THE TREATMENT OF YEAST FACTORY EFFLUENT BY AN ANAEROBIC SUBMERGED FILTER

BY

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A B S T R A C T

This Thesis reports the results of an experimental investigation into the treatment of yeast wastes by biological digestion in an anaerobic submerged filter. The waste to be treated was very strong, with a COD of 59 000 mg/l and was almost entirely soluble, with a high organic content.

Experiments showed that the waste could be treated by the anaerobic submerged filter, with a maximum loading applicable for extended periods of 10 kg COD/(m^3day), based on the void volume of the filter. The reduction in COD effected by the filter at these loadings varied between 40 and 60% of the applied COD, of which only approximately 70% was biologically degradable. Loadings of up to 16 kg COD/(m^3day) were applied with 40% COD reduction, but digestion at these loadings seemed unstable and could not be continued for long periods. Diluted yeast waste was used during the investigation in order to control loading rates and it was necessary to add sodium bicarbonate to the feed to give an alkalinity greater than 2 000 mg/l as calcium carbonate to buffer digestion at the optimum pH.

This thesis also reports the establishment of an operating procedure for a laboratory scale anaerobic submerged filter, and proposes recommendations for further work. This work is aimed at improving the performance of the filter by modifying the operating procedure and increasing the understanding of the digestion process by studies of a fundamental nature.

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TABLE OF CONTENTS

L I S T O F F I G U R E S

L I S T O F T A B L E S

CHAPTER 1

I N T R O D U C T I O N

1.1. INTRODUCTION

Industrial waste treatment, as a logical extension of Municipal sewage treatment has, until recent years, been largely a civil engineering domain. Chemical engineers, as a result of their background in the understanding of the reactions and unit operations involved, are better suited to the problems of treating industrial wastes, but have only become involved on a large scale in waste treatment within the last few years.

The research project forming the subject of this thesis was undertaken after a request to the Chemical Engineering Department of the University of Cape Town by a local yeast factory to develop a process to treat the factory effluent. By undertaking the investigation, the Department hoped to apply a recently discovered process to this specific industrial waste, and, at the same time, develop a laboratory operating procedure for the process and to gain experience in waste treatment.

The usual method of yeast production in South Africa is to use blackstrap molasses, a by-product of the cane-sugar industry, as a substrate upon which to grow the yeast seed. After the yeast has reached maturity, it is centrifuged off from the spent molasses. The latter, combined with filtrates and factory washings, is usually discharged to the Municipal sewer for treatment at the local sewage works in combination with domestic sewage and other industrial wastes. The high organic loading of this waste can easily overload a sewage treatment works not designed to handle it, resulting in the discharge of a substandard effluent, which can seriously pollute the receiving watercourse. Since local authorities have proposed to levy a charge on factories discharging waste to the sewers , based on the strength and volume of the effluent, it has become an economic necessity as well as a moral obligation to reduce the strength of yeast wastes as much as practicable.

The process by which yeast is produced and packed in a typical South African yeast factory, and the wastes which arise during the process are shown in Fig. 1.1. The raw molasses is first diluted with an approximately equal volume of water, is sterilized and then goes through a centrifugal clarifier. This removes the solid matter still present in the molasses, such as inorganic precipitates, cellulosic materials and other solids before the clarified molasses solution passes into the fermentation tanks. Nutrients required by the yeast are added and the medium is seeded. Yeast is grown aerobically until mature when the culture is centrifuged, the yeast cells washed, centrifuged again and finally filtered on a vacuum filter before being packed or dried. Wastes arise from the clarification of the molasses, the first and second separations of the mature yeast and its subsequent filtration and from equipment and floor washings. The approximate volumes and concentrations of the different streams are shown in Table 1.1. for a typical factory. From this table it is clear that the first separation waste arising from the separation of the yeast cells from the spent molasses constitutes the major portion of the total load from the factory. Since this stream is separable from the other factory wastes, it was decided to carry out the investigation on the first separation waste only. The characteristics of this waste stream are given in Table 1.2.

The possible treatment methods which could be used fall into two classes: physico-chemical and biological. Physico-chemical methods include flocculation and incineration, while biological methods are either aerobic or anaerobic in nature. Preliminary investigations ruled out evaporation and subsequent incineration as being too expensive, leaving flocculation as a possible method. This was confirmed as a possibility by Federov and Golod (14) who flocculated waste water from a yeast factory; by Clayton (8) who describes the colloids present in molasses and by Ross and Conradie (48) who flocculated an anaerobic digester effluent.

