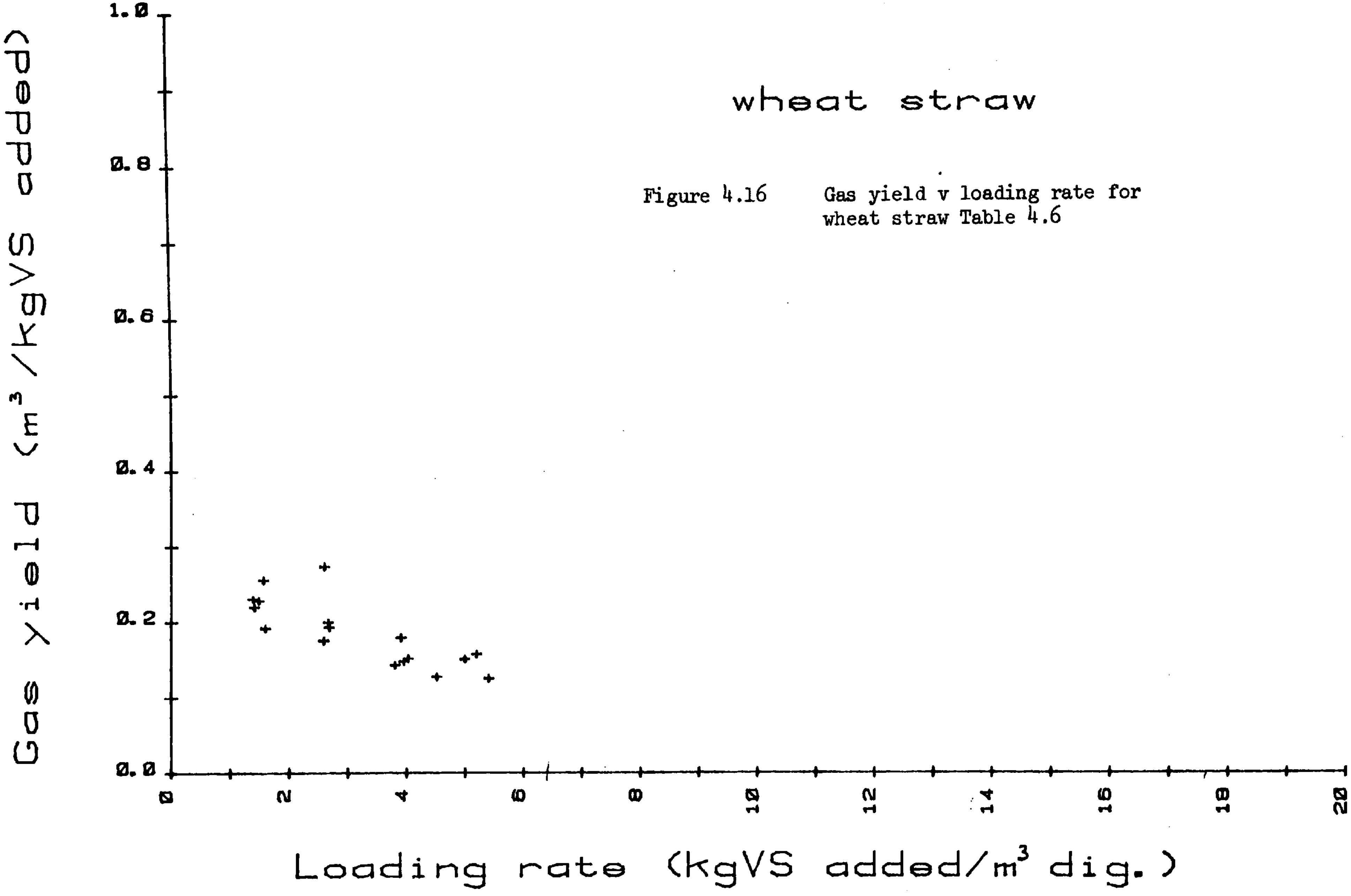


Figure 4.16 Gas yield v loading rate for wheat straw Table 4.6

TABLE 4.5 Results of digestion of poultry manure

Type of Digester	Loading Rate kg VS/m^3/day	Gas Yield m^3/kg VS added	R.T. Days	Ref.
Lab scale	2.000	0.500		1
	1.333	0.600		
	0.666	0.810		
	0.333	1.040		
	0.166	1.290		
	2.000	0.643	10	
	1.169	0.929	19	
Lab scale	2.448	0.370	20	2
Lab scale	3.828	0.239	24	3
	2.771	0.265	26.1	
	4.886	0.213	22.5	
Lab scale	1.409	0.354	20	4
Lab scale	4.200	0.415	20	5
	2.100	0.540	20	
	1.400	0.685	20	
	4.200	0.517	10	
	2.170	0.543	20	

Key to references:

1	Hawkes, D.L., Horton, R., Stafford, D.A. - 1976
2	Hawkes, F.R. - 1980
3	Hart, S.A. - 1963
4	Athonisen, A.C., Cassell, E.A. - 1974
5	Summers, R., Bousfield, S. - 1978

TABLE 4.6 Results of digestion of wheat straw

Type of Digester	Loading Rate kg VS/m^3/day	Gas Yield m^3/kg VS added	R.T. Days	Ref.
Pilot plant	5.00	0.151	3.8	1
	5.20	0.158	3.8	
	5.41	0.125	3.8	
	4.52	0.127	5.0	
	3.96	0.148	5.0	
	4.03	0.152	5.0	
	3.91	0.180	4.9	
	3.81	0.143	5.1	
	2.61	0.274	7.5	
	2.69	0.193	7.4	
	2.67	0.200	7.3	
	2.59	0.176	7.5	
	1.49	0.229	13.1	
	1.57	0.256	13.2	
	1.60	0.192	13.2	
	1.41	0.220	14.2	
	1.39	0.231	14.3	

Key to reference:

1 Wise, D.L. et al - January 1979

when energy generation is the main requirement (Horton and Hawkes 1979). Lower loading rates can result in greater net energy production and cheaper gas.

CHAPTER FIVE

PARAMETERS AFFECTING NET GAS OUTPUT

5.1 Sensitivity Index

5.1.A Identifying the Parameters

There are a large number of parameters which affect the net energy output from a digester. These include for example those shown in Table 5.1. Retention time will have an effect on the final gas production as will the total and volatile solids in the feed material. The degree of insulation and the ambient temperature will also have a direct bearing on the net energy produced.

The gas yield possible for a particular waste and the proportion of methane in the gas as well as the efficiency of the heat exchanger of any system using the gas to heat the digester, are more examples of 'input parameters' to a simple mathematical model. Many of these parameters are variable and so it is useful to be able to identify those which have the greatest net effect. Once they are known a tighter control may be exercised on these particular variables to maximise gas production.

i. Typical values of each parameter

It is possible with experience to make assumptions about the likely variation in each parameter and to chose a typical value for each. For example most digesters work at a retention time above 5 days although there are of course exceptions (Torpey 1955, 2.6 days), and below about 25 days. A typical value for a modern high rate digester may be 10 days.

Similarly for total solids percentage if digesters developed especially for treating low solids wastes (packed-bed for example) are discounted, then wastes are normally not lower than say 1% T.S.

TABLE 5.1 Parameters affecting net energy output from a digester

	Input Parameters	Symbol
1.	Retention time (days)	R.T.
2.	Total solids (%)	T.S.
3.	Volatile solids (%)	V.S.
4.	Excess capacity factor	ECF
5.	'U' factor for walls (W/m^2 °C)	U.W.
6.	U factor for roof (W/m^2 °C)	U.R.
7.	Lowest expected difference between air temperature and digester operating temperature (°C)	ATEMP
8.	Lowest expected difference between influent temperature and digester operating temperature (°C)	ITEMP
9.	Mean annual difference between air temperature and operating temperature (°C)	AATEM
10.	Mean annual difference between influent temperature and digester operating temperature (°C)	AITEM
11.	Gas yield (m^3/kg V.S. added)	MKG
12.	Calorific value of the gas produced (MJ/m^3)	M.J.
13.	Heat exchanger efficiency (%)	BOLEF

Similarly there are some digesters working on very high solids (Wong-Chong 1975) but most do not exceed about 9%. A typical value would be about 4%. Volatile solids do not usually exceed about 90% of the total solids or drop below 40%, and 73% could be chosen as a reasonable value. The insulation of a digester is going to affect the net energy production and values of 0.778 and 0.643 watts per square metre °K are values for a digester wall in contact with the digesting slurry and the digester roof in contact with the gas. These values are approximately correct for an insulation of 50 mm mineral wool with a weatherproof aluminium skin. Depending on the degree of insulation these U factors will change but most digesters fall between the limits of about 0.9 and 0.6 for the walls and 0.8 and 0.5 for the roof.

The worst expected difference between the air temperature and digester operating temperature during the winter in Britain will vary between about 47°C (-12°C air temperature) and 30°C (5°C air temperature) with a typical value of about 35°C. Influent temperatures will not fall much below zero or be expected to be much above 10°C unless using animal wastes coming straight from the animal pens. Again a good estimate would be 35°C difference for the worst winter temperatures.

The mean annual temperature in Britain is 10°C and a typical difference between both air and influent and the digester operating temperature on average throughout the year is 25°C with a range extending from 20°C to 30°C.

A further variable for which an input value must be assumed is gas yield which with wastes that are commonly digested varies quite widely but would normally exceed 0.31 m^3/kg V.S. added but be below 0.81 m^3/kg VS added with an average of 0.56 m^3/kg V.S. added.

Depending on the methane content of the gas the energy content will lie somewhere between 26 MJ/m3 (70% CH_4) and 22 MJ/m^3 (59% CH_4) usually with a good mean of about 24 MJ/m^3 (64% CH_4). Where some of the gas produced is used to heat the digester then the heat exchanger efficiency is a factor affecting the net energy produced. Some exchangers can be 85% efficient although this is unlikely with most digesting sludges. A low value would be about 55% although some may be even below that. An average efficiency may be taken as 70%.

ii. Effect on gas production of varying each parameter

The typical values shown above can be used to calculate the net energy production from a digester with a given volume of waste per day and the effect of varying these average baseline values between the expected maximum and minimum discussed above can be calculated, and the magnitude of the effect of this on the net energy output is a measure of the process sensitivity to each input parameter.

Table 5.2 shows the result of this exercise. The column headed "Baseline Energy Production" is the net energy production (M J) given by a digester operating under the conditions described by the first two columns and having a volume input of 2.8 m^3 per day (chosen to be large enough to give +ve values for the baseline energy production). The next two columns "Net Energy Produced" shows the net energy (MJ) for the extremes of each variable. Inspection of these two columns shows that the variation in total solids gives the greatest variation in net energy produced as compared to the baseline situation.

iii. Quantifying the effect of each variable

5.1.B A Sensitivity Ratio

From the data presented in Table 5.2, it can be seen that the net

TABLE 5.2 Sensitivity ratio for a number of parameters

Parameter Symbol*	Baseline Parameter	Parameter Limits		Baseline Energy Production (MJ)	Net Energy Produced (MJ)		Sensitivity Ratio	
		Upper	Lower		Upper Case	Lower Case	Upper	Lower
RT (days	10	25	5	561	461	605	-0.119	-0.157
TS (%)	4	9	1	561	1935	-263	1.959	1.958
VS (%)	73	90	40	561	817	64	1.959	1.959
UW (W/m^2 ^{o}C)	0.778	0.9	0.6	561	546	582	-0.170	-0.164
UR (W/m^2 ^{o}C)	0.643	0.9	0.5	561	555	567	-0.044	-0.048
ATEMP (^{o}C)	35	30	47	346	370	289	-0.485	-0.480
ITEMP (^{o}C)	35	25	35	346	513	346	-1.689	0
AATEM (^{o}C)	25	20	30	561	585	537	-0.214	-0.214
AITEM (^{o}C)	25	20	30	561	-45	477	-0.749	-0.749
MKG (m^3/kg VS)	0.56	0.8	0.3	561	1032	51	1.959	1.959
MJ (MJ/m^3)	24	26	22	561	653	469	1.968	1.968
BOLEF	0.7	0.85	0.5	561	656	346	0.790	1.341

* For explanation of symbols see Table 5.1

energy production is more affected by, that is more sensitive to, changes in some parameters than others. It is most sensitive to changes in total solids, volatile solids, gas yield and methane content of the gas.

The degree of sensitivity of the net energy yield to these changes can be measured as the ratio of the change in net energy yield (the output) to the change in input parameter. If there is a large variation in the output for only a small variation of the input then the sensitivity is said to be high.

All variations whether in input or output can only be meaningful if compared as a proportion of one to another. This can be done by comparing percentage differences from a given datum (in this case the average baseline value) or by comparing proportional differences from that datum.

The sensitivity ratio in the two final columns of Table 5.2 is calculated as a ratio of the proportional difference in net energy from the baseline value given in column 1 to the proportional difference in the controlling input from the baseline parameter. That is, the sensitivity ratio S is given by $S = \frac{P_{eb}}{P_{ib}}$ where P_{eb} is the proportional difference in energy variation from the baseline energy and P_{ib} is the proportional difference in the controlling input from the baseline input parameter.

Now $P_{eb} = \frac{E_v}{E_b}$ where E_v is the variation in energy produced and E_b is the energy output at baseline conditions.

Similarly $P_{ib} = \frac{I_v}{I_b}$ where I_v is the variation in input and I_b is the input baseline conditions.

Hence $S = \frac{E_v}{E_b} \cdot \frac{I_b}{I_v}$.

Now $E_v = E_{oi} - E_b$ where E_{oi} is the energy output due to the change in the input. Similarly $I_v = I_i - I_b$ where I_i is the input extreme,

$$\text{hence} \quad S = \frac{\dfrac{(E_{oi} - E_b)}{E_b}}{\dfrac{(I_i - I_b)}{I_b}}$$

The last two columns in Table 5.2 show the results of this calculation for the two extremes of the 13 parameters chosen.

The sensitivity ratio is highest for the percentage total solids, volatile solids, gas yield and energy content of the gas.

There is however a danger in being over-influenced by this as the following demonstrates:-

From Table 5.2 it would appear that the calorific value of the gas and the gas yield can apparently have as significant an effect on the net energy output from a digester as the percentage total solids. In fact the increase in net energy obtained by an increase in total solids is far in excess of that obtainable from an increase in either of the other parameters. For example consider two situations:-

a) <u>Total solids increased from 4 - 9%</u>

Net energy increases by $\dfrac{1935 - 561}{561} = 245\%$

Total solids control varied by $\dfrac{9 - 4}{4} = 125\%$

b) <u>Calorific value of gas increased from 24 to 26 MJ/m^3</u>

Net energy increases by $\dfrac{653 - 561}{561} = 16.4\%$

Calorific value varied by $\dfrac{26 - 24}{24} = 8.3\%$

Thus though the sensitivity ratios in Table 5.2 for total solids and calorific value are almost the same, the resultant net energy produced is 15 times higher if the total solids are changed from 4% to 9% than if the calorific value changes from 24 MJ/m^3 to 26 MJ/m^3. In other words a limitation of this sensitivity ratio is that it ignores the magnitude of the net energy output change.

5.1.C Sensitivity Index

As just stated the sensitivity ratio developed above has certain important limitations. A better measure of the sensitivity of the net energy yield from the digestion process to variations in input parameters is given by the Sensitivity Index. This is obtained by multiplying the sensitivity ratio shown in Table 5.2 by the variation in net energy output from the typical value which is called the baseline parameter. The results of this exercise are given in Table 5.3. When calculating the effect of increasing the retention time in Tables 5.2 and 5.3 it is assumed that there is no concomitant change in gas yield. This may not necessarily be the case. The only effect of increases in retention time which is considered is the increased energy losses due to a greater surface area of an increased size of digester necessary to treat the same volume of waste. As Table 5.3 shows, the parameters which affect the net energy production most are again the percentage total solids followed by the gas yield. However this time the value of the Index for these factors is in proportion to their effect. The parameter which has the least effect, of those examined here, when varied within the ranges suggested is the degree of insulation on the digester roof.

This Sensitivity Index is a useful measure of the relative importance of a change in any of these parameter (within the limits chosen) on the net energy produced by a digester.

TABLE 5.3 Modification of the Sensitivity Ratio:- The Sensitivity Index

Parameter	Sensitivity Ratio		Variation from Baseline		Sensitivity Index	
	Upper Case	Lower Case	Upper	Lower	Upper	Lower
RT*	-0.199	-0.157	-100	44	11.9	-6.9
TS	1.959	1.958	1374	-824	2692	-1613
VS	1.959	1.959	256	-497	502	-974
UW	-0.170	-0.164	-15	21	2.6	-3.4
UR	-0.044	-0.048	-6	6	0.26	-0.29
ATEMP	-0.485	-0.480	24	-57	-11.6	27.4
ITEMP	-1.689	0	167	0	-282	0
AATEM	-0.214	-0.214	24	-24	-5.1	5.1
AITEM	-0.749	-0.749	84	-84	-62.9	62.9
MKG	1.959	1.959	471	-510	922	-999
MJ	1.968	1.968	92	-92	181	-181
BOLEF	0.790	1.341	95	-215	75	-288

* For an explanation of the symbols and their units see Table 5.1

It is not surprising therefore that the constantly varying feed solids supplied to the pilot plants during the experimental period on sewage sludge described in Chapter 3 resulted in large fluctuations in the volume of gas produced. Table 5.3 indicates that the solids should be as high as is practically possible for maximum net gas production, and also that the gas yield has a very important effect.

i. Effect of loading rate on gas yield

It would appear from the pilot plant results (Chapter 3.4) that there is a definite relationship between gas yield and loading rate and this was confirmed by the results of other work discussed in Chapter 4. It is usually difficult to increase the total solids going into a digester, except perhaps by settling or in some cases centrifugation but the gas yield may be increased by lowering the loading rate.

The loading rate is a function of both total solids percentage and retention time. Since one is usually treating a fixed volume of waste the retention time can only be easily altered at the design stage. It was decided therefore to investigate further the parameter of gas yield as a function of both total solids and retention time.