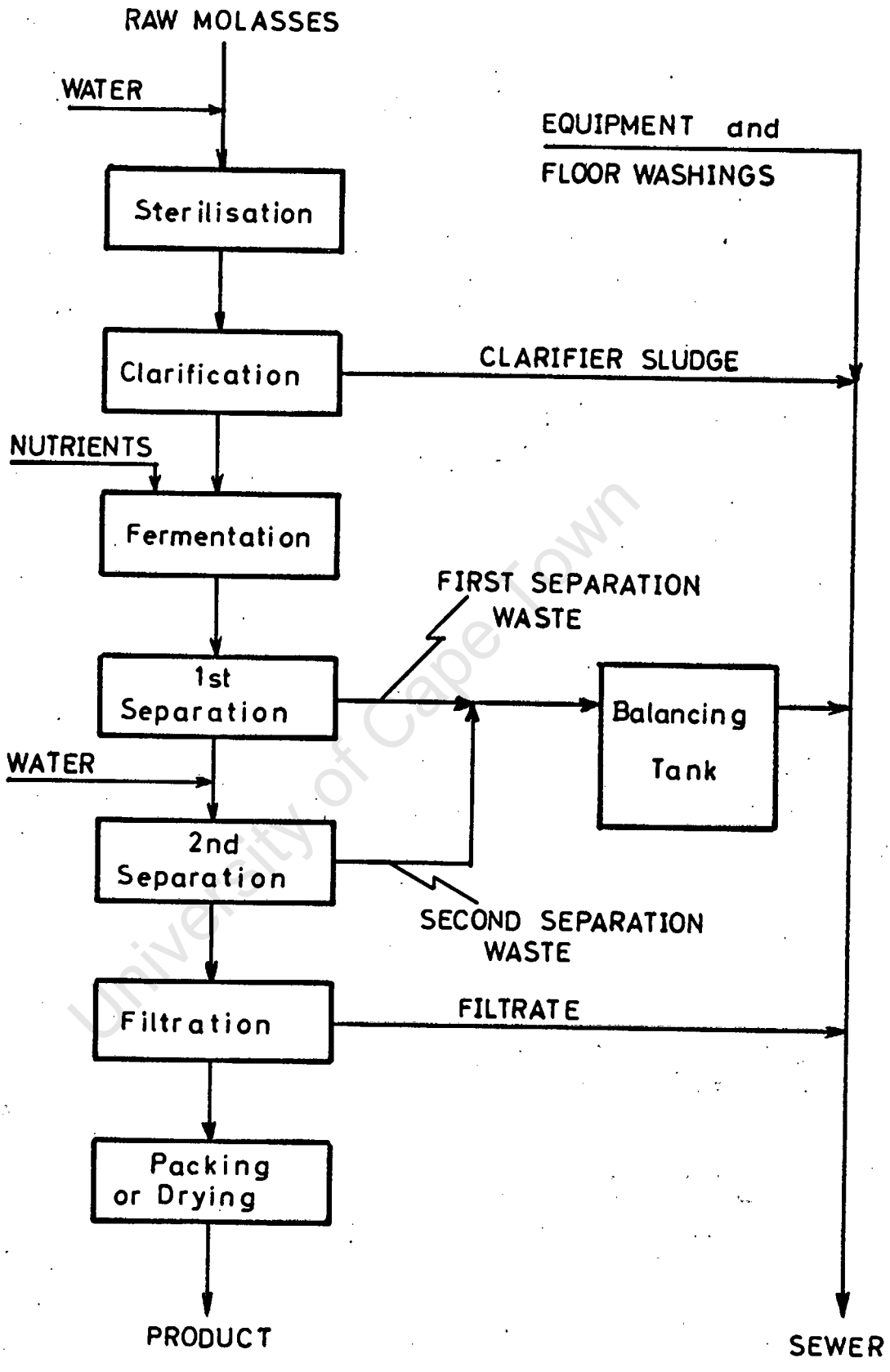

Fig 1.1 FLOW DIAGRAM OF YEAST PRODUCTION SHOWING EFFLUENT SOURCES

TABLE 1.1. EFFLUENT FLOWS AND OXYGEN CONSUMPTION LOADS FOR A TYPICAL SOUTH AFRICAN YEAST FACTORY

EFFLUENT SOURCE	NATURE	FLOW l/day	% OF TOTAL FLOW	OA * mg/l	LOAD kg OA/day	COD ** mg/l	LOAD kg COD/day	% OF TOTAL COD LOAD
Molasses Clarifier	Heavy Sludge	1 700	1,25	80 000	136,2	340 000	578,8	15,35
First Yeast Separation	Dark Brown Liquid	40 300	29,59	21 000	846,1	59 000	2 377,3	63,03
Second Yeast Separation	Light Brown Liquid	63 100	46,33	4 000	252,4	11 000	694,1	18,40
Yeast Filter	Lightly coloured Liquid	18 200	13,36	350	6,3	1 000	18,1	0,48
Equipment and Floor Washings	Water containing Detergents, Yeast and Molasses	12 900	9,47	2 700	34,9	8 000	103,5	2,74
	TOTALS	136 200	100,0		1 275,9		3 771,8	100,0

* Determined by the British Method. (See Appendix A, Section A.2.5., for definition.)

** For definition see Appendix A, Section A.1.

TEST	RESULT
pH	4,8
COD	59 000 mg/l
OA	21 000 mg/l
TOTAL SOLIDS	100 g/l
TOTAL VOLATILE SOLIDS	68 g/l
SUSPENDED SOLIDS	NEGLIGIBLE
ALKALINITY	4 300 mg/l as $CaCO_3$
KJELDAHL NITROGEN	400 mg/l
SULPHATE	2 800 - 4 500 mg/l
COLOUR	DARK BROWN
ODOUR	MOLASSES/YEAST

TABLE 1.2. CHARACTERISTICS OF FIRST SEPARATION WASTE

1.2. FLOCCULATION

A series of tests, as detailed in Appendix D were carried out on the first separation waste to determine whether or not flocculation would be a practicable treatment process on an industrial scale. The results tabled in Appendix D obtained from the laboratory scale tests conducted show that reductions in Oxygen Absorbed Value (OA)* of up to 60% can be achieved, but that the flocculant dosages required are impracticably high. On the basis of these results, the investigation was directed towards the biological treatment of the effluent.

1.3. BIOLOGICAL TREATMENT

The two basic types of biological treatment considered were aerobic oxidation, either by an activated sludge or trickling filter process or by anaerobic digestion. The choice between aerobic or anaerobic

* OA will be used as an abbreviation for "Oxygen Absorbed". Definitions of this and other terms will be found in Appendix A.

treatment is usually decided by the concentration of the waste. Cillie et al (7) give the concentration above which it is cheaper to treat a waste anaerobically as 4 000 mg COD/l. Since the first separation yeast waste was known to be largely organic in character with a COD of 59 000 mg/l the choice of anaerobic digestion was obvious. Further, the advantages to be gained by using this process outweigh the disadvantages. Briefly, these advantages are:

(a) Only about 10% of the waste metabolized appears as sludge requiring further disposal (28)

(b) The low sludge production means that nutritional requirements are correspondingly low

(c) No oxygen or air blowers are required

(d) The methane formed is a useful end product

The chief disadvantage is that the effluent from an anaerobic process usually requires further treatment before it can be discharged to a receiving stream. This subsequent treatment is often aerobic, e.g. the trickling filter used by Rudolfs and Trubnick (53).

The choice of which digestion system of those given in Chapter 2 was to be used was governed by the fact that the yeast waste to be treated is almost entirely free from suspended solids, see Table 1.2. In order to operate efficiently, however, an anaerobic digester needs a high sludge concentration, as well as suspended solids to support the micro-organisms. Hence, for efficient treatment of the yeast waste, some form of artificial support was needed for the sludge, as well as a means of maintaining high sludge concentrations. The anaerobic filter recently developed by Young and McCarty (32),(75), is suitable for treating a soluble waste.

The filter consists of a vertical column containing a packing material and fed from the bottom so as to submerge the packing completely. The sludge adheres to the surface of the packing and also forms flocs which

are suspended in the voids. Liquid effluent and gas produced by the digestion process are drawn off at the top of the filter. The packing material used by Young and McCarty (75) was smooth quartzite stones 2,5 to 3,8 cms in diameter. Since the void fraction of this packing material as packed in the filter was only 0,42, it was felt that the volume of the filter was not being used to its best extent, and so 1,2 cm porcelain Raschig rings were chosen as the packing material for the filters to be constructed for this investigation, since these were readily available and approximated a spherical type packing. As packed in the filter, these Raschig rings had a voidage of 0,62 and a specific surface of 400 m^2/m^3 (27).

Seed sludge was obtained from digesters treating wine distillery waste and also from the sludge digesters at the local Athlone Sewage Works. The filters were heavily seeded with sludge and feeding commenced, following an acclimation procedure. This was later found to be unnecessary and pure yeast waste was fed to the filters in increasing concentrations. The operation of the filters was very erratic, however, mainly because of unsuitable feed pumps. At the start of the investigation, the only published work available on anaerobic filters was that by Young and McCarty (75), who used synthetic media made up from pure chemicals as feed for their filters. This was sterilised and naturally did not contain any suspended solids to affect the metering pumps used. When this investigation was started the example set by Young and McCarty (75) was followed, in that the feed pump used was designed as a flexible chemical metering pump. When this was found to be unsuitable because of the nature of the feed, other metering pumps were used, with the same result, until it was realised that a different type of feeding mechanism was needed. The reason for this was that the waste was typically industrial, containing actively growing yeast and was far from sterile, with the result that sludge rapidly grew in feed tanks and lines, causing blockages and erratic feed rates. The different types of feeding mechanisms used in attempts to overcome this problem are described in Chapter 3, Section 3.1.3.

The liquid retention times used varied between 40 and 80 hours and although loadings of up to 16 kg COD/(m^3day) (COD is the Chemical Oxygen Demand - see Appendix A, Section A.1 for a definition) were applied for short periods, the maximum loading which could be applied for extended periods was 10 kg COD/(m^3day) based on the void volume of the filters. The reduction achieved with this loading varied between 40% and 60%

This performance by the filter was not as good as was hoped, however, and this is discussed in detail in Chapter 4. Also discussed in Chapter 4 are the results obtained from the operation of the filter, and the operating procedure developed. Conclusions are drawn in this Chapter and recommendations for further work proposed, and these are summarised in Chapter 5. The main conclusion drawn is that although the filter can treat yeast waste, the performance was not as good as was expected. Further work is proposed to improve the performance before the filter can be recommended for large-scale application, and to learn more about the principles of anaerobic digestion as it takes place in the anaerobic filter.

CHAPTER 2

LITERATURE SURVEY

2.1. PRINCIPLES OF ANAEROBIC DIGESTION

2.1.1. Introduction

A great deal of work has been done on anaerobic digestion in general and the digestion of sewage solids in particular. It is not proposed to review all that has been written on this subject, but some of the work that has been done towards gaining a better understanding of the process, and also its applications in the field of industrial waste treatment, will be considered. It is also proposed to review the different methods by which yeast wastes have been treated, and the development and applications of the anaerobic submerged filter.