5.2 Gas Yield as a Function of Percentage Solids and Retention Time

Chapter 4 reviewed some of the evidence for the existence of a definite relationship between gas yield and loading rate such that a decrease in loading rate results in an increase in gas yield. This increase in gas yield may well be sufficient to justify the larger digester which can give a lower loading rate for a fixed volume of waste.

The Sensitivity Index (Section 5.1, Table 5.3) showed the degree to which the net energy production is influenced by various parameters, in particular the solids content of the input material. The other parameter which strongly influences the net energy is the gas yield and as has been shown this appears to be a function of loading rate.

5.2.A Gas Yield as a Function of Loading Rate for Constant Solids

Loading rate is a function of both percentage volatile solids and retention time and so constant solids' results were examined for any clearer trend in the gas yield v loading rate relationship. Figure 5.1 shows one result for sewage sludge. Not enough data was available at one particular total solids and so a range had to be chosen. The range 4 - 6% TS was one with enough results to be able to investigate the relationship shown in Figure 5.1. These results were from a variety of sources previously described and summarized in Table 4.1.

For a constant total solids an infinitely small loading rate means an infinitely long retention time and hence one could expect a graph of gas yield v loading rate to cut the gas yield axis at some point representing the ultimate yield for that particular waste.

Also at some high but finite value of loading rate the gas yield would be expected to drop to zero quite suddenly when overloading occurs. The high values of loading rate shown in Figure 5.1 are data from Torpey (1955) and represent about the upper limit for sewage sludge digestion.

5.2.B Gas Yield as a Function of Loading Rate for Constant Retention Time

Retention time, being determined by volumetric measurement, can be fairly accurately known whereas the determination of total and volatile solids is more liable to error.

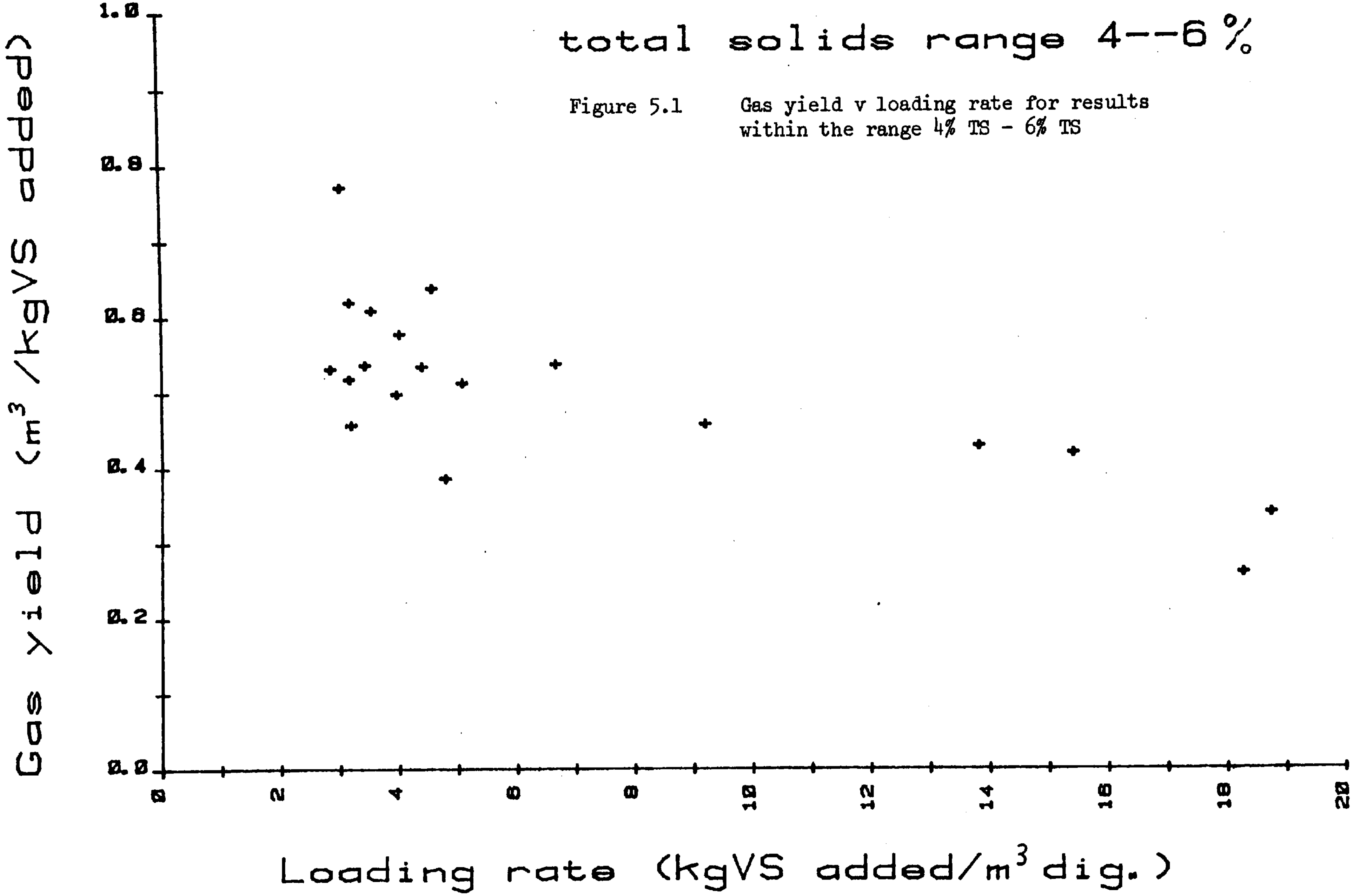


Figure 5.1 Gas yield v loading rate for results within the range 4% TS - 6% TS

This is because of the difficulties in sampling what is often a non-homogenous waste.

Table 5.4 shows data for a number of experiments on the digestion of sewage sludge, all at about 35°C, grouped according to retention times. For example group 1 are all results from retention times below 5 days, group 2 from between 5 and 10 days etc. Figures 5.2 to 5.6 inclusive show these results expressed on a loading rate v gas yield graph.

Results of Fisher (Ref. 7 in Table 5.4) have not been included since they appear to be uncharacteristic. For example in Table 5.4 the results (Reference 7) occur in groups 3, 4, 5, 6 and 8 and in each case are for three different total solids, 3%, 6% and 9% TS. It would appear that for a 3% sludge the gas yield (m^3/kg VS added) is higher at 20 day retention time than at 25 days, similarly for a 6% sludge the gas yield is apparently higher at 13.3 days than at 25 days. Assuming these results are correct it would suggest that this particular sludge on longer incubation, produced digestion products that were inhibitory, the effect being worst at a retention time of around 20 - 25 days. If this is the case then it is very unusual and does not appear to happen with any other digestion of sewage sludge. A more likely explanation of the anomaly is that there is an error in the method of operating the laboratory digesters.

The results expressed in Figures 5.2 to 5.6 show a wide scatter. This is not surprising since although in each experiment sewage sludge was used and the digestion temperature was around 35°C a number of different sources of sludge are represented in these figures. The curve

TABLE 5.4 Gas yield v loading rate for sewage sludge at various retention times

	Loading Rate kg VS/m^3 digester	Gas Yield m^3/kg VS added	R.T. days	T.S. %	Reference
1 Retention time below 5 days					
	6.680	0.540	4.7	4.2	1
	9.220	0.460	3.7	4.5	
	13.840	0.430	3.2	5.8	
	15.430	0.420	2.9	5.7	
	18.770	0.340	2.6	6.2	
	18.290	0.260	2.6	5.8	
2 Retention time between 5 - 10 days					
	4.805	0.388	6	(4)	2
	3.204	0.388	6	(2.7)	
	1.602	0.283	6	(1.4)	
	1.790	0.419	8	(2)	3
	3.450	0.539	8	(4)	
	5.570	0.500	8	(6.4)	
	7.525	0.538	8	(8.6)	
	5.090	0.515	6.4	4.5	1
	3.980	0.500	8.3	4.8	
	5.570	0.559	6	3.15	4
	4.130	0.575	8	3.05	
	3.550	0.611	9.8	5.2	5
	4.030	0.580	8.9	5.0	
	4.470	0.559	8.0	6.6	
	4.410	0.537	7.7	5.4	
	4.800	0.544	7.7	6.9	
	5.630	0.490	7.5	6.9	
	5.010	0.616	7.2	6.1	
	4.580	0.641	8.8	5.6	
3 Retention time between 10 - 15 days					
	4.805	0.484	12	(8)	2

3.204	0.459	12	(5.5)	
1.602	0.398	12	(2.7)	
3.044	0.774	14.5	5.7	6
1.320	0.575	11	*	3
2.700	0.548	11	*	
4.170	0.527	11	*	
5.410	0.602	11	*	
3.180	0.622	14	5.8	1
3.180	0.520	10	4.5	
3.660	0.774	14.3	6.3	
2.860	0.534	13.3	5.1	
3.340	0.579	10	2.99	4
4.310	0.529	10	7.5	5
3.500	0.458	11.8	6.0	
2.720	0.446	14.4	6.6	
1.066	0.575	14	*	3
2.170	0.635	14	*	
3.286	0.573	14	*	
4.240	0.672	14	*	
1.800	0.590	13.3	3	7
3.500	0.565	13.3	6	
5.650	0.670	13.3	9	

4 Retention time between 15 - 20 days

1.450	0.570	16	3	7
2.700	0.530	16	6	
4.150	0.540	16	9	
2.220	0.600	15	2.92	4
2.563	0.655	17.2	5.7	6
7.048	0.537	15	14.9	

5	Retention time between 20 - 25 days				
	4.485	0.736	24	13.8	6
	5.606	0.686	20	14.4	
	4.004	0.755	24	11.1	
	4.485	0.743	24	13.8	
	5.606	0.636	20	14.4	
	4.645	0.736	24	14.4	
	4.325	0.792	24	14.9	
	3.524	0.824	24	13.8	
	4.645	0.636	24	14.4	
	1.590	0.610	20	2.77	4
	1.000	0.620	20	3	7
	2.000	0.530	20	6	
	3.100	0.555	20	9	
6	Retention time between 25 - 30 days				
	0.900	0.540	25	3	7
	1.650	0.530	25	6	
	2.550	0.470	25	9	
7	Retention time between 30 - 35 days				
	2.402	0.736	30	9.4	6
	3.524	0.736	30	13.8	
	2.402	0.724	30	9.4	
	3.202	0.761	30	11.1	
8	Retention time above 35 days				
	0.400	0.635	50	3	7
	0.900	0.620	50	6	
	1.400	0.600	50	9	

References:

1 Torpey (1955)

2 Malina (1962)

3 Sawyer and Schmidt (1955)

4 Sawyer and Roy (1955)

5	Morgan (1954)
6	Albertson
7	Fisher

Notes: *denotes no available data, figures in brackets denotes estimated values.

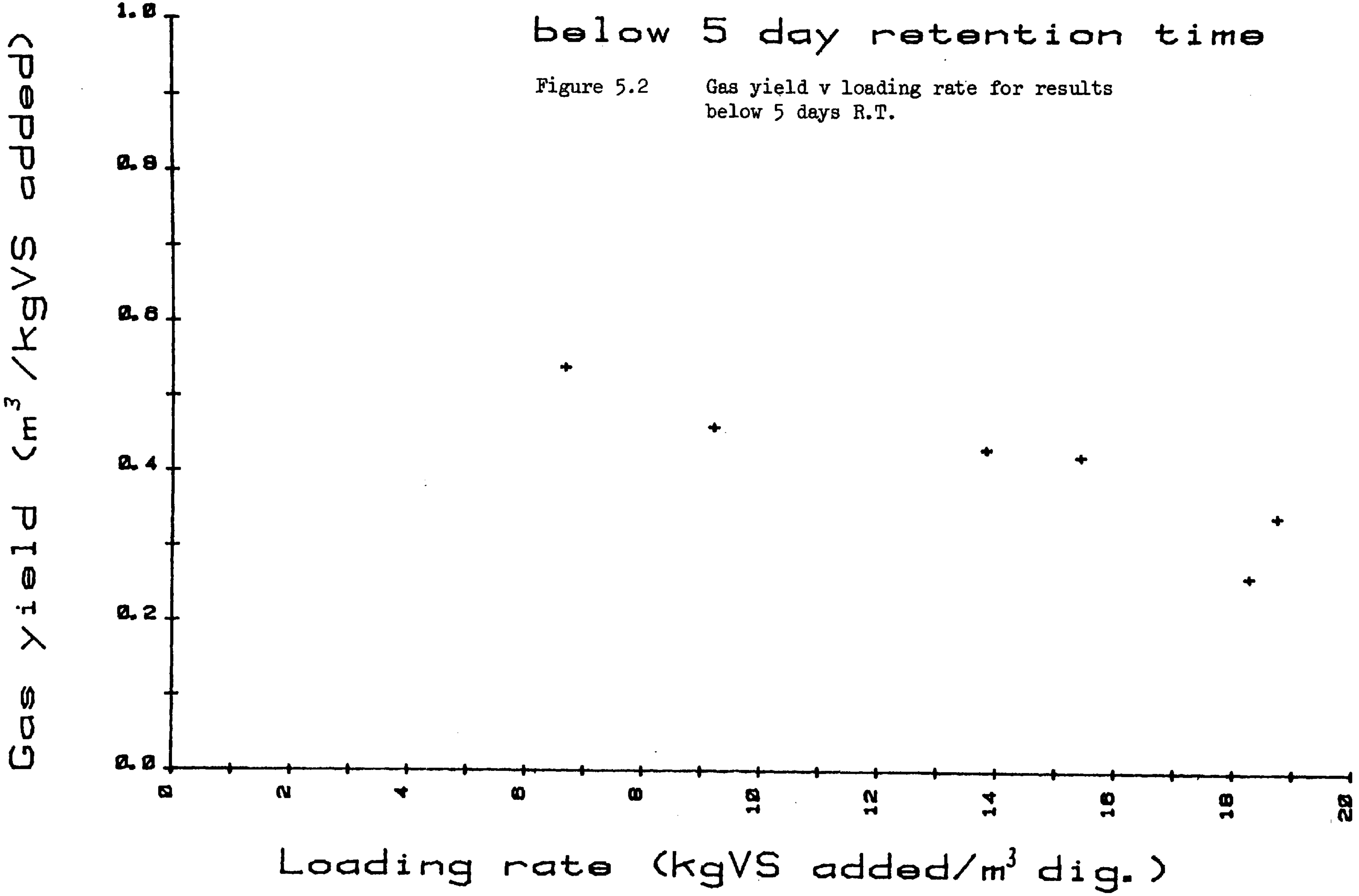


Figure 5.2 Gas yield v loading rate for results below 5 days R.T.

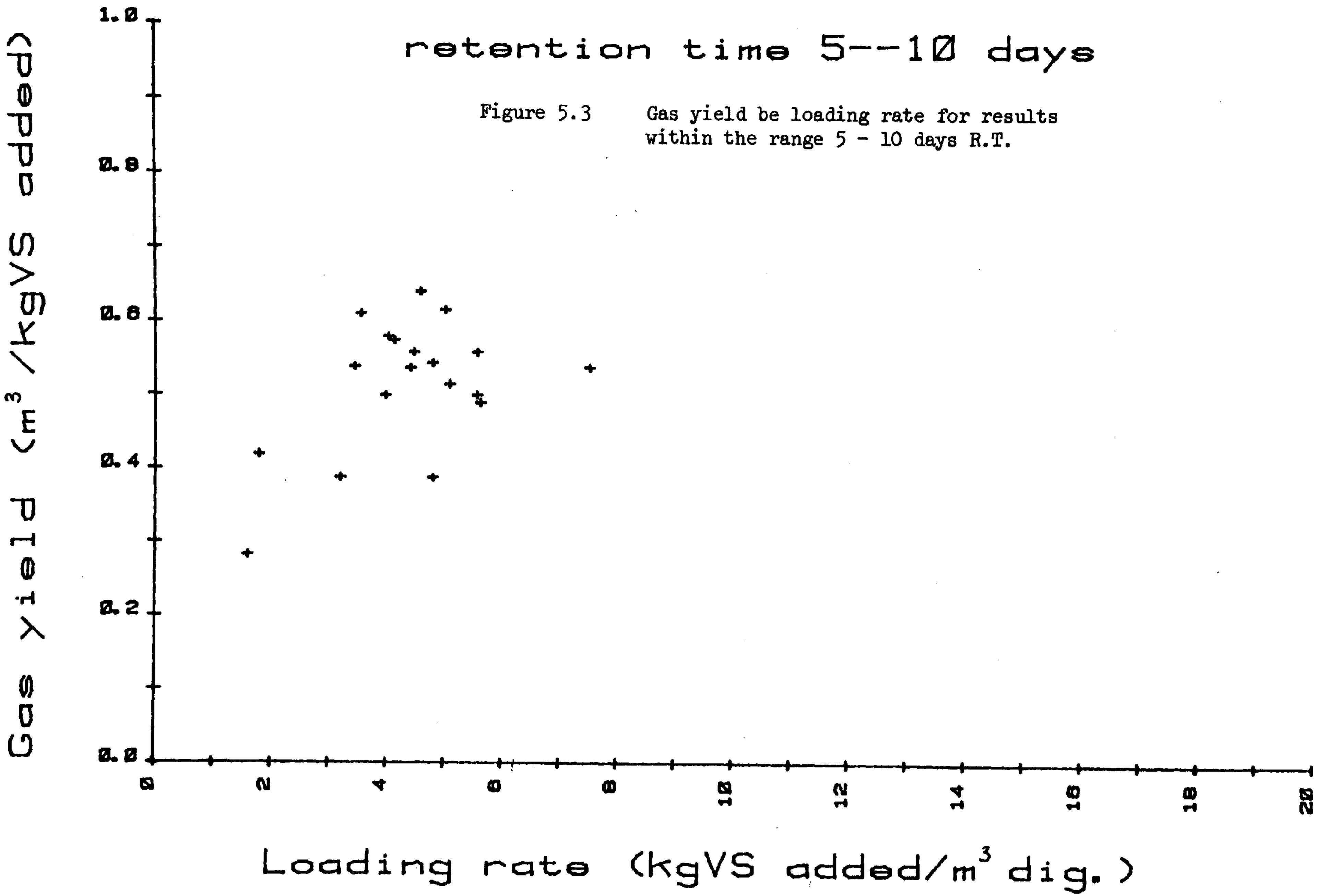


Figure 5.3 Gas yield be loading rate for results within the range 5 - 10 days R.T.