It is generally accepted that there are three stages in the anaerobic digestion process (23):

(i) the hydrolysis by extracellular enzymes of complex organics (often present as solids) to simple organic compounds;

(ii) the fermentation of these simple organics by acid-forming bacteria to simple fatty acids;

(iii) the fermentation of these acids to methane and carbon dioxide by methane-forming bacteria.

The rates at which these reactions are carried out depend on the environmental conditions prevailing in the digester. These conditions include: temperature, pH and the presence of inhibitory or toxic substances. The efficiency of the digestion process is determined by the concentrations of the sludge and substrate and the type of digestion system used.

2.1.2. Temperature

Since the digestion process is the result of the metabolic activity of a heterogeneous population of bacteria, the effect of temperature on the process is a reflection of the behaviour of the bacteria at different temperatures (22). The temperature ranges for optimum bacterial growth can be divided conveniently into three regions: the psychrophilic (20°C); the mesophilic (20 - 45°C) and the thermophilic (45°C), (69). The temperature range chosen for the operation of a digester will determine the efficiency of the process by its effect on the species and numbers of bacteria prevailing in the digester under the given conditions.

For the most economical application of the process, the highest efficiencies are required. Since the well-known rule of an approximate doubling in the rate of a chemical reaction with a 10°C rise in temperature applies roughly to biological systems in the narrow temperature ranges of interest (67), it is apparent that the higher ranges are the most desirable for operation. There is, however, a temperature range over which the rate of reaction does not increase as rapidly as would be expected, and this sets a practical limit to the ranges of temperature which are used for digestion. This falling-off in rate occurs between 37°C and about 50°C (31), (35), (67) and gives rise to the usual operating temperatures of 35°C for the mesophilic range and 55°C for the thermophilic range, Fig. 2.1. Above about 55°C the rate decreases due to denaturation of the proteins and nucleic acids making up the cells (22).

2.1.3. pH

The effects of pH on the rates of reaction are far more varied in their nature than those of temperature. This is evidenced by the large amount of work, not all of it in agreement, however, that has been published dealing with the control of pH and its effects on digester performance. In particular, the practice of adding lime to failing digesters has been widely discussed. Those who favour liming believe that the low pH itself, i.e. the high H^+ ion concentration, is toxic to the methane-