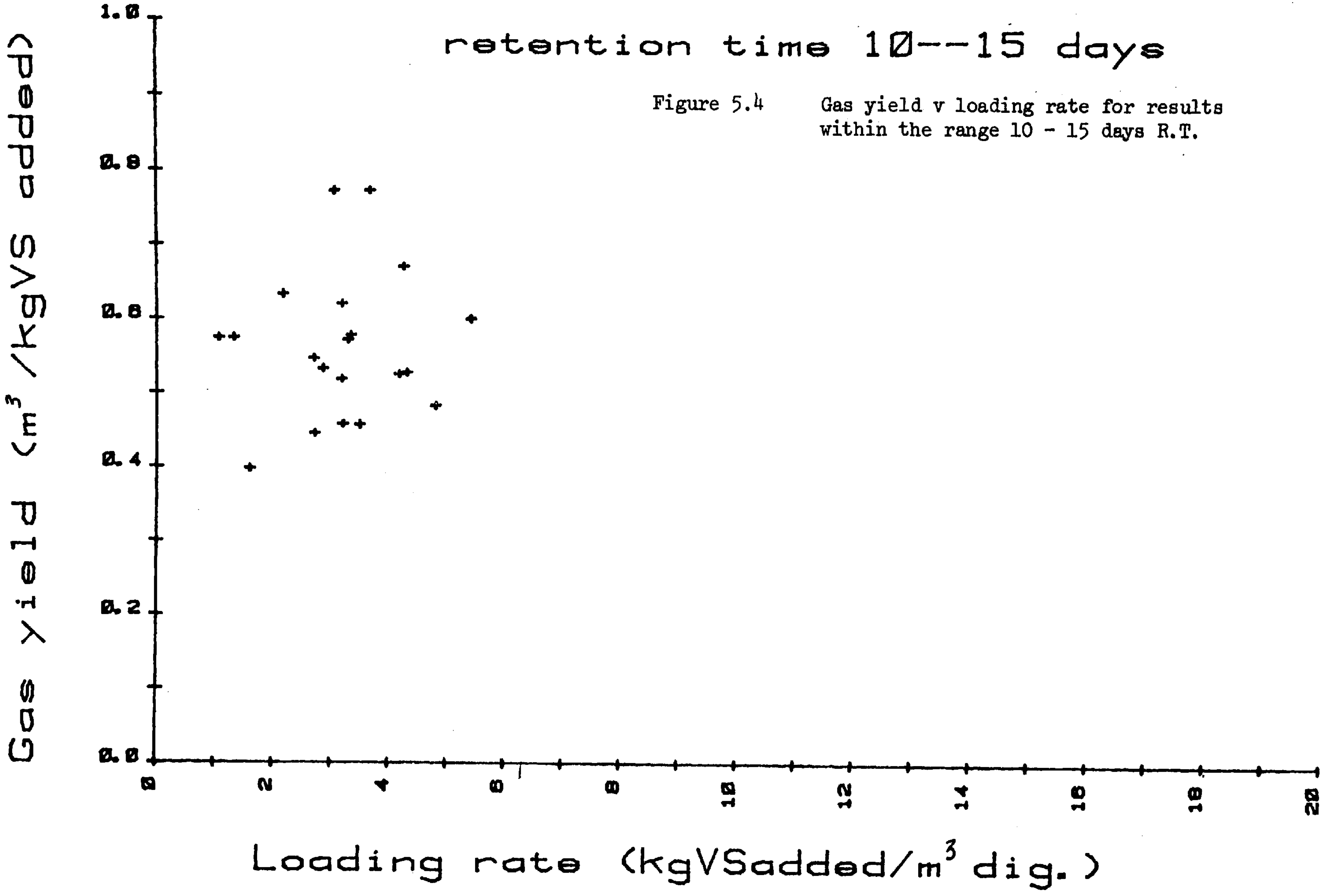


Figure 5.4 Gas yield v loading rate for results within the range 10 - 15 days R.T.

Figure 5.5 Gas yield v loading rate for results within the range 20 - 25 days R.T.

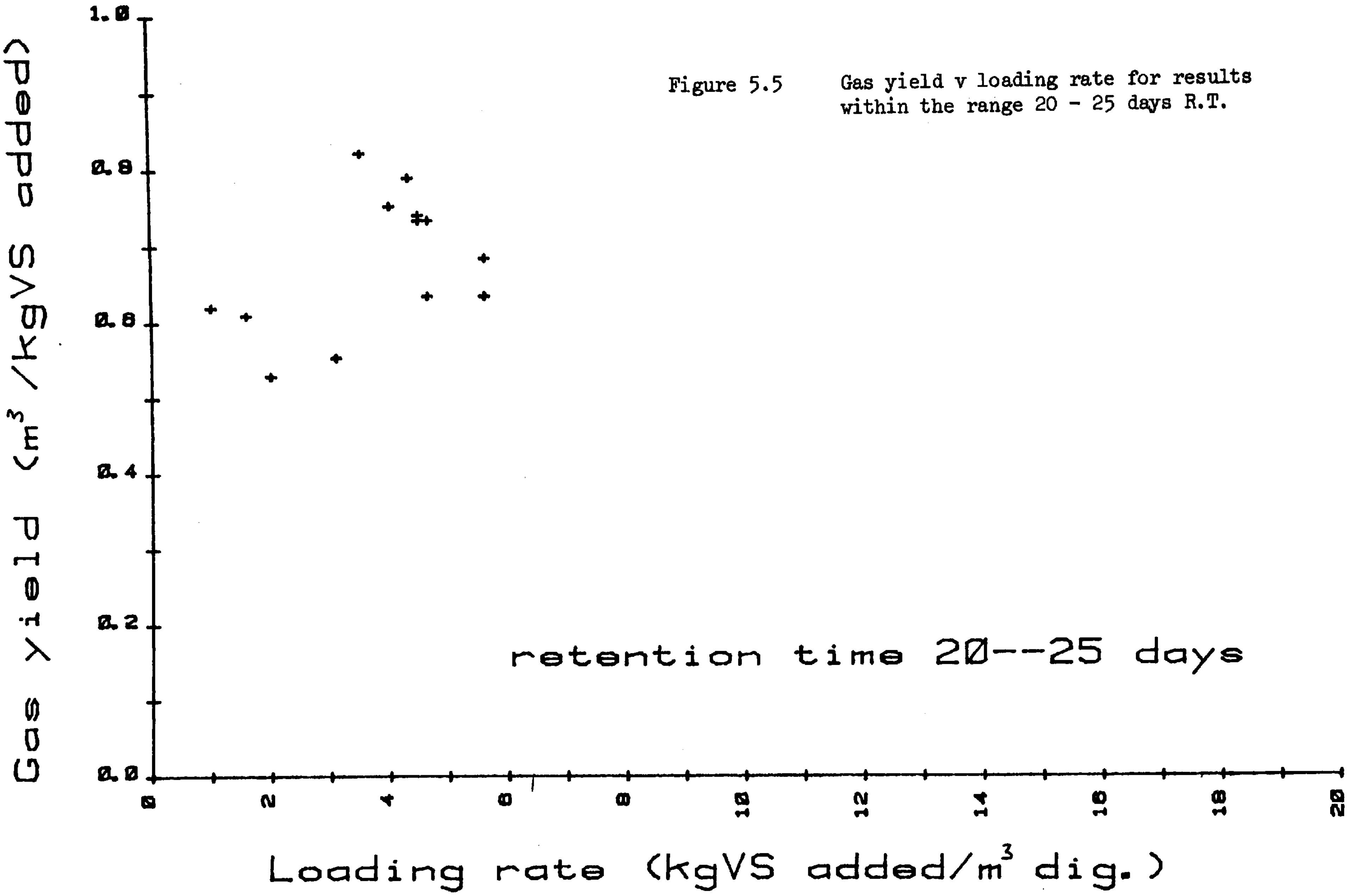
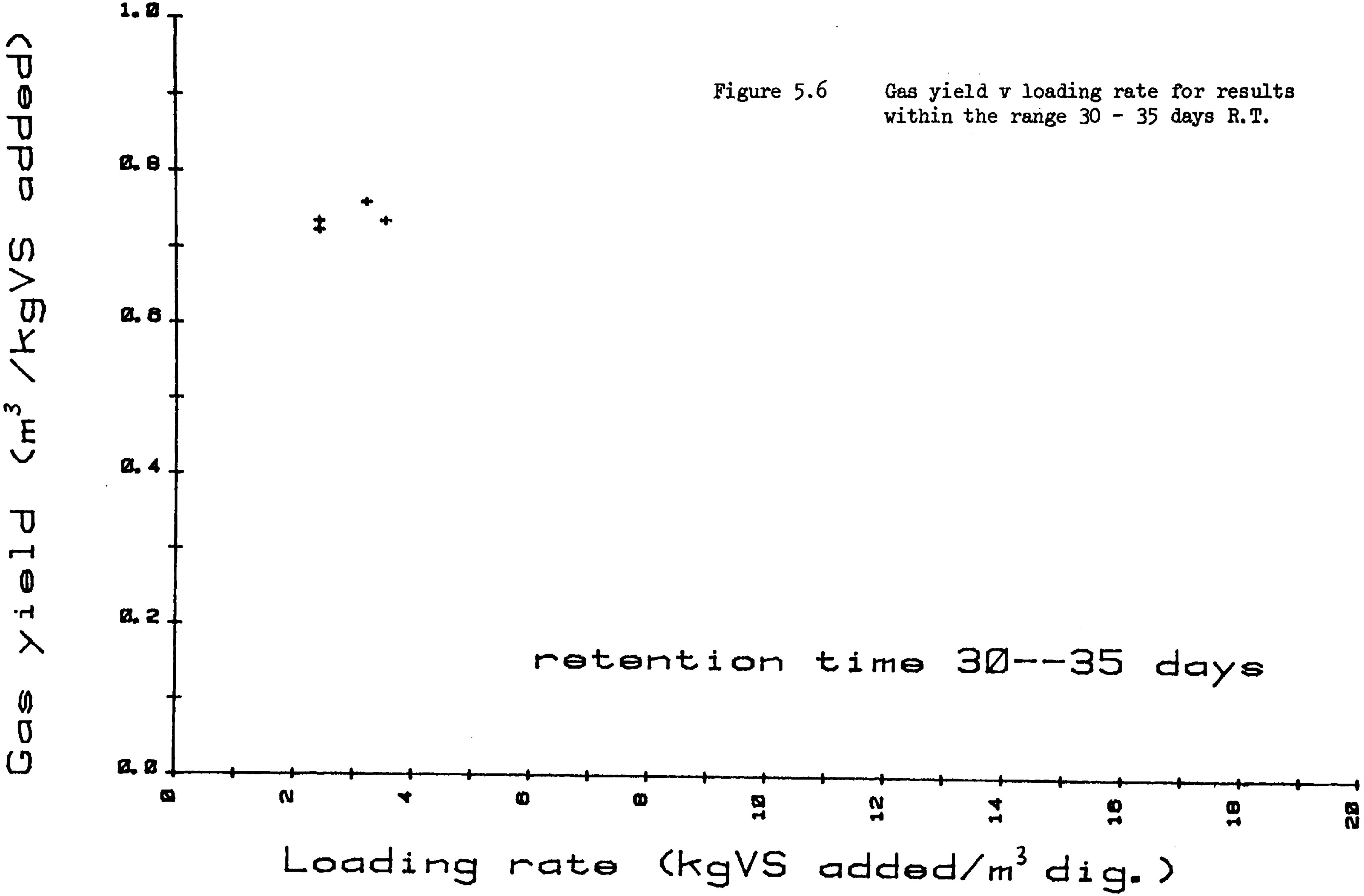


Figure 5.6 Gas yield v loading rate for results within the range 30 - 35 days R.T.



hrough the points in each case must tend to pass through the origin ince for any particular retention time an infinitely low loading rate ust represent an infinitely low solids content and hence zero gas ield due to wash-out. Even with such a large scatter it can be seen hat if a 'best fit' curve were drawn through the data towards the rigin each suceeding retention time group would give a steeper curve. his was carried out for each of the groups of data shown and each 'best it' curve was assumed to be representative of the mean value of the etention times in that group. Once a line of constant retention ime had been obtained for each group of data, points of known volatile olids could be added. These were calculated from the knowledge of etention time and loading rate. Each of the constant retention time ines were plotted on one common diagram and the various points of onstant volatile solids joined up by smooth curves. This carpet plot as then redrawn to give equal increments with whole numbers of retention imes and volatile solids and is shown in Figure 5.7.

Loading rate is a function of both retention time and percentage olatile solids and therefore Figure 5.7 can be drawn as a graph of etention time v gas yield for a family of constant solids lines as in igure 5.8.

.2.C The L.Y.R.S. Diagram

The diagram shown in Figure 5.7 expresses the Loading rate against he Gas Yield for Retention time and Volatile Solids content and will e called the LYRS diagram for convenience. This diagram is extremely seful since it readily shows the effect of any change in retention ime or volatile solids on the gas yield. The grid shown also represents he approximate practical limits, as far as is known, for digestion of

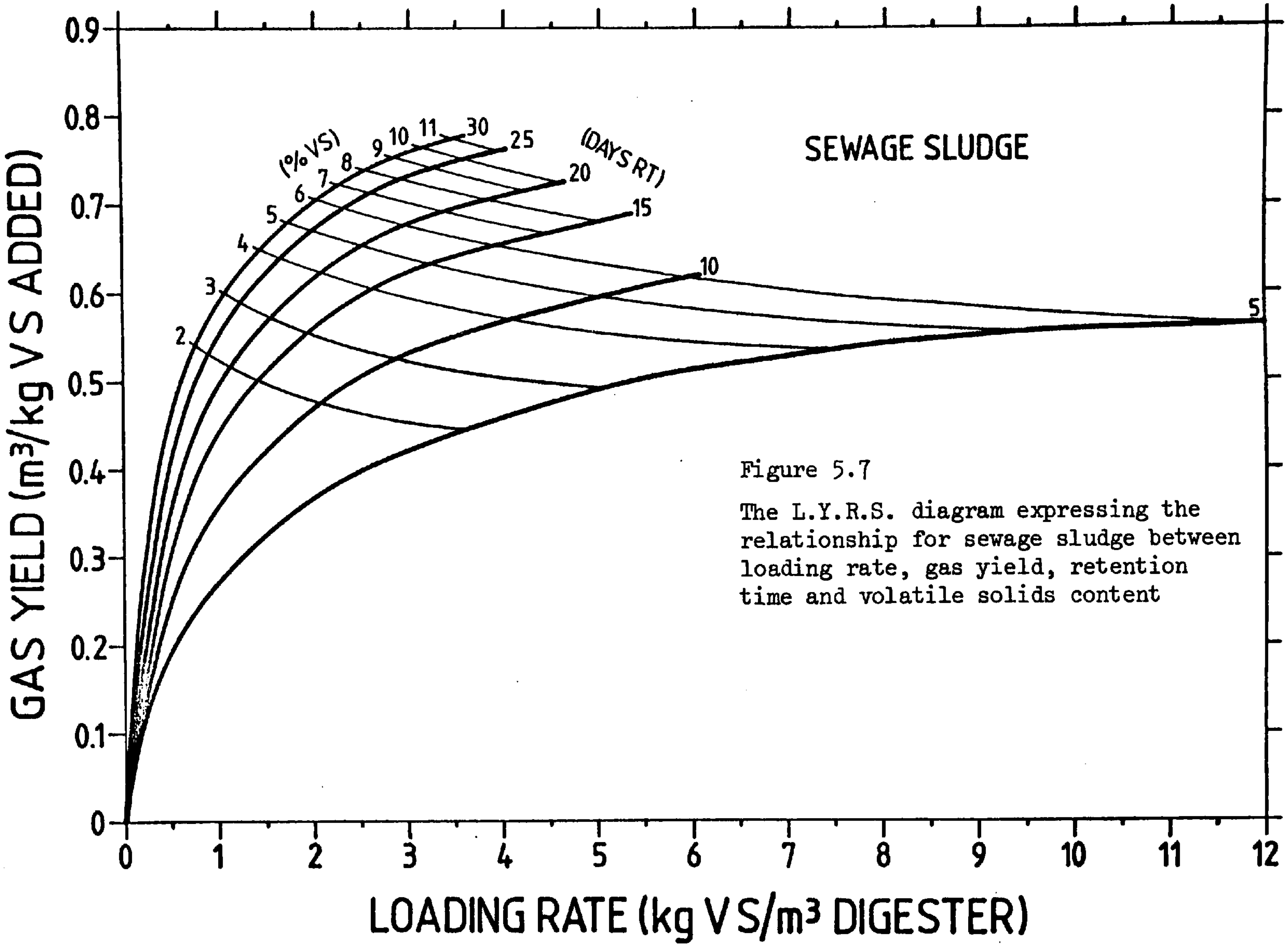


Figure 5.7

The L.Y.R.S. diagram expressing the relationship for sewage sludge between loading rate, gas yield, retention time and volatile solids content