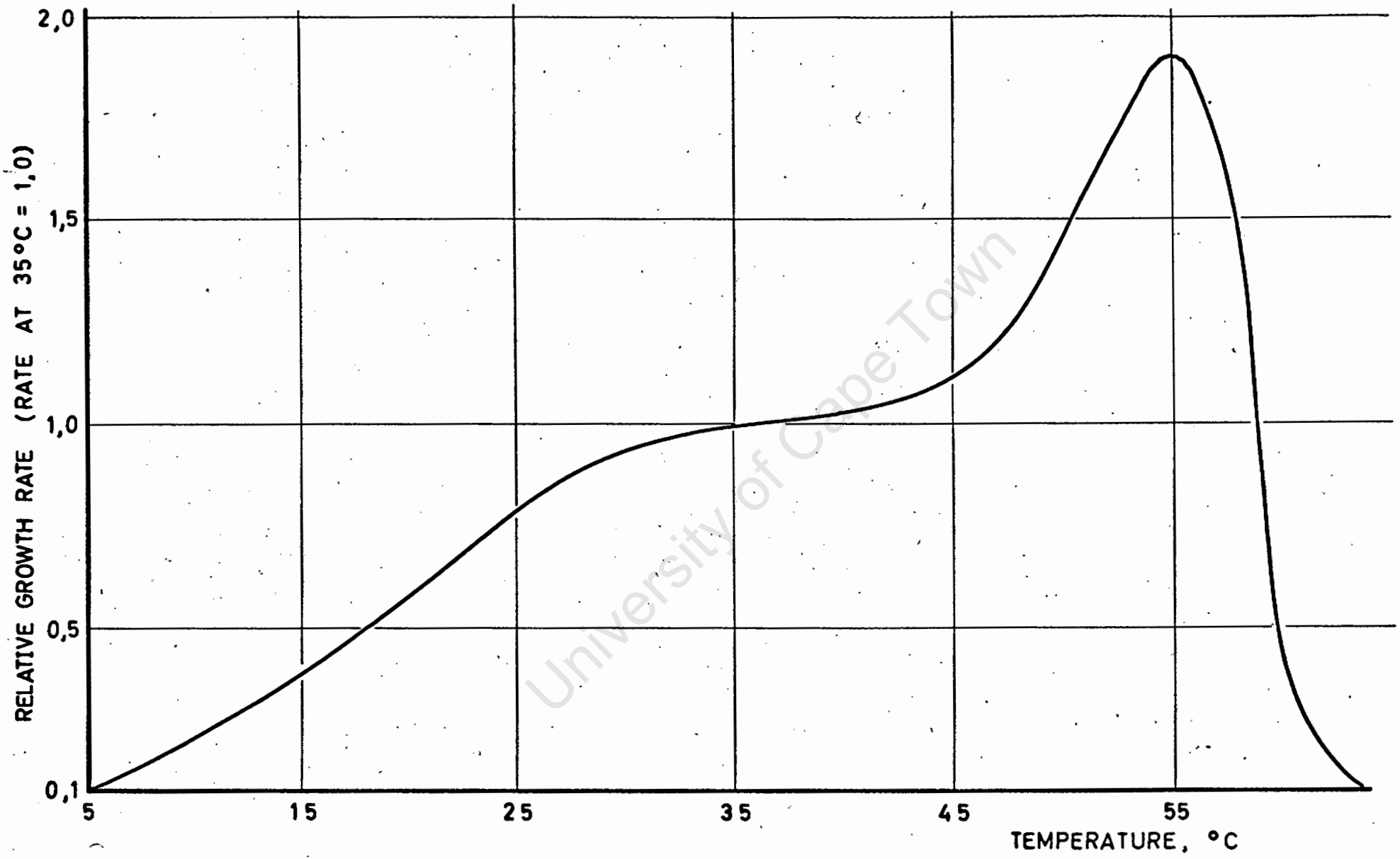

Fig 2.1 EFFECT OF TEMPERATURE ON MICROBIAL GROWTH RATE (31)

forming organisms, and hence the addition of lime, by raising the pH, will relieve the toxic effect. These investigators include Cassell and Sawyer (5); Sawyer, Howard and Pershe (56) and Kaplovsky (21).

Others, however, believe that it is the volatile acids themselves which are directly toxic to the methane-formers in concentrations greater than 2 000 mg/l as acetic acid. Hence the only way this toxicity can be relieved is by reducing the organic load on the digester or by diluting the contents. This group of investigators includes Buswell and Hatfield (4); Schulze, and Raju (60); Mueller, Hindin, Lumsford and Dunstan (37) and Schlenz (58).

In an effort to resolve this controversy, McCarty and McKinney (33) put forward the explanation that in a digester treating sewage solids, the concentration of materials in true solution in the raw sludge fed to the digester is relatively low, the vast majority of the load being carried by the suspended solids. The dissolved materials, however, are the only ones capable of affecting the organisms. In the digester, the suspended solid matter is slowly hydrolyzed and brought into solution by extracellular enzymes. Under normal conditions, this organic matter is the then rapidly broken down to volatile acids and, in turn, to methane and carbon dioxide, the total concentration of dissolved matter remaining relatively low. There is, however, a build-up to a steady value of salts such as ammonium, calcium and magnesium bicarbonates resulting from the breakdown of soaps and proteins. Under unbalanced conditions the volatile acids are not removed as fast as they are formed and so a build-up of acids in solution occurs, causing a rapid rise in total dissolved material. As a result of laboratory investigations McCarty and McKinney (33) concluded that the decrease in activity of the methane-formers was the result of salt toxicity, caused by high concentrations of the cations associated with the volatile acid anions. Further investigations by McCarty and McKinney (34) into the toxicity of different cations revealed Ca^{++} to be the least toxic.

On the basis of these investigations lime appears to be the most suitable chemical for pH control, since not only is it the least toxic, but once balanced conditions have been restored, the excess calcium precipitates out of solution because of the low solubility of calcium carbonate at the pH normally encountered in a healthy digester. Further discussion on the use of lime will be found in Chapter 4, Section 4.4.4.

2.1.4. Inhibitors

In addition to the toxic or inhibitory concentrations of cation associated with the acids found in anaerobic digesters, other toxic sugstances are frequently encountered in sewage treatment plants treating industrial wastes. McCarty (30) has reviewed the most common of these inhibitors and the usual methods of reducing their effects. Inhibition by the alkali and alkaline earth metals - sodium, potassium calcium and magnesium - is usually best dealt with by the antagonistic effects of the individual toxicities, e.g. Ca^{++} is antagonistic to the toxicity of high Na^{+} concentrations, and so a digester operating in an area of hard water will be less susceptible to Na^{+} toxicity than one operating in an area of soft water. Other inhibitors reviewed by McCarty are ammonia at high pH, sulphides and heavy metals. The inhibitory effects of each of these can be reduced by dilution of the digester contents, but use can often be made of the very low solubility of heavy metal sulphides to precipitate out the offending inhibitor.

2.1.5. Digestion Processes

At high substrate concentrations , the rate of waste stabilization is essentially dependent only on the sludge concentration (23). Hence the requirement for rapid stabilization, and consequently small digesters, is that the sludge concentration be kept high. As the understanding of the digestion process has grown, leading to this requirement, so the configurations of the treatment systems have changed.

The simplest anaerobic digestion system is the anaerobic lagoon, Fig. 2.2. As its name implies, this is simply a lagoon 3 to 5 m deep with no mixing or aeration. The top metre is sometimes aerobic because of diffusion of oxygen from the atmosphere, but usually a scum is allowed to form on the surface. This scum layer reduces oxygen transfer to the surface and eliminates any mixing effects that might have been caused by wind action. The insulating effect of this scum can maintain liquid temperatures high enough for digestion, even during freezing winters (47). Sludge control is usually minimal, consisting simply of removal of a portion of the sludge should the level rise too much, causing sludge to enter the effluent line.