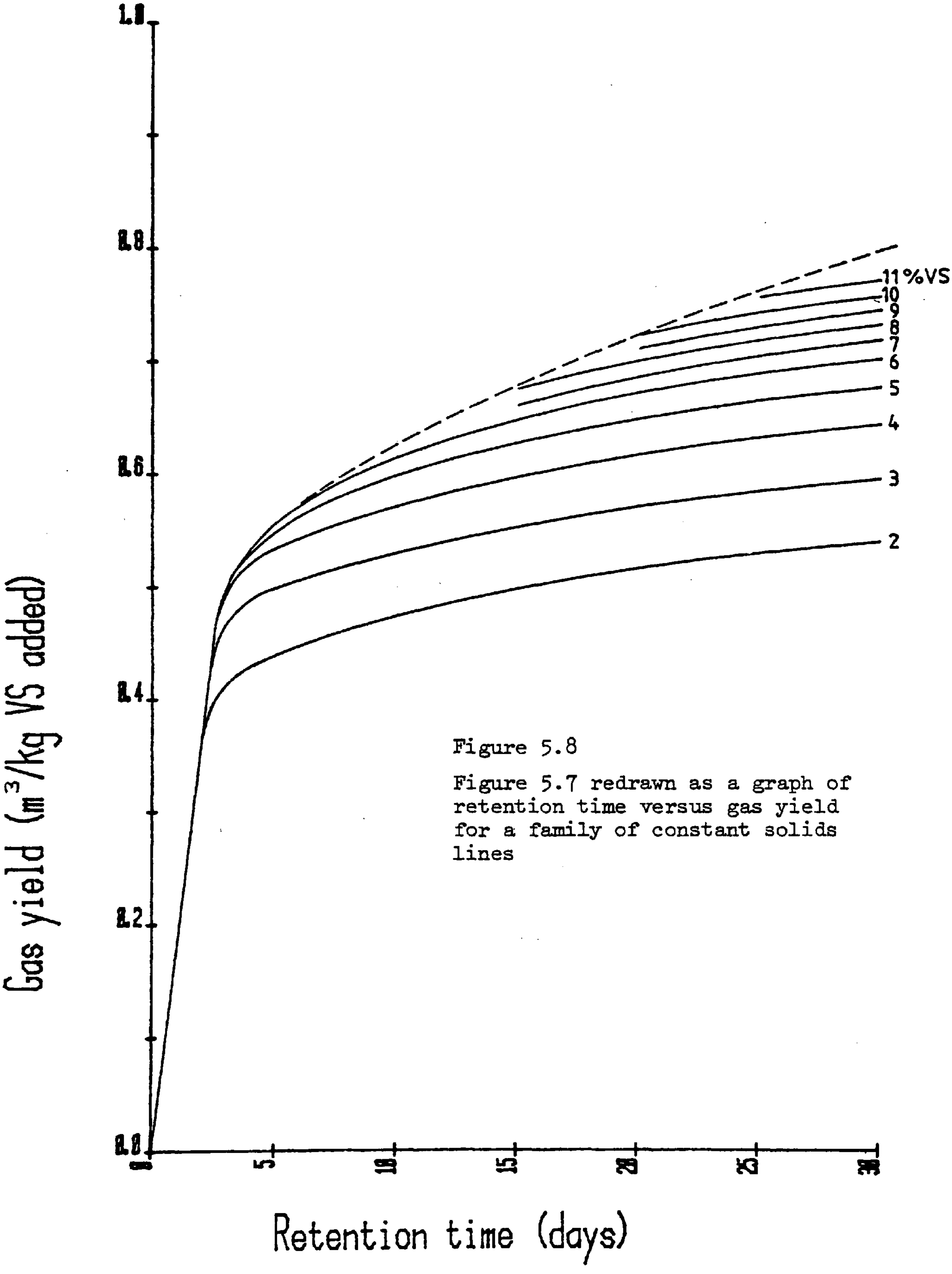


Figure 5.8

Figure 5.7 redrawn as a graph of retention time versus gas yield for a family of constant solids lines sewage sludge.

Consider a 3% VS sludge at a 10 day retention time; this represents, from the LYRS diagram, a loading rate of 2.75 kg VS/m^3 of digester and will give approximately 0.52 m^3/kg VS added. In order to increase the gas yield it is possible at the design stage to choose a longer retention time. For example if we follow the line of constant volatile solids to the 30 day retention time line then the predicted gas yield will rise to about 0.6 m^3/kg VS added.

Similarly if a method is used to thicken the solids, then by going from 3% VS to say 6% VS the gas yield rises from 0.52 to 0.62 m^3/kg VS added. Clearly, if it is possible, the way to achieve the maximum increase in gas yield is to go vertically up as far as possible, within the LYRS diagram grid. That is if 6% VS or more is possible then this together with an increased retention time is most desirable.

The constraints will be technical and financial. There will be technical limits as to how high a solids can be obtained with methods such as settling and centrifugation and also as to the maximum size of digester that can be built in the particular situation. The main limits are of course financial and a cost optimising exercise is necessary to determine whether for example the cost of a larger digester, to enable a longer retention time, is more than offset by the increased value of extra gas that can be obtained.

5.3 A Computer Model

This section contains information concerning the program used for determining net energy production from a full size digester of a type similar to the pilot plant described in Chapter 3, and which was used to determine the Sensitivity Index already described. The program has been run on the Polytechnic's DEC system 20 computer. It comprises the main program PFADP2 which performs the calculations together with data files for a number of different wastes and a curve fitting program PFGCF2 which computes gas yields from experimental data stored in the files. No attempt has been made to predict effluent quality or to include information on any system components before or after digestion.

The model also includes cost calculations and has a subroutine PORQGM for determining the digester gas mixing requirements.

5.3.A Modelling Methods

The usual method for determining gas production in mathematical models of anaerobic digesters involves kinetic equations. (Quindry et al 1976, Ashare et al 1977, Graef S.P. 1972). Kinetic equations similar to those developed in Appendix A are incorporated in the models, the constants being found from plots of experimental data and forming some of the inputs to the computer program. Method 1 (Appendix A) involves plotting the volume of gas produced against a function of the substrate used and the retention time to obtain the proportionality constant. The substrate affinity constant and the maximum specific growth rate can be determined from a graph of retention time against the reciprocal of the available substrate concentration. Method 2 involves the use of a single rate of reaction constant found from a plot of retention time and gas yield. Both of these methods have at times been used by, for example, Athonisen and Cassell (1974) and Pfeffer and Quindry (1978). It was however decided to develop a third method using parameters such as retention time and gas yield directly, rather than the kinetic constants derived from them (see Appendix B program PFADP 2). It is felt that this method is likely to be more accurate since less manipulation of the original experimental results is involved.

Since gas yield depends upon many factors for example physical condition of the substrate, pH, inhibitors, etc. these are thus accounted for in the model,providing the experimental data were obtained on similar waste to the system for which the predictions are being made. This proviso applies to any of the methods that are used. The temperature of digestion, if other than 35°C, can be taken into account by means of a relative gas production curve arrived at by using a curve fitting subroutine POLFIT (line 05900). In the absence of other data the curve shown in Figure 1.6 was used in the program. As further experimental results become available of the effects of temperature on gas yield they can be added to the data store from which the relative gas production curve is obtained.

5.3.B Data Input

The data for the model includes all of the parameters used in the Sensitivity Index (Section 5.1). The daily volume of waste available for digestion is also included as input data. A retention time is specified although the optimum retention time is usually a factor which is to be determined. This is done by a series of computer program runs at different retention times. Net energy production can then be plotted against retention time to determine the optimum.

A digester 'excess capacity factor' is included as a safety factor where this is needed. Digester insulation 'U' factors are included to take account of different constructional methods which may be employed in the digester manufacture.

The temperature of digestion is an input since this can vary at the design stage. A relative gas production curve based on experimental data is used to compute the gas yield that can be expected if the digeste operating temperature is not 35°C. Minimum expected ambient temperature and incoming slurry temperature together with mean annual temperatures are input.

The gas yield can either be computed from an existing data file where this is available or input separately where not enough data exists for computation.

The design of digester for which this program is suited assumes that some of the gas produced may be used to heat the digester. The efficiency of the heat exchanger is therefore input to the program.

5.3.C Calculations

The program PFADP 2 computes the digester volume required for the conditions outlined and then the geometry. Since relatively little energy is lost through the digester walls, if well lagged, (Hawkes D.L., Horton R. 1979) no attempt was made to compute digester dimensions to minimise surface area. Instead the dimensions are computed to give a digester diameter: height ratio of 1 : 0.44 which was substantiated by experiment (Horton R. 1980) to be the best for mixing by gas recirculation. The area of the digester walls in contact with the contents is calculated as is the area of roof in contact with the gas. This is used to compute the heat loss through the walls and roof. The heat required to raise the feed to the digester operating temperature is also calculated.

The gross gas production calculation requires knowledge of the gas yield. This is either input as a single value or in the form of a set of experimental data for each type of waste. Where this is done the data is in the form of arrays of gas yield for particular loading rates. A subroutine POLFIT is used within the program PFGCF 2 (see Appendix B) to find the 'best fit' curve through the points. This curve is then used to arrive at the gas yield for the loading rate computed by the main program.

5.3.D Output

The output includes a full listing of the input data together with the calculated values such as gas production and net energy available after heating and mixing the digester. A sample full output of one set of results is shown in Figure 5.9a and 5.9b and an example of an abbreviated output of 4 sets of results is shown in Figure 5.10. Table 5.5 lists the program main variables.

Figure 5.9 A sample output from the computer program PFADP 2

```
                    ANAEROBIC DIGESTER PROGRAM:

                    INPUT STREAM DATA:
VOLUME OF WASTE PER DAY                                      2.400  CUBIC METRES
DIGESTER RETENTION TIME                                     20.000  DAYS
PERCENTAGE OF TOTAL SOLIDS                                   7.500
PERCENTAGE OF VOLATILE SOLIDS                               70.000
EXCESS CAPACITY FACTOR                                       1.000

                    ENERGY DATA:
U FACTOR FOR DIGESTER WALLS                                  0.778  WATTS/SQUARE  METRE  DEGREE  C
U FACTOR FOR DIGESTER ROOF                                   0.643  WATTS/SQUARE  METRE  DEGREE  C
DIGESTER OPERATING TEMPERATURE                              25.000  DEGREES CENTIGRADE
AIR TEMPERATURE IN WORST CASE                               10.000  DEGREES CENTIGRADE
INFLUENT TEMPERATURE IN WORST CASE                          10.000  DEGREES CENTIGRADE
AVERAGE AIR TEMPERATURE                                     15.000  DEGREES CENTIGRADE
AVERAGE INFLUENT TEMPERATURE                                15.000  DEGREES CENTIGRADE
LOADING RATE                                                 2.625  KILOGRAMS V.S. PER CUBIC METRE PER DAY
GAS PRODUCTION RATE                                          0.328  CUBIC METRES OF GAS PER KG OF VS ADDED
MJ PER CUBIC METRES OF GAS                                  26.000
BOILER EFFICIENCY                                            0.6

                    COST DATA:
COST INDEX FROM PROCESS ENG                                  1.000
KNOWN COST OF DIGESTER OF CERTAIN SIZE                   29000.000  POUNDS
CAPACITY OF KNOWN DIGESTER                                 380.000  CUBIC METRES

                    COMPUTED RESULTS:
CAPACITY OF REQUIRED DIGESTER                               48.000  CUBIC METRES
DIGESTER DIAMETER                                            4.824  METRES
AREA OF DIGESTER SURFACE BELOW LIQUID LEVEL                 55.468  SQUARE METRES
AREA OF DIGESTER SURFACE ABOVE LIQUID LEVEL                 18.916  SQUARE METRES
TOTAL SURFACE AREA OF DIGESTER                              74.384  SQUARE METRES
```

Figure 5.9 continued

```
HEAT LOST THROUGH DIGESTER WALLS                      55.928  MEGA JOULES
HEAT LOST THROUGH DIGESTER ROOF                       15.763  MEGA JOULES
INFLUENT HEATING REQUIREMENTS IN WORST CASE          150.725  MEGA JOULES
TOTAL HEAT LOST                                      222.415  MEGA JOULES
ENERGY REQUIRED TO POWER THE PLANT                   370.692  MEGA JOULES
AVERAGE ENERGY REQUIRED FOR HEATING INFLUENT         100.483  MEGA JOULES
AVERAGE ENERGY LOST THROUGH DIGESTER WALLS            37.285  MEGA JOULES
AVERAGE ENERGY LOST THROUGH DIGESTER ROOF             10.509  MEGA JOULES
AVERAGE TOTAL ENERGY REQUIRED                        148.277  MEGAJOULES
AVERAGE ENERGY REQUIRED                              247.128  MEGA JOULES
GAS PRODUCTION                                        41.373  CUBIC METRES
GAS PRODUCTION                                      1075.689  MEGA JOULES
NET ENERGY PRODUCED IN WORST CASE                    704.996  MEGA JOULES
NET ENERGY AVAILABLE IN AVERAGE CASE                 828.560  MEGA JOULES
CAPITAL COST OF PLANT                               7300.788  POUNDS
QUANTITY OF GAS REQUIRED FOR MIXING                    0.338  CUBIC METRES PER MINUTE
POWER FOR GAS COMPRESSION                              1.132  KW
```

```
                  SUMMARY OF COMPUTED RESULTS:

VOL            2.400       2.400       2.400       2.400
RT            20.000      10.000      25.000      30.000
TS             7.500       7.500       7.500       7.500
VS            70.000      70.000      70.000      70.000
ECF            1.000       1.000       1.000       1.000
UW             0.778       0.778       0.778       0.778
UR             0.643       0.643       0.643       0.643
DITEM         25.000      25.000      25.000      25.000
ATEM          10.000      10.000      10.000      10.000
ITEM          10.000      10.000      10.000      10.000
AATE          15.000      15.000      15.000      15.000
AITE          15.000      15.000      15.000      15.000
LDRAT          2.625       5.250       2.100       1.750
MKGVS          0.328       0.228       0.353       0.371
MJCUM         26.000      26.000      26.000      26.000
BOLEF          0.600       0.600       0.600       0.600
CINDX          1.000       1.000       1.000       1.000
Y          29000.000   29000.000   29000.000   29000.000
C2           380.000     380.000     380.000     380.000
C1            48.000      24.000      60.000      72.000
DGDIA          4.824       3.828       5.196       5.522
ALIQ          55.468      34.943      64.365      72.683
AROF          18.916      11.916      21.950      24.787
TAREA         74.384      46.859      86.315      97.470
HLOSW         55.928      35.232      64.898      73.286
HLOSR         15.763       9.930      18.291      20.655
INFHT        150.725     150.725     150.725     150.725
THTLO        222.415     195.887     233.914     244.666
ENROD        370.692     326.478     389.857     407.777
AVINF        100.483     100.483     100.483     100.483
ALOSW         37.285      23.488      43.265      48.857
ALOSR         10.509       6.620      12.194      13.770
AVTOT        148.277     130.591     155.943     163.111
AVENR        247.128     217.652     259.905     271.851
GASP          41.373      28.739      44.500      46.715
EGASP       1075.689     747.225    1157.001    1214.595
ENNET        704.996     420.747     767.143     806.819
AVENT        828.560     529.573     897.096     942.744
CCOST       7300.708    4599.208    8471.814    9566.739
QGRQD          0.338       0.268       0.364       0.387
MXPO           1.132       0.898       1.219       1.296
```

Figure 5.10 A typical abbreviated output from program PFADP 2 for 4 sets of results

TABLE 5.5 List of program main variables for PFADP 2

Name	Description
AATE	Average ambient temperature throughout the year (°C)
AITE	Average influent temperature throughout the year (°C)
ALIQ	Surface area of digester below the liquid surface (m^2)
ALOSR	Average heat lost through digester roof throughout the year (MJ)
ALOSW	Average heat lost through digester walls throughout the year (MJ)
AROF	Surface area of digester roof (m^2)
ATEM	Ambient temperature (°C) in the worst expected case
AVENT	Average energy content of the net gas produced throughout the year (MJ)
AVINF	Average influent heat required throughout the year (MJ)
BOLEF	Heat exchanger efficiency (%)
CCOST	Capital cost of digester (£)
CINDX	Engineering cost Index
C1	Computed capacity of digester (m^3)
C2	Capacity of digester of known cost Y (m^3)
DGDIA	Digester diameter (m)
DITEM	Digester temperature (°C)
ECF	Excess capacity factor
EGASP	Energy content of the gross gas produced (MJ)
ENNET	Energy value of the net gas produced (MJ)
ENROD	Energy required to power the digester (MJ)
GASP	Gross gas production (m^3)

HLOSR	Heat lost through digester roof (MJ)
HLOSW	Heat lost through the digester walls (MJ)
INFHT	Influent heating requirements (MJ)
ITEM	Influent temperature, (°C) in the worst expected case
LDRAT	Loading rate (kg VS added/m^3 digester/day)
MJCUM	Calorific value of gas (MJ/m^3)
MKGVS	Gas yield (m^3/kg VS added per day)
MXPO	Power required for gas recirculation (kW)
QGRQD	Quantity of gas required for mixing (m^3/min)
RT	Retention time (days)
TAREA	Total surface area of digester (m^2)
THTLO	Total heat lost from digester (MJ)
TS	Total solids content (%)
UR	'U' factor for the digester roof (watts per m^2 per °K)
UW	'U' factor for the digester walls (watts per m^2 per °K)
VOL	Volume of material for digestion (m^3)
VS	Volatile solids content (%)
Y	Known cost of a digester of capacity C2 (£)

CHAPTER SIX

ANAEROBIC DIGESTION - ITS POTENTIAL

6.1 Anaerobic Digestion - Its Benefits

In order to attempt to assess the potential of anaerobic digestion it is necessary to look both at the benefits and the costs of the process. There is an obvious benefit in the surplus gas that can be generated if the plant is designed correctly. Perhaps less obvious is the energy that is saved by using the process of anaerobic digestion for pollution control rather than its alternatives.

6.1.A Gas Production

Almost 90% of the world's total energy comes from fossil fuels which are by definition limited in their life. Table 6.1 shows a breakdown of world energy supplies, with oil providing the majority source at the present time. Renewable energy, that is, that provided from water power, wood fuel and, debatably, nuclear fuel, accounted for only about 10% of the world's energy in 1976 (Baxter 1978).

The amount of energy consumed by the world's population is increasing each year. In North America for example the percentage annual growth for the years 1966-1976 was 3.0% whereas for the year 1975-1976 it was 5.0%. Similar increases were found throughout the world with the overall world percentage annual growth being 4.0% for the ten years 1966-1976. For the year 1975-1976 the world annual growth was 5.0%. (Crabbe and McBride 1978.)

At the same time that energy consumption is increasing the available energy reserves are being depleted. The rate at which they are disappearing and the estimates of their present size are matters for debate. It is now however generally accepted that a large proportion of the world's oil has already been used up. In 1956 a geologist with Shell Oil presented a paper at a conference sponsored by the American

TABLE 6.1 An estimate of the annual amount of energy used by the world's population

	Source	Amount MJ x 10^{12}
Fossil	Oil	120.5
	Solid (coal etc)	81.2
	Natural gas	47.7
Renewable	Water power	15.5
	Wood fuel	12.0
	Nuclear fuel	4.2

Petroleum Institute and demonstrated that the peak of U.S. oil production would be reached in about 10 - 15 years from then (Hubbert M.K. 1956). Despite subsequent discoveries of new oil fields there is evidence to support the view that U.S. oil production did peak in 1970 and that by now a large proportion of the reserves in the United States has been used up (Hayes D. 1977).

The way in which prices have risen recently is an indication of the ever increasing demands on available world oil supplies. The Organisation of Petroleum Exporting Countries (OPEC) was founded in 1960 and has a current membership of 13 states. Between them these countries control more than 50% of the world's energy resources. In November 1973 OPEC assumed the right to set crude oil prices and immediately doubled the price. In January 1974 it was doubled again. By January 1979 the price of Saudi Arabian 'marker' crude had risen to $13.34 a barrel (a barrel is equal to 159 litres) and by July 1979 to $18. The fixed price for oil agreed by OPEC was abandoned in December 1979 with Saudi Arabia unilaterally declaring a price of $24. The spot market trades only about 4% of the total world oil production (December 1979) but the prices here are about double the contracted ones, indicating that the world will shortly be prepared to pay much more for this valuable commodity.

It is because of factors such as these that there has been in recent years a gradually increasing urgency in the search for new sources of energy. For the poorer developing nations this is of even greater importance than for the wealthy West which is better able to afford the increased prices. Solar energy is of course renewable and anaerobic digestion is usually catagorised under this heading since the organic raw material is photosynthetically produced. In many countries the major interest in the process is in the direct production of methane gas. In India for example the rural population, as well as facing a severe shortage of fertilizer, is finding that fuel in the form of firewood (a traditionally large proportion of their primary fuel) is also in very short supply. The only source of inexpensive fuel left to many is cow dung which when dried in the sun burns well. It is estimated (Hayes 1977) that about 68 million tons of dry cow dung are burned in this way each year, when virtually all the nutrients are lost and only about 9% of the heat energy is available for use. The widespread introduction of small biogas plants encouraged by the government means that the fertilizer content of the cow dung is retained and the energy available in this organic material is more efficiently extracted. The Khadi and Village Industries Commission gives financial and technical assistance to farmers wishing to install such equipment. The Commission has been working on the 'Gobar Gas' scheme for about 15 years; in 1973 there were about 6250 plants installed in various states (Kashkari 1975) and by 1976 numbers had risen to 25,000. Even in 1973 the volume of gas produced by the plants was over 10 million cubic metres. This is perhaps an insignificant amount of energy by world standards but is very significant to those who benefit from it.

The funds allocated for research in the field of anaerobic digestion or other 'alternative energy' sources throughout the world have been low. Recently however there has been a move to increase the research and development in these areas and in industrialised countries this has been partly due to changes in government attitudes and partly through private industry beginning to see a future for this 'soft' technology. In the United States firms have, for example, begun to exploit the vast sanitary landfills for the recovery of methane. These are in effect huge batch digesters which produce gas for up to 20 years. In the Palos Verdes landfill of the Los Angeles County Sanitation District Authority over 56,600 m^3 per day of pipeline quality gas, almost pure methane, are now being delivered directly to the Southern California Gas Company for distribution (Hekimian et al 1976). It has been estimated that methane recovery in the order of 2,830,000 m^3 per day is possible from the largest landfills and by the mid-1980's perhaps as much as 1.2% of the U.S.A.'s natural gas may be generated from this source alone.

One of the largest sources of natural organic waste available in many countries for anaerobic digestion is cattle manure and this is resulting in much experimental work using this material, aimed mainly at improving the technology involved. Work in the U.S.A. by Hamilton Standard (Coe et al 1973) on the digestion of cattle manure was so successful that they concluded that a feedlot of more than 5000 head of cattle could be economically suitable for anaerobic digestion, a decision reached even in the days of cheap oil. A plant now operating at Guymon, Oklahoma is capable of processing 500 tonnes of cattle manure daily. It is now producing methane gas which is being bought by the People's Gas Corporation, Chicago. A lot of work is also going on in the U.S.A. in the development of small scale units (Jewell 1979).

If all the animal waste and crop residues produced in the U.S.A. were to be digested then the resulting methane could yield the equivalent of about 20% of the 1973 natural gas consumption according to Prof. P. McCarty (De Renzo 1977). This is only slightly lower than the

TABLE 6.2 U.K. consumption of primary fuels for energy

Coal		315.2×10^4 TJ
Petroleum		362.4×10^4 TJ
Natural Gas		165.5×10^4 TJ
Primary Electricity		39.7×10^4 TJ
	Total	882.8×10^4 TJ

TABLE 6.3 Possible energy production by anaerobic digestion from already occuring organic waste

Source		Energy Available
Municipal Refuse		1.0×10^4 TJ
Cattle Manure		3.0×10^4 TJ
Poultry Manure		1.8×10^4 TJ
Pig Slurry		1.2×10^4 TJ
Sewage Sludge		1.4×10^4 TJ
	Total	8.4×10^4 TJ

figure estimated for the United Kingdom (Stafford, Horton, Hawkes 1979). Table 6.2 shows the U.K. consumption of primary fuels for energy (H.M.S.O. 1978).

Table 6.3 shows the energy available from some sources of waste computed from currently available mean gas yields but without taking into account the energy required to run the process. It has been assumed that these gross figures could be the net figures with very little process development (Stafford, Horton, Hawkes 1979).

Similar figures have been reported elsewhere (Langley 1979) based on a report commissioned for the U.K. Department of Energy on the potential of Anaerobic Digestion (Ader 1979). Table 6.4 summarises these findings in terms of potential energy (in Mtce) from a number of wastes in the short/medium term and by the year 2000.

TABLE 6.4 Availability of wastes suitable for anaerobic digestion

Summary of Waste Arisings	Short/Medium Term Quantity (Mt/y)	Energy Yield (Mtce)	By Year 2000 Quantity (Mt/y)	Energy Yield (Mtce)
Cattle manure	0.6 - 0.7	0.2	5.5 - 7.0	2.5
Pig slurry	0.7 - 1.0	0.4	0.7 - 1.0	0.4
Poultry waste	0.2 - 0.4	0.1	0.5 - 0.8	0.4
Sewage sludge	0.5 - 0.7	0.2	1.0 - 1.7	0.5
Sugar beet residues	0.1 - 0.2	0.05	0.5 - 0.6	0.2
Total	2.1 - 3.0	1	8.3 - 11.1	4

In this table the quantities of arisings are calculated as dry and ash free, i.e. volatile solids, and energy yields are based on an average figure of 8.5 GJ/tonne of dry solids. This is equivalent to 0.35 m^3/kg VS, a not unreasonable figure. In the short to medium term the energy believed to be available from these wastes is about 1 Mtce, that is 2.7 x 10^4 TJ, and by the year 2000 about four times this, that is 10.8 x 10^4 TJ. Neither of these estimates takes into account energy crops which are currently being studied as a further large source of biomass suitable for conversion by anaerobic digestion.

The cost of energy produced by anaerobic digestion has been predicted in a report (Ader 1979) to the Energy Technology Support Unit (ETSU), to be between £4.9 per GJ and £1.5 per GJ depending upon the scale of operation. For the largest digester capacity envisaged in that report, 5000 m^3, the cost of gas produced was estimated to be between £1.5/GJ and £2.0/GJ. This was for a digester capital cost estimated to be £108 per m^3. The cost of natural gas was then (March 1979) £1.4/GJ to £1.9/GJ and of liquid propane £3.3/GJ to £3.8/GJ. Liquid propane is widely used in many farming situations and hence these costs are included for comparison with the expected cost of gas from anaerobic digesters.

Although these figures both of predicted quantity and cost are encouraging an even greater benefit would result if the net energy from digesters could be improved. As was seen in Chapter 5 the parameter which has the largest effect on net energy is gas yield and this can be increased by operating digesters at a higher solids feed and at a longer retention time. Even an apparently small change in gas yield can result in a substantial increase in net energy and the figure of 10.8 x 10^4 TJ by the year 2000 could no doubt be greatly improved upon.

6.1.B <u>Energy Saving</u>

The methods used for the disposal of animal wastes and sewage involve either large volumes for storage for long periods or a considerable energy input. With respect to the disposal of sewage sludge the following methods (Table 6.5) are the most common. The costs in £ per tonne of dry solids, as at October 1974 price levels, are also given (Porch et al 1977) in Table 6.5.

1. Lagooning - This involves storage of the sludge for 2 years in a lagoon in which cold anaerobic digestion takes place. The solids are reduced by about 35% by this method.

2. Belt Pressing - Here the sludge is passed through a belt press in order to dewater it before disposal to land. The cost advantages of this method over direct sludge to land are in the reduced transport costs.

3. Lime Stabilization - Sludges may be stabilized by the addition of lime after thickening and before transporting to land.

4. Plate Pressing - Filter plate presses can be used to dewater the sludge usually after adding polyelectrolytes, lime or copperas. It is a batch process and is more expensive than belt pressing.

5. Digestion - This is the most expensive of the methods shown in Table 6.5.

6.2 The Cost

The figures in Table 6.5 are based on costing procedures used in the Water Industry and it is largely because of the high capital cost of sewage digesters that the process is not more widespread. The cost of U.K. municipal mesophilic digesters on average is £101 per m^3 for a 2941 m^3 capacity (based on data originating between the mid 1960's and the mid 1970's but corrected to 1976 prices) (Water Research Centre 1977).

Costs for a similar size digester (3000 m^3) based on prices quoted by manufacturers of digesters for farm wastes and extrapolated using the six tenths rule, common in chemical engineering costing, could be

TABLE 6.5 Methods of disposal of sewage sludge with their approximate costs in 1974

	Method of Disposal	Costs £/tonne dry solids
1	Treatment lagoons - tanker to land	19
2	Belt press - store - cake to land	27
3	Thicken - lime stabilization - tanker to land	28
4	Thicken - plate press (lime and copperas added) - cake to tip	33
5	Thicken - plate press (polyelectrolyte added) - cake to land	31
6	Mesophilic digestion - thicken - tanker to land	35

less than half that for a municipal digester (Stafford, Hawkes, Horton 1980), £53/m^3 in 1978.

Work in the U.S.A. specifically on the development of low cost digesters at Cornell University suggests that it should be possible to achieve a digester cost as low as £5/m^3 for a capacity of 5500 m^3 (Jewell 1979) using flexible liners of the type being operated at Cornell. Much of the present research in engineering design of digesters is aimed at reducing the cost in this way and although £5/m^3 may be considered too optimistic it is certain that there will be a considerable reduction from the present U.K. cost of £101/m^3 for large municipal digesters. When this happens the process will be very much more attractive as a method of pollution control since, providing the solids content is high enough, no energy would be required to run the process. This is not the case with any of the alternatives except lagooning which has other disadvantages. Thus the energy savings which are possible by using the anaerobic digestion process, a net energy producer, rather than one of the alternative systems, which are energy users, must be considerable although difficult to quantify.

CHAPTER SEVEN

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

7.1 General Observations on Scientific Method

Science is defined as systematic and formulated knowledge. The science of anaerobic digestion is in its infancy since despite the relatively large 'body of information' that there is about the process, collected over many years, there is very little in the way of a collection of quantitative data from which theories concerning digester performance could be originated. The scientific approach is one in which improvements are made, through trial and error, in theories and predictions. New hypotheses are repeatedly postulated and tested against observed data; predictions are made deducing logically what the theory predicts in certain circumstances. The observed data, from one's own experiements or those of others, is used to test these predictions. If there is little or no agreement then a further and hopefully better theory is originated; this creative process is known as induction.

7.2 Conclusions

The objective of the research was the examination of the major variables which affect gas production in mesophilic digestion. The most important conclusions are summarised below:

(a) The specially designed pilot plants proved suitable for the digestion of sewage sludge and the simple device used for retaining solids was effective. It was observed that the frequency of gas mixing made no difference to the total volume of gas produced.

(b) A relationship between gas yield and loading rate was observed such that a lower loading rate produced a higher gas yield.

(c) This 'scientific theory' relating gas yield and loading rate was tested using other experimental data from both sewage sludge and animal wastes. There was a qualified agreement with the predictions.

(d) A Sensitivity Index demonstrated that the major factors influencing net gas production were the gas yield and the solids content of the feed.

(e) The relationship postulated between gas yield and loading rate was found to be more complex than expressed in conclusion (b), since loading rate is a function of both retention time and feed solids. The gas yield increases with increasing retention time and with increasing solids.

(f) This relationship can usefully be expressed in the form of a L.Y.R.S. diagram.

7.3 Suggested Further Work

i. Data Collection - What is needed now is a programme of experimentation on animal and other wastes in which gas yield is measured with accurately controlled solids feeds at various retention times.

This can be carried out more readily in a laboratory situation than on a large pilot scale digester and since the conclusion of the author's research programme an SRC grant has been awarded elsewhere within the Polytechnic of Wales to examine the digestion of chicken litter specifically with this relationship in view.

ii. Storage and Use of Data - It is not enough to carry out experiments and collect data; the information gained must be stored in a readily accessible form so that it may be used. The computer model described in this thesis is able to draw upon experimentally determined values for gas yields to predict net energy production. At present there are a number of data files containing information on a variety of waste materials. These are in the form of gas yield v loading rate graphs. As more data becomes available it is necessary to analyse and store this in a convenient standard format. The computer programme necessary for input storage and output is now being written. The task of arranging the new data and putting it into the files is one of the subjects of a Department of Energy grant application for 1980.

When sufficient data is available to construct an L.Y.R.S. diagram for the various wastes, other than sewage sludge, some modification of the computer programme will be necessary to take this into account.

iii. Experimental Work to Develop a Simple Inexpensive Gas Detector System - The problem of the control of digesters is one that has not yet been adequately solved. There are several methods that have been advocated in the past. For example monitoring of pH and control by the addition of an alkali has often been practised. Unfortunately this method has the disadvantage that a change in pH occurs sometime after the methane bacteria have been inhibited especially in a well buffered system such as sewage sludge digestion. If the digester is to be used for energy generation then the best parameter for monitoring the activity of the methane producing bacteria is the methane gas itself. Any sudden reduction of the proportion of methane in the biogas produced usually indicates problems with digestion, often organic overload, and can be corrected by reducing the feed. If the proportion of methane together with the quantity of biogas were both measured continuously then it should be possible to use these parameters for the control of the digester operating regime.

Several methods of gas detection based on various chemical and physical principles are now available, for example: a. <u>Detection Tube</u>

This device is based on a colour change which results from a chemical reaction between the gas and the tube contents. This is an accurate quantitive system but each tube can only be used once and so although suitable for spot checking it is not suitable for continuous monitoring.

b. Catalytic Combustion This system is widely used for gas detection although not usually in digesters. It is based on the temperature change produced by catalytic combustion on a platinum wire sensor. The system requires a relatively expensive amplifier.

c. Infra Red Spectrophotometry/Gas Chromatography These systems are the ones used for the daily monitoring of gas composition throughout the experimental period reported in this thesis. They are highly accurate but for continuous detection the costs are very high.

d. Semi-conductor Detector This device is often used in low cost gas detection systems for example fire alarms, alcohol detectors and air pollution monitors. The semi-conductor sensor is based on N type sintered SnO_2 and when combustible or reducing gases are absorbed on the sensor surface a marked decrease in electrical resistance occurs. Modern sensors such as that marketed by Figaro Engineering Inc.* are very reliable and long lasting and, of particular interest in the application to digesters, are low in price and use low cost circuitry. They are extremely sensitive to traces of certain gases (several hundred ppm of gas can be detected). This is not necessary for monitoring changes in biogas composition but it should be possible to reduce this sensitivity either by coating the semi-conductor or by altering the circuitry associated with it.

* 373 Higashitoyouaka, Toyonaka City, Osaka 560, Japan.

It is envisaged that a number of semi-conductors could be put in the gas line each one modified to respond to a different level of methane in carbon dioxide; thus changes in methane content of the gas could be monitored. No information could be found to show if this were possible and whether the device would respond to mixtures of methane in carbon dioxide. (All the applications quoted by the manufacturer were for the detection of a gas in air.)

A simple test was therefore carried out to see if this idea was worth pursuing. A Figaro TGS gas sensor type 109 was set up with the basic measuring circuit shown below in Figure 7.1.

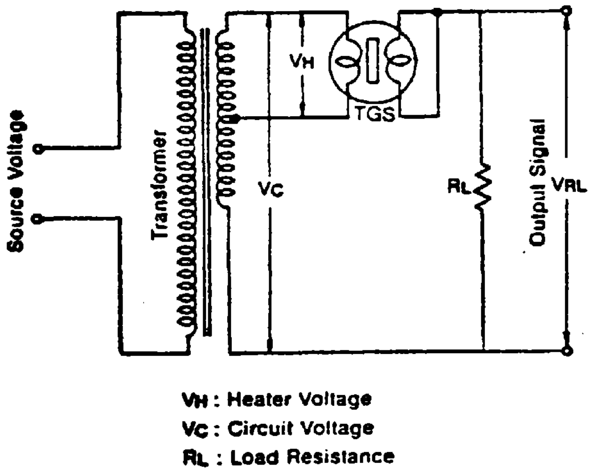


Figure 7.1 Basic measuring circuit with sensor type 109

The variation in resistance of the TGS sensor was measured indirectly as a change in voltage appearing across the load resistor R_L. The sensor was set up in a container which could be filled with either CO_2 or CH_4; the results were as follows.