The next simplest digestion system is the completely mixed digester of the type long used for the digestion of sewage solids, Fig. 2.3. The digester is simply a large completely mixed heated tank, usually covered in order to collect and utilize the gas generated. Since the tank is completely mixed, the solids and liquid retention times are equal. High solids concentrations are achieved by using long retention times - of the order of thirty days. When large volumes of waste are to be treated, however, this requires extemely large digesters and so the anaerobic contact process was developed. In this process a completely mixed digester is followed by a settling tank in which the sludge separates out from the liquid effluent, Fig. 2.4. This allows recycle of the sludge in order to maintain a high solids retention time and concentration while allowing a relatively short liquid retention time. This process can be applied to less concentrated wastes or wastes that have low suspended solids concentrations. A problem that often arises with this process is that gas production in the settling tank causes sludge to rise and be lost in the effluent. This has been overcome in a system treating slaughterhouse wastes by the installation of a vacuum degasifier before the effluent stream enters the settling tank (71).

With soluble wastes containing very few suspended solids, it is usually difficult to maintain a high sludge concentration since the sludge

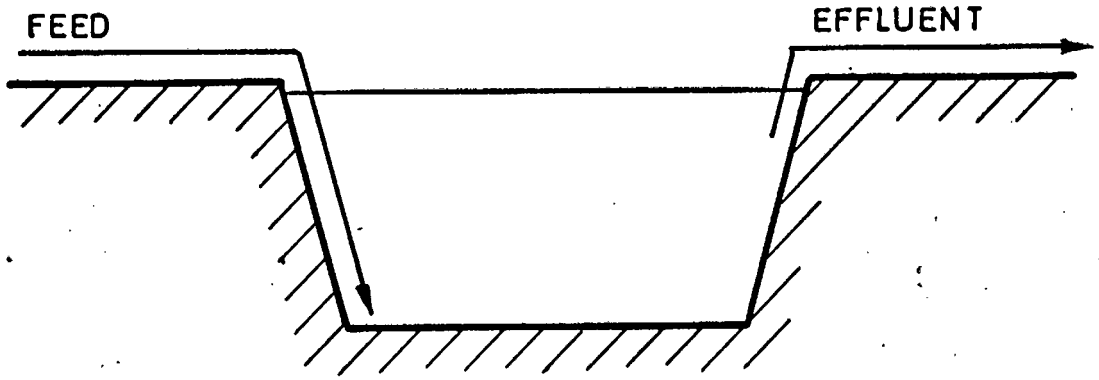

Fig 2.2 ANAEROBIC LAGOON

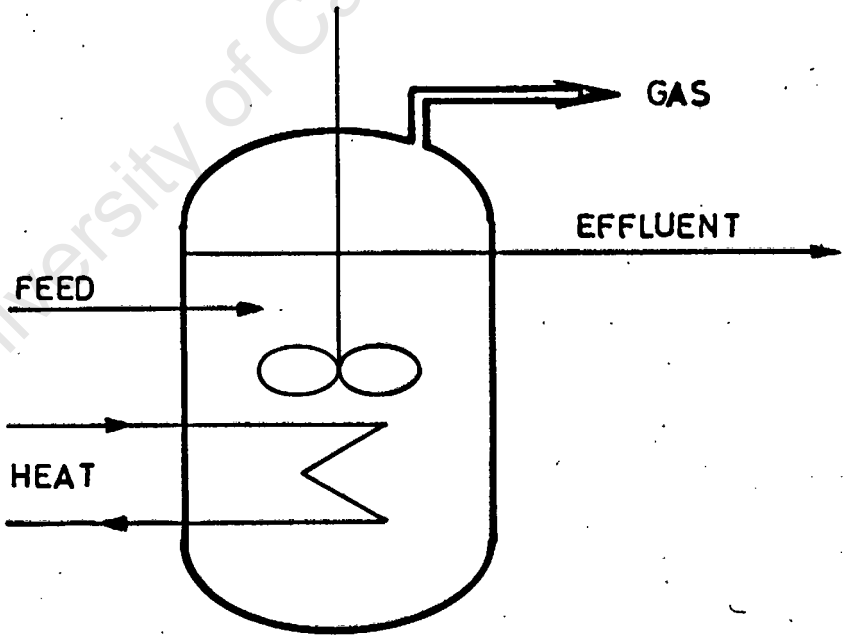

Fig 2.3 COMPLETELY MIXED DIGESTER

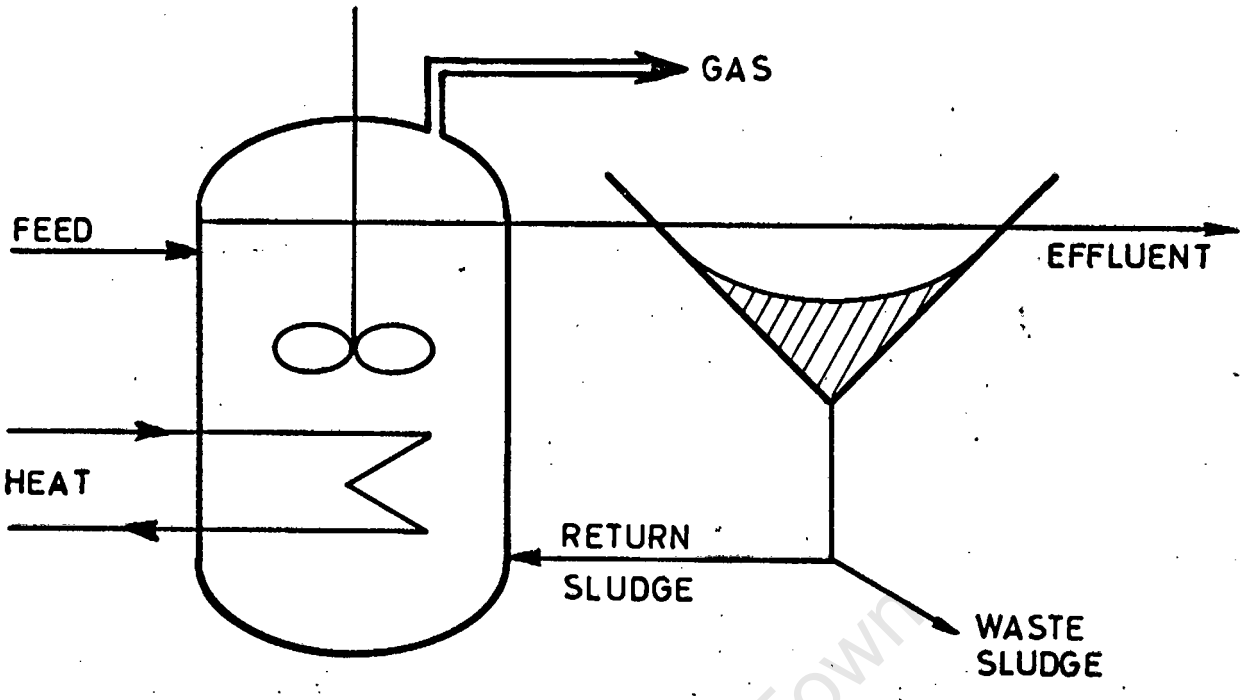

Fig 2.4 ANAEROBIC CONTACT PROCESS

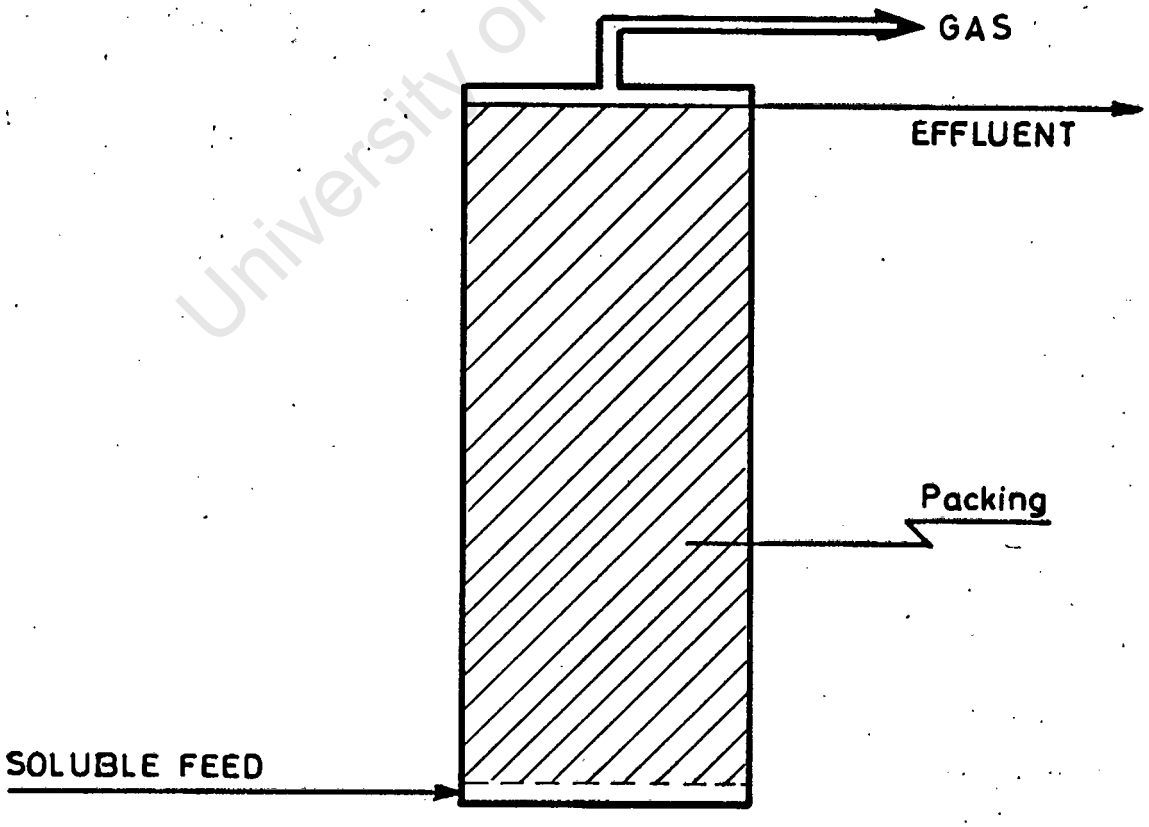

Fig 2.5 ANAEROBIC FILTER

needs some form of solid support. A new process has been developed by Young and McCarty (32), (75), which will successfully treat these wastes, however. In this process the micro-organisms are held in the digester by a packing medium, the micro-organisms either attaching themselves to the surface of the packing, or else growing in flocs physically trapped in the voids, Fig. 2.5. This anaerobic submerged filter is ideally suited to the treatment of soluble wastes or wastes of relatively low strength, as the extremely long solids retention time - a hundred days has been reported (75), (19) - allows high sludge concentrations to be maintained. Hence the hydraulic retention time can be reduced to very low values - 0,5 hours has been reported for the denitrification of agricultural wastewater (72) - and a small filter can handle a large volume of waste.

2.2. DIGESTION OF INDUSTRIAL WASTES

2.2.1. Meat-Packing Wastes

The anaerobic digestion process has been applied in its several forms to different types of industrial wastes, with varying degrees of success. In particular a waste which the process has been successful in treating is that from slaughter- and meat-packing-houses. This success can probably be ascribed to the large numbers of micro-organisms which would be present in the waste from paunch manure or similar sources and to the presence in the waste of easily putrescible organic matter.

Anaerobic lagoons have been used successfully for the treatment of this waste. Sollo (63) describes both pilot and full-scale pond treatment of meat-packing wastes. The anaerobic pond used in the investigation, some 4,3 m in depth, achieved between 81 and 95% reduction in Biochemical Oxygen Demand (BOD) of the feed, which averaged 1 100 mg/l BOD. No heat was added to the pond, but the mild climate of Georgia, where the investigation was carried out, kept the temperature about 24°C for most of the time. A drop in efficiency was noted when the temperature fell below 24°C for prolonged periods. In these tests

the anaerobic lagoon was followed by an aerobic oxidation pond which served to stabilize the effluent. Rollag and Dornbush (47) described an anaerobic-aerobic pond system to treat meat-packing wastes in Minnesota. This system gave overall BOD removals of approximately 95% and consisted of two anaerobic ponds in series followed by two aerobic ponds. These tests were carried out in winter with an average air temperature of -3,7°C, but a 23 cm thick scum layer which formed on the surface of the first anaerobic pond provided sufficient insulation to keep the pond temperature above 24°C. The anaerobic ponds achieved a reduction in BOD of 58%, while the first was being loaded at 0,26 kg BOD/(m^3day). That anaerobic lagoons can effectively treat meat-packing wastes in extreme climates has been shown by Stanley (70) who obtained 80 to 90% reduction in BOD in two anaerobic ponds treating the combined waste from three meat-packing plants in Edmonton, Canada. The effluent from the ponds was stored during the winter without