Gas	Voltage
Air only	2 - 3 volts
CO_2 only	2.8 - 3.4 volts
CH_4 only	59 volts

These results are sufficient to show that there is a large difference between the voltage of the semi-conductor in pure CO_2 and in pure CH_4. What is required now is accurate calibration for various levels of these two gases followed by the development of a practical low cost device for measuring relatively large changes in composition of biogas. The continuous measurement of gas volume is comparatively straight-forward. These two parameters, gas composition and volume with the addition of a microprocessor could be used to control the digester feeding mechanism and hence loading rate. Adequate control of the loading rate in relation to the production of methane would be a suitable way of preventing or correcting an organic overload or washout - two of the most common causes of digester failure.

iv. Effects of Temperature - Most work on anaerobic digestion has been carried out in the region of 35°C for the mesophilic range since this is regarded as about the optimum temperature for the process from the <u>gross</u> gas production point of view. In terms of the <u>net</u> energy production however 35°C may not be the best temperature at which to operate the digester. Figure 1.4 in Chapter 1 shows some of the data available for sewage sludge and this has been used in the computer programme. The facility is built in to allow the up-dating of this curve as and when further information becomes available. The gas production results for pig slurry at various temperatures are at present sparse and somewhat conflicting. For example results from the Rowett

Institute (Summers R. 1979) suggest that for pig slurry a large proportion of the gas produced at 35°C is still produced at 25°C whereas the proportion according to Lettinga (1979) is much less. More work needs to be carried out in this area since running digesters at below 35°C has many advantages and could result in large energy savings. It is therefore proposed that the Polytechnic's digesters are run at a series of temperatures from 15°C to 35°C to determine the optimum temperature for net energy production for a variety of wastes.

APPENDIX A

KINETIC MODELLING

A1 Kinetics

Anaerobic digestion depends upon the growth of micro-organisms and as such it should be possible to explain the kinetics of the process using basic principles that are applied to bacterial growth. For example the classic growth curve for micro-organisms in batch culture involves firstly a lag phase, the course of which depends on the character of the medium that the micro-organisms had come from, the properties of the cell and the type of cultivation. The growth rate continues increasing up to its maximum value during which there is a logarithmic increase in the number of cells being formed. During this phase the mass of cells increase at the expense of the substrate and the growth rate is proportional to the amount of biomass. Thus from the slope of this straight part of the curve can be determined the specific growth rate μ, a constant which expresses the rate of increase of cell mass to the mass of cells present.

Eventually the growth and dividing of cells slows down as nutrients are used up and the specific growth rate gradually approaches zero. Finally growth stops and the culture passes into the stationary phase. In the continuous culture of micro-organisms such as occurs in modern high rate anaerobic digesters, ideally the inflow of fresh nutrient media into the digester is the same as the outflow of the used nutrient.

The ratio of inflowing amount of nutrient per time to the volume of the culture is called the dilution rate, D, which is the reciprocal of the retentiontime. If the dilution rate is kept constant the concentration of a certain principle substrate is adjusted by the influences of cell metabolism to a value making the specific growth rate, μ, equal to D. If the so called critical dilution rate is not exceeded and $D < \mu_{max}$ then the total rate of substrate inflow and the concentration of the constituents becomes constant and a steady state ensues which can be maintained indefinitely. The resulting specific growth rate at which the biomass is formed is therefore proportional to the effective concentration of some nutrient.

According to Monod the dependance of growth rate constant on the limiting substrate concentration is given by

$$\mu = \mu_{max} \cdot \frac{s}{k_s + s} \qquad (1)$$

where k_s is the substrate affinity constant or saturation constant, i.e. the limiting substrate concentration at which $\mu = \frac{1}{2}\mu_{max}$, and where s is the available substrate concentration.

For a continuous flow completely mixed bacterial culture the cell balance can be described by the differential equation:

increase = growth - output + input - death

$$\frac{dX}{dt} = \mu X - DX + 0 - 0 \qquad (2)$$

assuming there is no input of cells and that cell autolysis is negligible X is the cell concentration.

When steady state conditions are reached the increase is zero i.e.

$$\frac{dX}{dt} = 0$$

thus $0 = \mu X - DX$

or $\mu = D$ (3)

Equation (3) is characteristic of a continuous flow completely mixed culture.

The dilution rate D cannot exceed μ_{max} the maximum growth rate constant attained only during constant growth phase and when $D \simeq \mu_{max}$

a continuous culture is operating at the maximum rate.

If we now replace μ with D in equation (1) we get

$$D = \frac{\mu_{max} \cdot s}{k_s + s}$$

rearranging we get

$$s = \frac{D\, k_s}{\mu_{max} - D} \qquad (4)$$

or

$$\frac{1}{D} = \frac{k_s}{\mu_{max}} \left(\frac{1}{s}\right) + \frac{1}{\mu_{max}} \qquad (5)$$

which is an equation of a straight line when $\frac{1}{D}$ is plotted against $\frac{1}{s}$ with $\frac{1}{\mu_{max}}$ as the ordinate intercept and $\frac{k_s}{\mu_{max}}$ the slope of the line.

The substrate balance in the digester can be expressed by

change = Input - Output - Consumption (6)

Now the volatile solids measurement does not truly reflect the level of biodegradable organics in the feed to the digester and the substrate input in equation (6) is the available substrate, that is the biodegradable portion of the volatile solids.

Estimates of this available portion can be made as follows:

The volatile solids concentration can be represented by equation (7)

$$S_{vs} = (TS) \times (\%\ VS) \qquad (7)$$

where S_{vs} is the measured volatile solids concentration in mg/l, TS is the total % TS x 10000 and % VS is the percentage of volatile solids as measured.

If we assume that only part of S_{vs} is available for microbial degradation this can be expressed as follows:

$$S_{VS} = S_B + S_U \qquad (8)$$

where S_B is the biodegradable portion and S_U is the unavailable portion. Subscripts F and C are used to indicate feed and digester contents thus:

${}_FS_B$ stands for the biodegradable portion of the volatile solids in the feed and ${}_CS_U$, the unavailable portion in the digester contents.

Returning to equation (6) this can be written as

$$\frac{ds}{dt} = D.{}_FS_B - D.{}_CS_B - \frac{\mu X}{Y} \qquad (9)$$

where X is the cell concentration and Y is the yield coefficient, that is the organisms produced divided by the substrate utilised. The assumption is made for equation (9) that the input of cells to the digester is negligible and that autolysis is negligible when steady state conditions are operating.

At steady state conditions

$\frac{ds}{dt} = 0$ and equation (9) becomes

$$Y\ ({}_FS_B - {}_CS_B) = \frac{\mu X}{D} \qquad (10)$$

In practice it is difficult to measure the cell concentration X and similarly a direct determination of Y cannot easily be made.

A2 Determination of Gas Production

A.2.A Method 1

It may be reasonably assumed that the total daily gas production is directly proportional to the amount of substrate utilised. Equation (10) can then be expressed as

$$Q = k_1\ ({}_FS_B - {}_CS_B)\ .\ V.D. \qquad (11)$$

where Q is the volume of gas produced per day, k_1 is the proportionality constant (l/mg) and V is the digester volume.

Combining equations (10) and (11) we get

$$\mu X = \frac{QY}{k_1 V} \qquad (12)$$

Equation (12) shows that for a digester volume of V maintained at a dilution rate D the gas production is directly proportional to microbial concentration. The constant k_1 can be obtained from a plot of Q versus $({}_FS_B - {}_CS_B)$. V.D. Substituting equation (4) into (11) gives

$$Q = k_1 V.D. \left({}_FS_B - \frac{D\,k_s}{\mu_{max} - D}\right) \qquad (13)$$

Equation (13) shows that daily gas production Q is dependant on the constants k_1, k_s, μ_{max}, V the digester volume ${}_FS_B$ the available substrate in the feed and the dilution rate D.

An estimate of the biodegradable solids available for microbial breakdown is given by a plot of S_{VS} against dilution rate when the intercept on S_{VS} axis at a zero dilution rate (an infinite retention time) is a measure of the unavailable substrate S_V.

A.2.B Method 2

Another approach also assumes that the measured gas yield expressed as m^3/kg VS added is directly proportional to the amount of substrate utilised. In this method a plot of the log of gas production against dilution rate gives an intercept which represents the level of gas at an infinite retention time or an estimate of the initial level of biodegradable organics expressed as m^3/kg VS.

Then ${}_FS_B - {}_CS_B$ = portion used up which is a measure of the gas yield.

i.e. $${}_FS_B - {}_CS_B = \text{gas yield} \qquad (14)$$

dividing through by ${}_CS_B$,

$$\frac{{}_F S_B}{{}_C S_B} = \frac{\text{gas yield}}{{}_C S_B} + 1 \tag{15}$$

Now the rate of reaction of the microbial process is equal to a constant K times the substrate concentration,

$$\text{Rate of reaction} = K \times {}_C S_B \tag{16}$$

and also rate of reaction for an anaerobic digester is expressed by the gas yield divided by the retention time i.e.

$$\text{Rate of reaction} = \frac{\text{gas yield}}{RT} \tag{17}$$

equating (16) and (17) we get

$$\text{gas yield} = RT \times K \times {}_C S_B \tag{18}$$

and substituting (18) into (15)

$$\frac{{}_F S_B}{{}_C S_B} = \frac{RT \,.\, K \,.\, {}_C S_B}{{}_C S_B} + 1$$

or

$$\frac{{}_F S_B}{{}_C S_B} = RT \,.\, K + 1 \tag{19}$$

${}_F S_B$ and ${}_C S_B$ if expressed as the gas yield can be easily measured as can RT so that K can be found from a plot of equation (19).

The total gas production can then be obtained from the expression

$$Q = \frac{K \,.\, RT \,.\, {}_F S_B}{(K \,.\, RT + 1)} \times \text{biodegradable solids mass flow rate,}$$

${}_F S_B$ and the flow rate being characteristics of the feed.

APPENDIX B

PROGRAM LISTINGS

Program PFADP 2

```
COMMENT:  'THIS PROGRAM IS SUITABLE FOR ANY WASTE BUT
C           WITH HORTON/HAWKES DESIGN OF DIGESTER ONLY'
C
C
C
C
      REAL INFHT,ITEM,ITEMP,LDRAT,MKGVS,MJCUM
      DOUBLE PRECISION FILE
      DIMENSION COEFF(10),RES(10)
      DIMENSION DT(2)
      DIMENSION NAMIN(18),NAMINA(1),NAMOUT(22)
      DIMENSION VALIN(18,50),VALINA(1,50)
      DIMENSION NCF(10),CF(10,10)
      DIMENSION FX(4),FY(4)
      COMMON ILIST,IRUN,DGDIA,VALOUT(22,50)
      DATA FX/15.0,20.0,25.0,35.0/
      DATA FY/0.69,0.81,0.91,1.0/
      DATA MAXRUN/50/
      DATA NAMIN(1)/'VOL  '/
      DATA NAMIN(2)/'RT   '/
      DATA NAMIN(3)/'TS   '/
      DATA NAMIN(4)/'VS   '/
      DATA NAMIN(5)/'ECF  '/
      DATA NAMIN(6)/'UW   '/
      DATA NAMIN(7)/'UR   '/
      DATA NAMIN(8)/'DITEM'/
      DATA NAMIN(9)/'ATEM'/
      DATA NAMIN(10)/'ITEM'/
      DATA NAMIN(11)/'AATE'/
      DATA NAMIN(12)/'AITE'/
      DATA NAMIN(13)/'MKGVS'/
      DATA NAMIN(14)/'MJCUM'/
      DATA NAMIN(15)/'BOLEF'/
      DATA NAMIN(16)/'CINDX'/
      DATA NAMIN(17)/'Y    '/
      DATA NAMIN(18)/'C2   '/
      DATA NAMINA(1)/'LDRAT'/
      DATA NAMOUT(1)/'C1   '/
      DATA NAMOUT(2)/'DGDIA'/
      DATA NAMOUT(3)/'ALIQ '/
      DATA NAMOUT(4)/'AROF '/
      DATA NAMOUT(5)/'TAREA'/
      DATA NAMOUT(6)/'HLOSW'/
      DATA NAMOUT(7)/'HLOSR'/
      DATA NAMOUT(8)/'INFHT'/
      DATA NAMOUT(9)/'THTLO'/
      DATA NAMOUT(10)/'ENROD'/
      DATA NAMOUT(11)/'AVINF'/
      DATA NAMOUT(12)/'ALOSW'/
      DATA NAMOUT(13)/'ALOSR'/
      DATA NAMOUT(14)/'AVTOT'/
      DATA NAMOUT(15)/'AVENR'/
      DATA NAMOUT(16)/'GASP '/
      DATA NAMOUT(17)/'EGASP'/
      DATA NAMOUT(18)/'ENNET'/
      DATA NAMOUT(19)/'AVENT'/
      DATA NAMOUT(20)/'CCOST'/
      DATA NAMOUT(21)/'QGRQD'/
      DATA NAMOUT(22)/'MXPO '/
      CALL POLFIT(4,FX,FY,2,NORDER,COEFF,RES)
 1100 CALL DATE(DT)
      WRITE(5,1000)DT
      WRITE(5,1074)
 1074 FORMAT('0','IS CURVE AVAILABLE FOR MKGVS?, TYPE YES OR NO:',2X,$)
      READ(5,1093)ANS
      IF(ANS.EQ.'YES  ')IEQ=1
      IF(ANS.EQ.'NO   ')IEQ=0
```

```
      IF(IEQ.EQ.0)GOTO 1104
      WRITE(5,1075)
      READ(5,1094)ICODE
      IF(ICODE.EQ.101)FILE='CUR101.DAT'
      IF(ICODE.EQ.102)FILE='CUR102.DAT'
      IF(ICODE.EQ.103)FILE='CUR103.DAT'
      IF(ICODE.EQ.20)FILE='CUR20.DAT'
      IF(ICODE.EQ.30)FILE='CUR30.DAT'
      IF(ICODE.EQ.40)FILE='CUR40.DAT'
      IF(ICODE.EQ.50)FILE='CUR50.DAT'
      IF(ICODE.EQ.60)FILE='CUR60.DAT'
      IF(ICODE.EQ.70)FILE='CUR70.DAT'
      IF(ICODE.EQ.80)FILE='CUR80.DAT'
      OPEN(UNIT=1,DEVICE='DSK',ACCESS='SEQIN',FILE=FILE)
      ITERM=0
 1101 ITERM=ITERM+1
      READ(1,1099,END=1103)NCF(ITERM)
 1099 FORMAT(I0)
      DO1102 I=1,NCF(ITERM)
      READ(1,1091)CF(ITERM,I)
 1102 CONTINUE
      GOTO 1101
 1103 NTERMS=ITERM-1
 1104 WRITE(5,1071)
 1105 READ(5,1090)NRUN
      IF(NRUN.GE.1.AND.NRUN.LE.MAXRUN)GOTO 1110
      WRITE(5,1060)
      GOTO 1105
 1110 WRITE(5,1072)
      READ(5,1092)NVOL,NRT,NTS,NVS,NECF,NUW,NUR,NDITEM,NATEM,NITEM,NAATE
     1,NAITE,NMKGVS,NMJCUM,NBOLEF,NCINDX,NY,NC2
      IF(NVOL.EQ.0)NVOL=NRUN
      IF(NRT.EQ.0)NRT=NRUN
      IF(NTS.EQ.0)NTS=NRUN
      IF(NVS.EQ.0)NVS=NRUN
      IF(NECF.EQ.0)NECF=NRUN
      IF(NUW.EQ.0)NUW=NRUN
      IF(NUR.EQ.0)NUR=NRUN
      IF(NDITEM.EQ.0)NDITEM=NRUN
      IF(NATEM.EQ.0)NATEM=NRUN
      IF(NITEM.EQ.0)NITEM=NRUN
      IF(NAATE.EQ.0)NAATE=NRUN
      IF(NAITE.EQ.0)NAITE=NRUN
      IF(NMKGVS.EQ.0)NMKGVS=NRUN
      IF(NMJCUM.EQ.0)NMJCUM=NRUN
      IF(NBOLEF.EQ.0)NBOLEF=NRUN
      IF(NCINDX.EQ.0)NCINDX=NRUN
      IF(NY.EQ.0)NY=NRUN
      IF(NC2.EQ.0)NC2=NRUN
      WRITE(5,1080)
      DO1150 IRUN=1,NRUN
      IF(IRUN.LE.NVOL)WRITE(5,1073)NAMIN(1),IRUN
      IF(IRUN.LE.NVOL)READ(5,1091)VALIN(1,IRUN)
      IF(IRUN.GT.NVOL)VALIN(1,IRUN)=VALIN(1,IRUN-1)
      IF(IRUN.LE.NRT)WRITE(5,1073)NAMIN(2),IRUN
      IF(IRUN.LE.NRT)READ(5,1091)VALIN(2,IRUN)
      IF(IRUN.GT.NRT)VALIN(2,IRUN)=VALIN(2,IRUN-1)
      IF(IRUN.LE.NTS)WRITE(5,1073)NAMIN(3),IRUN
      IF(IRUN.LE.NTS)READ(5,1091)VALIN(3,IRUN)
      IF(IRUN.GT.NTS)VALIN(3,IRUN)=VALIN(3,IRUN-1)
      IF(IRUN.LE.NVS)WRITE(5,1073)NAMIN(4),IRUN
      IF(IRUN.LE.NVS)READ(5,1091)VALIN(4,IRUN)
      IF(IRUN.GT.NVS)VALIN(4,IRUN)=VALIN(4,IRUN-1)
      IF(IRUN.LE.NECF)WRITE(5,1073)NAMIN(5),IRUN
      IF(IRUN.LE.NECF)READ(5,1091)VALIN(5,IRUN)
      IF(IRUN.GT.NECF)VALIN(5,IRUN)=VALIN(5,IRUN-1)
```

```
     IF(IRUN.LE.NUW)WRITE(5,1073)NAMIN(6),IRUN
     IF(IRUN.LE.NUW)READ(5,1091)VALIN(6,IRUN)
     IF(IRUN.GT.NUW)VALIN(6,IRUN)=VALIN(6,IRUN-1)
     IF(IRUN.LE.NUR)WRITE(5,1073)NAMIN(7),IRUN
     IF(IRUN.LE.NUR)READ(5,1091)VALIN(7,IRUN)
     IF(IRUN.GT.NUR)VALIN(7,IRUN)=VALIN(7,IRUN-1)
     IF(IRUN.LE.NDITEM)WRITE(5,1073)NAMIN(8),IRUN
     IF(IRUN.LE.NDITEM)READ(5,1091)VALIN(8,IRUN)
     IF(IRUN.GT.NDITEM)VALIN(8,IRUN)=VALIN(8,IRUN-1)
     IF(IRUN.LE.NATEM)WRITE(5,1073)NAMIN(9),IRUN
     IF(IRUN.LE.NATEM)READ(5,1091)VALIN(9,IRUN)
     IF(IRUN.GT.NATEM)VALIN(9,IRUN)=VALIN(9,IRUN-1)
     IF(IRUN.LE.NITEM)WRITE(5,1073)NAMIN(10),IRUN
     IF(IRUN.LE.NITEM)READ(5,1091)VALIN(10,IRUN)
     IF(IRUN.GT.NITEM)VALIN(10,IRUN)=VALIN(10,IRUN-1)
     IF(IRUN.LE.NAATE)WRITE(5,1073)NAMIN(11),IRUN
     IF(IRUN.LE.NAATE)READ(5,1091)VALIN(11,IRUN)
     IF(IRUN.GT.NAATE)VALIN(11,IRUN)=VALIN(11,IRUN-1)
     IF(IRUN.LE.NAITE)WRITE(5,1073)NAMIN(12),IRUN
     IF(IRUN.LE.NAITE)READ(5,1091)VALIN(12,IRUN)
     IF(IRUN.GT.NAITE)VALIN(12,IRUN)=VALIN(12,IRUN-1)
     IF(IEQ.EQ.0.AND.IRUN.LE.NMKGVS)WRITE(5,1073)NAMIN(13),IRUN
     IF(IEQ.EQ.0.AND.IRUN.LE.NMKGVS)READ(5,1091)VALIN(13,IRUN)
     IF(IEQ.EQ.0.AND.IRUN.GT.NMKGVS)VALIN(13,IRUN)=VALIN(13,IRUN-1)
     IF(IRUN.LE.NMJCUM)WRITE(5,1073)NAMIN(14),IRUN
     IF(IRUN.LE.NMJCUM)READ(5,1091)VALIN(14,IRUN)
     IF(IRUN.GT.NMJCUM)VALIN(14,IRUN)=VALIN(14,IRUN-1)
     IF(IRUN.LE.NBOLEF)WRITE(5,1073)NAMIN(15),IRUN
     IF(IRUN.LE.NBOLEF)READ(5,1091)VALIN(15,IRUN)
     IF(IRUN.GT.NBOLEF)VALIN(15,IRUN)=VALIN(15,IRUN-1)
     IF(IRUN.LE.NCINDX)WRITE(5,1073)NAMIN(16),IRUN
     IF(IRUN.LE.NCINDX)READ(5,1091)VALIN(16,IRUN)
     IF(IRUN.GT.NCINDX)VALIN(16,IRUN)=VALIN(16,IRUN-1)
     IF(IRUN.LE.NY)WRITE(5,1073)NAMIN(17),IRUN
     IF(IRUN.LE.NY)READ(5,1091)VALIN(17,IRUN)
     IF(IRUN.GT.NY)VALIN(17,IRUN)=VALIN(17,IRUN-1)
     IF(IRUN.LE.NC2)WRITE(5,1073)NAMIN(18),IRUN
     IF(IRUN.LE.NC2)READ(5,1091)VALIN(18,IRUN)
     IF(IRUN.GT.NC2)VALIN(18,IRUN)=VALIN(18,IRUN-1)
1150 CONTINUE
     WRITE(5,1065)
1065 FORMAT(' ','DO YOU WANT THE FULL OUTPUT; TYPE YES OR NO:',2X,$)
1152 READ(5,1093)ANS
1093 FORMAT(A5)
     IF(ANS.EQ.'YES  '.OR.ANS.EQ.'NO   ')GOTO 1154
     WRITE(5,1066)
1066 FORMAT('+','INVALID; PLEASE RETYPE:',2X,$)
     GOTO 1152
1154 IF(ANS.EQ.'YES  ')ILIST=1
     IF(ANS.EQ.'NO   ')ILIST=0
     DO1160 IRUN=1,NRUN
     VOL=VALIN(1,IRUN)
     RT=VALIN(2,IRUN)
     TS=VALIN(3,IRUN)
     VS=VALIN(4,IRUN)
     ECF=VALIN(5,IRUN)
     UW=VALIN(6,IRUN)
     UR=VALIN(7,IRUN)
     DITEM=VALIN(8,IRUN)
     ATEM=VALIN(9,IRUN)
     ITEM=VALIN(10,IRUN)
     AATE=VALIN(11,IRUN)
     AITE=VALIN(12,IRUN)
     IF(IEQ.EQ.0)MKGVS=VALIN(13,IRUN)
     IF(IEQ.EQ.0)GOTO 6580
     LDRAT=(VOL*1000.0*(TS/100.0)*(VS/100.0))/(VOL*RT)
```

```
      VALINA(1,IRUN)=LDRAT
      MKGVS=0.0
      DO6570 ITERM=1,NTERMS
      EXFNA=0.0
      DO6565 IK=1,NCF(ITERM)
      EXFNA=EXFNA+CF(ITERM,IK)*LDRAT**(IK-1)
 6565 CONTINUE
      MKGVS=MKGVS+EXP(EXFNA)
 6570 CONTINUE
      VALIN(13,IRUN)=MKGVS
 6580 MJCUM=VALIN(14,IRUN)
      BOLEF=VALIN(15,IRUN)
      CINDX=VALIN(16,IRUN)
      Y=VALIN(17,IRUN)
      C2=VALIN(18,IRUN)
      FAC=COEFF(1)
      IF(NORDER.EQ.0)GOTO6590
      DO6588 I=1,NORDER
      FAC=FAC+COEFF(I+1)*DITEM**I
 6588 CONTINUE
 6590 CONTINUE
      MKGVS=FAC*MKGVS
      VALIN(13,IRUN)=MKGVS
      IF(ILIST.EQ.1)WRITE(5,1000)DT
      IF(ILIST.EQ.1)WRITE(5,1001)
      IF(ILIST.EQ.1)WRITE(5,1002)VOL
      IF(ILIST.EQ.1)WRITE(5,1003)RT
      IF(ILIST.EQ.1)WRITE(5,1004)TS
      IF(ILIST.EQ.1)WRITE(5,1005)VS
      IF(ILIST.EQ.1)WRITE(5,1006)ECF
      IF(ILIST.EQ.1)WRITE(5,1011)
      IF(ILIST.EQ.1)WRITE(5,1012)UW
      IF(ILIST.EQ.1)WRITE(5,1013)UR
      IF(ILIST.EQ.1)WRITE(5,1096)DITEM
      IF(ILIST.EQ.1)WRITE(5,1014)ATEM
      IF(ILIST.EQ.1)WRITE(5,1015)ITEM
      IF(ILIST.EQ.1)WRITE(5,1019)AATE
      IF(ILIST.EQ.1)WRITE(5,1020)AITE
      IF(IEQ.EQ.1.AND.ILIST.EQ.1)WRITE(5,1025)LDRAT
      IF(ILIST.EQ.1)WRITE(5,1016)MKGVS
      IF(ILIST.EQ.1)WRITE(5,1017)MJCUM
      IF(ILIST.EQ.1)WRITE(5,1018)BOLEF
      IF(ILIST.EQ.1)WRITE(5,1021)
      IF(ILIST.EQ.1)WRITE(5,1022)CINDX
      IF(ILIST.EQ.1)WRITE(5,1023)Y
      IF(ILIST.EQ.1)WRITE(5,1024)C2
      IF(ILIST.EQ.1)WRITE(5,1030)
      ATEMP=DITEM-ATEM
      ITEMP=DITEM-ITEM
      AATEM=DITEM-AATE
      AITEM=DITEM-AITE
      VOLDG=VOL*RT*ECF
      C1=VOLDG
      VALOUT(1,IRUN)=C1
      IF(ILIST.EQ.1)WRITE(5,1031)C1
      DGDIA=(VOLDG/0.4277)**(1.0/3.0)
      VALOUT(2,IRUN)=DGDIA
      IF(ILIST.EQ.1)WRITE(5,1032)DGDIA
      ALIQ=2.384*DGDIA**2
      VALOUT(3,IRUN)=ALIQ
      IF(ILIST.EQ.1)WRITE(5,1033)ALIQ
      AROF=0.813*DGDIA**2
      VALOUT(4,IRUN)=AROF
      IF(ILIST.EQ.1)WRITE(5,1034)AROF
      TAREA=ALIQ+AROF
      VALOUT(5,IRUN)=TAREA
```

```
      IF(ILIST.EQ.1)WRITE(5,1035)TAREA
      HLOSW=(ALIQ*ATEMP*UW*86400.0)/(10.0**6)
      VALOUT(6,IRUN)=HLOSW
      IF(ILIST.EQ.1)WRITE(5,1036)HLOSW
      HLOSR=(AROF*ATEMP*UR*86400.0)/(10.0**6)
      VALOUT(7,IRUN)=HLOSR
      IF(ILIST.EQ.1)WRITE(5,1037)HLOSR
      INFHT=(VOL*1000.0*ITEMP*4186.8)/(10.0**6)
      VALOUT(8,IRUN)=INFHT
      IF(ILIST.EQ.1)WRITE(5,1038)INFHT
      THTLO=HLOSW+HLOSR+INFHT
      VALOUT(9,IRUN)=THTLO
      IF(ILIST.EQ.1)WRITE(5,1039)THTLO
      ENROD=THTLO/BOLEF
      VALOUT(10,IRUN)=ENROD
      IF(ILIST.EQ.1)WRITE(5,1040)ENROD
      AVINF=(VOL*AITEM*4186.8*1000.0)/(10.0**6)
      VALOUT(11,IRUN)=AVINF
      IF(ILIST.EQ.1)WRITE(5,1041)AVINF
      ALOSW=(ALIQ*AATEM*UW*86400.0)/(10.0**6)
      VALOUT(12,IRUN)=ALOSW
      IF(ILIST.EQ.1)WRITE(5,1042)ALOSW
      ALOSR=(AROF*AATEM*UR*86400.0)/(10.0**6)
      VALOUT(13,IRUN)=ALOSR
      IF(ILIST.EQ.1)WRITE(5,1043)ALOSR
      AVTOT=AVINF+ALOSW+ALOSR
      VALOUT(14,IRUN)=AVTOT
      IF(ILIST.EQ.1)WRITE(5,1044)AVTOT
      AVENR=AVTOT/BOLEF
      VALOUT(15,IRUN)=AVENR
      IF(ILIST.EQ.1)WRITE(5,1045)AVENR
      GASP=VOL*1000.0*(TS/100.0)*(VS/100.0)*MKGVS
      VALOUT(16,IRUN)=GASP
      IF(ILIST.EQ.1)WRITE(5,1046)GASP
      EGASP=GASP*MJCUM
      VALOUT(17,IRUN)=EGASP
      IF(ILIST.EQ.1)WRITE(5,1047)EGASP
      ENNET=EGASP-ENROD
      VALOUT(18,IRUN)=ENNET
      IF(ILIST.EQ.1)WRITE(5,1048)ENNET
      AVENT=EGASP-AVENR
      VALOUT(19,IRUN)=AVENT
      IF(ILIST.EQ.1)WRITE(5,1049)AVENT
      CCOST=CINDX*Y*(C1/C2)**(2.0/3.0)
      VALOUT(20,IRUN)=CCOST
      IF(ILIST.EQ.1)WRITE(5,1050)CCOST
      CALL FORQGM
1160  CONTINUE
      WRITE(5,1000)DT
      WRITE(5,1055)
      J1=1
1180  J2=MIN0(NRUN,J1+7)
      DO1185 I=1,18
      IF(IEQ.EQ.1.AND.I.EQ.13)WRITE(5,1056)NAMINA(1),(VALINA(1,J),J=J1,J
     12)
      WRITE(5,1056)NAMIN(I),(VALIN(I,J),J=J1,J2)
1185  CONTINUE
      DO1190 I=1,22
      WRITE(5,1056)NAMOUT(I),(VALOUT(I,J),J=J1,J2)
1190  CONTINUE
      WRITE(5,1080)
      WRITE(5,1080)
      J1=J2+1
      IF(J2.LT.NRUN)GOTO 1180
      DO1195 I=1,4
      WRITE(5,1080)
```

```
1195 CONTINUE
     CALL EXIT
1000 FORMAT(////' ',20X,'ANAEROBIC DIGESTER PROGRAM;  DATE:  ',2A5)
1001 FORMAT('-',20X,'INPUT STREAM DATA:')
1002 FORMAT('0' ,'VOLUME OF WASTE PER DAY',27X,F12.3,2X,'CUBIC METRES')
1003 FORMAT('0' ,'DIGESTER RETENTION TIME',27X,F12.3,2X,'DAYS')
1004 FORMAT('0' ,'PERCENTAGE OF TOTAL SOLIDS',24X,F12.3)
1005 FORMAT('0' ,'PERCENTAGE OF VOLATILE SOLIDS',21X,F12.3)
1006 FORMAT('0' ,'EXCESS CAPACITY FACTOR',28X,F12.3)
1011 FORMAT('-',20X,'ENERGY DATA:')
1012 FORMAT('0' ,'U FACTOR FOR DIGESTER WALLS',23X,F12.3,2X,'WATTS/SQUA
        1RE  METRE  DEGREE  C')
1013 FORMAT('0' ,'U FACTOR FOR DIGESTER ROOF',24X,F12.3,2X,'WATTS/SQUAR
        1E  METRE  DEGREE  C')
1096 FORMAT('0','DIGESTER OPERATING TEMPERATURE',20X,F12.3,2X,'DEGREES
    1CENTIGRADE')
1014 FORMAT('0','AIR TEMPERATURE IN WORST CASE',21X,F12.3,2X,'DEGREES C
    1ENTIGRADE')
1015 FORMAT('0','INFLUENT TEMPERATURE IN WORST CASE',16X,F12.3,2X,'DEGR
    1EES CENTIGRADE')
1019 FORMAT('0','AVERAGE AIR TEMPERATURE',27X,F12.3,2X,'DEGREES CENTIGR
    1ADE')
1020 FORMAT('0','AVERAGE INFLUENT TEMPERATURE',22X,F12.3,2X,'DEGREES CE
    1NTIGRADE')
1016 FORMAT('0' ,'GAS PRODUCTION RATE',31X,F12.3,2X,'CUBIC METRES OF GAS
    1S PER KG OF VS ADDED')
1017 FORMAT('0' ,'MJ PER CUBIC METRES OF GAS',24X,F12.3)
1018 FORMAT('0' ,'BOILER EFFICIENCY',33X,F12.3)
1021 FORMAT('-',20X,'COST DATA:')
1022 FORMAT('0' ,'COST INDEX FROM PROCESS ENG',23X,F12.3)
1023 FORMAT('0' ,'KNOWN COST OF DIGESTER OF CERTAIN SIZE',12X,F12.3,2X,
    1'POUNDS')
1024 FORMAT('0' ,'CAPACITY OF KNOWN DIGESTER',24X,F12.3,2X,'CUBIC METRE
    1S')
1025 FORMAT('0','LOADING RATE',38X,F12.3,2X,'KILOGRAMS V.S. PER CUB
    1IC METRE PER DAY')
1030 FORMAT('-',20X,'COMPUTED RESULTS:')
1031 FORMAT('0' ,'CAPACITY OF REQUIRED DIGESTER',21X,F12.3,2X,'CUBIC ME
    1TRES')
1032 FORMAT('0' ,'DIGESTER DIAMETER',33X,F12.3,2X,'METRES')
1033 FORMAT('0' ,'AREA OF DIGESTER SURFACE BELOW LIQUID LEVEL',7X,F12.3
    1,2X,'SQUARE METRES')
1034 FORMAT('0' ,'AREA OF DIGESTER SURFACE ABOVE LIQUID LEVEL',7X,F12.3
    1,2X,'SQUARE METRES')
1035 FORMAT('0' ,'TOTAL SURFACE AREA OF DIGESTER',20X,F12.3,2X,'SQUARE
    1METRES')
1036 FORMAT('0' ,'HEAT LOST THROUGH DIGESTER WALLS',18X,F12.3,2X,'MEGA
    1 JOULES')
1037 FORMAT('0' ,'HEAT LOST THROUGH DIGESTER ROOF',19X,F12.3,2X,'MEGA
    1 JOULES')
1038 FORMAT('0' ,'INFLUENT HEATING REQUIREMENTS IN WORST CASE',7X,F12.3
    1,2X,'MEGA JOULES')
1039 FORMAT('0' ,'TOTAL HEAT LOST',35X,F12.3,2X,'MEGA JOULES')
1040 FORMAT('0' ,'ENERGY REQUIRED TO POWER THE PLANT',16X,F12.3,2X,'MEG
    1A JOULES')
1041 FORMAT('0' ,'AVERAGE ENERGY REQUIRED FOR HEATING INFLUENT',6X,F12.
    13,2X,'MEGA JOULES')
1042 FORMAT('0' ,'AVERAGE ENERGY LOST THROUGH DIGESTER WALLS',8X,F12.3,
    12X,'MEGA JOULES')
1043 FORMAT('0' ,'AVERAGE ENERGY LOST THROUGH DIGESTER ROOF',9X,F12.3,2
    1X,'MEGA JOULES')
1044 FORMAT('0' ,'AVERAGE TOTAL ENERGY REQUIRED',21X,F12.3,2X,'MEGA
    1JOULES')
1045 FORMAT('0' ,'AVERAGE ENERGY REQUIRED',27X,F12.3,2X,'MEGA JOULES')
1046 FORMAT('0' ,'GAS PRODUCTION',36X,F12.3,2X,'CUBIC METRES')
1047 FORMAT('0' ,'GAS PRODUCTION',36X,F12.3,2X,'MEGA JOULES')
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 1048 FORMAT('0' ,'NET ENERGY PRODUCED IN WORST CASE',17X,F12.3,2X,'MEGA
     1 JOULES')
 1049 FORMAT('0' ,'NET ENERGY AVAILABLE IN AVERAGE CASE',14X,F12.3,2X,'M
     1EGA JOULES')
 1050 FORMAT('0' ,'CAPITAL COST OF PLANT',29X,F12.3,2X,'POUNDS')
 1055 FORMAT('-',20X,'SUMMARY OF COMPUTED RESULTS:'/)
 1056 FORMAT(' ',A5,2X,8F12.3)
 1060 FORMAT('+','INVALID-NO. OF COLS MUST BE BETWEEN 1 AND 50 INC.; PLE
     1ASE RETYPE:'2X,$)
 1070 FORMAT('0','ANAEROBIC DIGESTER PROGRAM:')
 1071 FORMAT('0','INPUT NO. OF COLUMNS OF DATA:',2X,$)
 1072 FORMAT(' ','INPUT DATA REPETITION CODES (IF NO REPETITIONS TYPE <R
     1ETURN> ONLY):',2X,$)
 1073 FORMAT('+',A5,' IN COLUMN',I3,':',2X,2X,$)
 1075 FORMAT('0','INPUT CODE:',2X,$)
 1080 FORMAT(' ')
 1090 FORMAT(I0)
 1091 FORMAT(F0.0)
 1092 FORMAT(30I0)
 1094 FORMAT(I0)
      END
C
C
C
C     COMMENT:   SUBROUTINE TO CALCULATE POWER REQUIREMENTS FOR
C                GAS MIXING.
C
C
C
C
      SUBROUTINE PORQGM
      REAL MXPO1,MXPO2,MXPO3
      COMMON ILIST,IRUN,DGDIA,VALOUT(22,50)
 1100 QGRQD=0.07*DGDIA
      VALOUT(21,IRUN)=QGRQD
      IF(ILIST.EQ.1)WRITE(5,1000)QGRQD
 1105 IF(DGDIA/2.GE.1.5)GOTO 1110
      MXPO1=1.9459*QGRQD
      VALOUT(22,IRUN)=MXPO1
      IF(ILIST.EQ.1)WRITE(5,1001)MXPO1
      RETURN
 1110 IF(DGDIA/2.GE.4.5)GOTO 1115
      MXPO2=3.3525*QGRQD
      VALOUT(22,IRUN)=MXPO2
      IF(ILIST.EQ.1)WRITE(5,1001)MXPO2
      RETURN
 1115 IF(DGDIA/2.GE.7.5)GOTO 1120
      MXPO3=5.2513*QGRQD
      VALOUT(22,IRUN)=MXPO3
      IF(ILIST.EQ.1)WRITE(5,1001)MXPO3
      RETURN
 1120 WRITE(5,1002)
      RETURN
 1000 FORMAT('0','QUANTITY OF GAS REQUIRED FOR MIXING',15X,F12.3,2X,'CU
     1BIC METRES PER MINUTE')
 1001 FORMAT('0','POWER FOR GAS COMPRESSION',25X,F12.3,2X,'KW'//)
 1002 FORMAT('0','THE POWER REQUIRED IS TOO GREAT'//)
      END
      SUBROUTINE POLFIT(NTERMS,X,Y,MAXORD,NORDER,COEFF,RES)
C
C     SUBROUTINE TO CALCULATE A WEIGHTED LEAST SQUARES POLYNOMIAL
C     BY FORSYTHE'S METHOD USING ORTHOGONAL POLYNOMIALS.
C     NTERMS IS THE NUMBER OF DATA POINTS (MAX VALUE = 100)
C     X & Y ARE ARRAYS CONTAINING THE DATA POINTS
C     WEIGHT IS AN ARRAY CONTAINING THE WEIGHTS
C     YC ARRAY CONTAINS THE CALCULATED Y COORDINATES ON ORIGINAL SCALE
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C     RES ARRAY CONTAINS (OBSERVED Y - CALCULATED Y) ON ORIGINAL SCALE
C     MAXOR1 IS THE MAXIMUM DEGREE OF THE POLYNOMIAL TO BE TESTED FOR +1
C     NORDER IS SET ON EXIT TO THE DEGREE OF THE POLYNOMIAL FOUND
C     SIGMA2 IS AN ARRAY WHICH ON EXIT CONTAINS GOODNESS OF FIT TERMS
C       IE (SCALED SIGMA Y SQUARED/(NO.TERMS-ORDER-1))
C     COEFF IS AN ARRAY WHICH ON EXIT CONTAINS THE COEFFICIENTS OF THE
C     BEST POLYNOMIAL FOUND.
C     IF ON ENTRY L=0 THEN ALL THE POLYNOMIALS FROM 0 TO MAXOR1-1 ARE
C     EXAMINED, AND FROM THE GOODNESS OF FIT
C     THE BEST POLYNOMIAL IS FOUND, AND THE CONSTANTS FOR THIS
C     ARE REPORTED.  IF ON ENTRY L=1 THEN THE POLYNOMIAL REPORTED
C     IS OF DEGREE MAXOR1-1.
C     BOTH THE X & Y COORDINATES ARE SCALED IN THE SUBROUTINE TO REDUCE
C     ROUNDING ERRORS.
C     AX & BX ARE USED TO SCALE X TERMS, AY & BY TO SCALE Y TERMS.
C
      DIMENSION X(200),Y(200),COEFF(10),RES(200)
      DIMENSION WEIGHT(200),TP(200),XLP(200)
      DIMENSION YC(200),SIGMA2(10)
      DIMENSION CTP(10),CPSAVE(10),CP(10),CLP(11)
      DIMENSION AL(10),BE(10),S(10)
C
      DO30 I=1,NTERMS
      WEIGHT(I)=1.0
   30 CONTINUE
      MAXOR1=MAXORD+1
      L=0
C
      NORDER=MAXORD
      DO 1 I=1,MAXOR1
    1 CP(I)=0.0
      BE(1)=0.0
      CLP(2)=0.0
      CLP(1)=0.0
      DELSQ=0.0
      PM=0.0
      TW=0.0
      SIMIN=0.0
      ISW=0
      CTP(1)=1.0
      ICOM=1
C
C     FIND THE MAXIMUM AND MINIMUM Y
      YMAX=Y(1)
      YMIN=Y(1)
      DO 2 I=2,NTERMS
      IF(Y(I).GT.YMAX) YMAX=Y(I)
      IF(Y(I).LT.YMIN) YMIN=Y(I)
    2 CONTINUE
      AY=(YMAX+YMIN)/2.0
      BY=(YMAX-YMIN)/2.0
      IF(BY.GT.0.0) GO TO 3
      COEFF(1)=Y(1)
      NORDER=0
      RETURN
C
C     SCALE Y TERMS
    3 DO 4 I=1,NTERMS
      Y(I)=(Y(I)-AY)/BY
      DELSQ=DELSQ+WEIGHT(I)*Y(I)**2
      TP(I)=1.0
      XLP(I)=0.0
      PM=PM+WEIGHT(I)*Y(I)
    4 TW=TW+WEIGHT(I)
      S(1)=PM/TW
      CP(1)=S(1)
```

```
      DELSQ=DELSQ-S(1)*PM
      SIGMA2(1)=ABS(DELSQ/FLOAT(NTERMS-1))
      AX=4.0/(X(NTERMS)-X(1))
      BX=-2.0-AX*X(1)
C
C     SCALE X
      DO 5 I=1,NTERMS
    5 X(I)=AX*X(I)+BX
      DO 13 I=1,MAXORD
      DU=0.0
      DO 6 J=1,NTERMS
    6 DU=DU+WEIGHT(J)*X(J)*TP(J)**2
      AL(I+1)=DU/TW
      XLW=TW
      TW=0.0
      PM=0.0
      DO 7 J=1,NTERMS
      DU=BE(I)*XLP(J)
      XLP(J)=TP(J)
      TP(J)=(X(J)-AL(I+1))*TP(J)-DU
      TW=TW+WEIGHT(J)*TP(J)**2
    7 PM=PM+WEIGHT(J)*Y(J)*TP(J)
      BE(I+1)=TW/XLW
      S(I+1)=PM/TW
      DELSQ=DELSQ-S(I+1)*PM
      SIGMA2(I+1)=ABS(DELSQ/FLOAT(NTERMS-I-1))
C
C     ENTER IF L=0 AND PROGRAM HAS TO DECIDE ON THE BEST ORDER.
      IF(L.GT.0) GO TO 10
      IF(ICOM.EQ.0) GO TO 13
      IF(ISW.EQ.1) GO TO 9
      IF(SIGMA2(I+1).LT.SIGMA2(I)) GO TO 10
      NORDER=I-1
      ICOM=1
      ISW=1
      SIMIN=SIGMA2(I)
      DO 8 J=1,MAXOR1
    8 CPSAVE(J)=CP(J)
      GO TO 10
    9 IF (SIGMA2(I+1).GE.(0.6*SIMIN)) GO TO 10
      ICOM=0
      ISW=0
      NORDER=MAXORD
C
   10 DO 11 J=1,I
      DU=CLP(J+1)*BE(I)
      CLP(J+1)=CTP(J)
      CTP(J)=CLP(J)-AL(I+1)*CTP(J)-DU
   11 CP(J)=CP(J)+S(I+1)*CTP(J)
      CP(I+1)=S(I+1)
      CTP(I+1)=1.0
      CLP(I+2)=0.0
      IF(ICOM.EQ.0.OR.ISW.EQ.0) GO TO 13
      IF(I.NE.MAXORD) GO TO 13
      DO 12 J=1,MAXOR1
   12 CP(J)=CPSAVE(J)
   13 CONTINUE
      CLP(1)=1.0
      CPSAVE(1)=1
      COEFF(1)=CP(1)
      DO 14 I=2,MAXOR1
      CLP(I)=1
      CPSAVE(I)=BX*CPSAVE(I-1)
   14 COEFF(1)=COEFF(1)+CP(I)*CPSAVE(I)
      DO 16 J=2,MAXOR1
      CLP(1)=CLP(1)*AX
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      COEFF(J)=CP(J)*CLP(1)
      KK=2
      J1=J+1
      IF(J1.GT.MAXOR1) GO TO 17
      DO 15 I=J1,MAXOR1
      CLP(KK)=AX*CLP(KK)+CLP(KK-1)
      COEFF(J)=COEFF(J)+CP(I)*CLP(KK)*CPSAVE(KK)
   15 KK=KK+1
   16 CONTINUE
C
C     CONVERT X ARRAY BACK TO ORIGINAL SCALE
   17 AX=1.0/AX
      DO 18 I=1,NTERMS
   18 X(I)=(X(I)-BX)*AX
C
C     CALCULATE YCALC & RESIDUAL FOR EACH POINT (ON ORIGINAL SCALE).
      DO 20 I=1,NTERMS
      J=NORDER+1
      YCAL=COEFF(J)
      DO 19 K=1,NORDER
      YCAL=COEFF(J-1)+(X(I)*YCAL)
      J=J-1
   19 CONTINUE
      YC(I)=YCAL*BY+AY
      RES(I)=(Y(I)-YCAL)*BY
   20 CONTINUE
C
C     CONVERT COEFF & Y ARRAYS BACK TO ORIGINAL SCALE
      COEFF(1)=(COEFF(1)*BY)+AY
      DO 21 I=2,MAXOR1
      COEFF(I)=COEFF(I)*BY
   21 CONTINUE
      DO 22 I=1,NTERMS
   22 Y(I)=Y(I)*BY+AY
      RETURN
      END
@
```

B2 Other Programs

Apart from the program PFADP2 the other major program used was PFGCF2. This program reads the data file appropriate to the material under consideration by means of a call code and computes the coefficients for a best fit curve of the gas yield against loading rate. This information is then input to program PFADP2 so that for any particular loading rate a gas yield can be calculated. PFGCF2 was also developed at the Polytechnic.

Another program used during the analysis of the experimental data was STATPK an integrated interactive package written originally at Western Michigan University, U.S.A. and adopted for use with the Polytechnic's DEC System 20 to allow statistical analysis from a terminal. An example of the type of output from this package is shown in Figure B.2.1.

Figure B.2.1 An example of the output obtainable from STATPK a program package used in the analysis of experimental data

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THERE ARE     5 VARIABLES AND  102 OBSERVATIONS

VAR.          MEANS          STD.DEV.           VARIANCE
TS          2.500118         1.394448          1.944484
VS          1.960735         1.016065          1.032387
RT          15.31667         11.29416          127.5580
LR          1.648186         1.081702          1.170080
GY         0.5170686        0.3044651         0.9269898E-01



VAR.        MEDIAN           MODE               MAXIMUM          MINIMUM
TS          2.265000        2.100000            7.219000        0.1500000
VS          1.853500        2.722000            5.053000        0.1360000
RT          12.00000        7.000000       *    73.00000         5.000000
LR          1.283000       0.1250000       *    5.082000        0.1250000
GY         0.4525000       0.3760000            1.438000        0.6500000E-01

* MORE THAN 1 MODE EXISTS - ONLY THE FIRST IS SHOWN



VAR.     STD ERR OF MEAN   SKEWNESS      COEF. OF VAR.
TS         0.1380709       0.7187615        55.77529
VS         0.1006054       0.4258993        51.82058
RT          1.118298        2.456322        73.73771
LR         0.1071045       0.8608203        65.62985
GY         0.3014653E-01   0.7905007        58.88291
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APPENDIX C

GLOSSARY OF TERMS

C. Glossary of Terms

Autolysis	The self destruction of biological cells after death, as a result of the action of their own enzymes.
Biological Oxygen Demand (B.O.D.)	A measure of the oxygen consumed during the oxidation (stabilisation) of organic matter by a mixed microbial population and under aerobic conditions. It is an indication of the amount of oxygen which would be taken out of a stream or water course when the same organic matter was disposed of; it is thus a measure of pollution load.
Buffering Capacity	Buffering is the capacity of a solution to resist pH changes when small amounts of acid or alkali are added.
Carbohydrates	Organic compounds composed of carbon (C), hydrogen (H) and oxygen (O) only. They include sugars, starches and cellulose.
Carbon : Nitrogen Ratio (C/N)	The ratio by weight of carbon to nitrogen in a sample. A ratio of about 20 or 30 : 1 is often considered best for anaerobic digestion.
Cellulose	A fibrous carbohydrate, and forms the bulk of the cell wall material in all green plants. It is a polymer with the general chemical formula $(C_6 H_{10} O_5)_n$.

Chemical Oxygen Demand (C.O.D.)	A measure of the oxygen required for oxidation by chemicals of organic matter. Chemical oxidation is more complete than that achieved by bacteria and hence the C.O.D. is generally greater than the B.O.D. for the same sample.
Correlation Coefficient	A quantity which indicates the overall goodness of fit of a regression model; usually denoted by R. It lies between -1 and +1. The closer the value is to zero the lower is the correlation; an R of -1 or +1 indicates a perfect fit.
Retention Time	(Sometimes called detention time or residence time.) This is the average length of time a sample of waste remains in the digester.
Dilution Rate	The reciprocal of the mean retention time of the flowing medium in a digester.
Fatty Acids	Organic acids of the general formula R. COOH. During anaerobic digestion the acid forming bacteria produce chiefly fatty acids whose 'R' group contain 0 - 3 carbon atoms. These are known as volatile or short-chain fatty acids.
Hemicellulose	A polymeric material related to cellulose; it also occurs as part of the cell wall in green plants and especially in

Hemicellulose (cont.)	older lignified tissue. Plant material normally contains hemicellulose and cellulose in the ratio of 0.5 : 1 to 1 : 1.
Inoculum (Seed)	The sample of partly digested waste with its associated bacteria added to a digester at the start to provide sufficient micro-organisms for the process to proceed at a satisfactory rate.
Kinetics (or Reaction Kinetics)	Involves the mathematical description of the rates of cell growth or substrate removal as a function of the conditions in the digester.
Lignin	Occurs in older plants or trees (20 - 30% of wood is lignin). It is a complex organic compound which is very resistant to bacterial breakdown.
Loading Rate	Usually expressed as the rate of addition of mass of volatile matter to the digester per unit digester capacity. (Typical units are kg VS/m^3 day.)
Mesophilic Bacteria	Those bacteria which appear to grow best at temperatures in the middle range (i.e. 30 - 40 °C).
Monod Equation	Possibly the most widely used kinetic model for organism growth, and relates the cell growth rate to the concentration of limiting substrate.

Multiple Regression	An extension of simple regression to deal with more than one explanatory variable.
Pathogens or Pathogenic Organisms	Those which can cause disease.
pH	A measure of the acidity or alkalinity of a solution. A scale of 0 - 14 is used to express hydrogen ion concentration.
Regression Coefficients	The calculated numerical values in a regression equation.
Residual	The difference between an actual value and its estimate from a regression model.
Simple Regression	A statistical technique for deriving a model relating a variable to just one explanatory variable.
Supernatant	The liquor which collects at or near the surface when a slurry or mixture of solids and liquids is allowed to settle.
Thermophilic Bacteria	Those bacteria which appears to function best at higher temperatures (i.e. 40 - 60°C).
Volatile Acids	(See Fatty Acids)

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