odour nuisance. An anaerobic contact process to treat slaughterhouse wastes has been developed from an initial laboratory and pilot plant study by Fullen (15). The process achieved 95 to 96% removal of BOD in 24 hours or less at loadings of up to 1,35 kg BOD/(m^3day) It was necessary, however, to use vacuum degasification of the digester effluent in order to ensure adequate separation of sludge for recycle. This pilot plant was further developed until the digester was loaded at 3,20 kg BOD/(m^3day) and the retention time reduced to 12 hours based on raw flow, while the BOD removal remained at 95% (59). The final full-scale plant based on these pilot plant developments treats 1,4 million U.S. gallons (5,3 million litres) per day of waste water with an effluent BOD of 1 380 mg/l from the Wilson and Company packing plant at Albert Lea, Minn. (71). The process achieves an average 90,8% reduction of the 7 320 kg BOD applied per day, with a retention time in the digesters of 12 to 13 hours.

2.2.2. Wool-Scouring Wastes

Wool-scouring wastes have been treated successfully by anaerobic fermentation. Nevzorov (39) subjected the undefatted waste water from wool-washing by the soap-soda process, with a BOD_{20} of 9 000 to 22 000 mg/l to anaerobic fermentation. The charge dose was 4% giving a retention time of 25 days at a temperature of 35°C. A 90% reduction in BOD_{20} was obtained, the fats were reduced by 67% and the volatiles in the solid residue by 45%. Nine to ten m^3 of gas were liberated per m^3 of waste water fed. Fermentation of the waste water under thermophilic conditions (daily dose 5%, temperature 55°C) reduced the BOD_{20} by 75%. The BOD_{20} of the fermented waste was 2 400 to 2 800 mg/l. He recommends mesophilic digestion at a charge close of 4% (600 g BOD_{20}/m^3day) for design purposes. Grishina (16) describes a pilot plant for purifying waste waters from wool washing by filtration and anaerobic fermentation. The waste water to be purified has a BOD_{abs} of 20 000 mg/l and pH of 9,2 and contains 2,50 to 3,35% solid matter, of which 0,8% is wool fat. The method makes possible a decrease in pH to 8,3; BOD_{abs} to 25 to 30 mg/l and the complete elimination of wool fat. The NO_3^- and NO_2^- content of purified waste water was 31 and 0,1 mg/l respectively.

2.2.3. Paper-Mill Sludge

The waste sludge from paper mills have also been treated by anaerobic digestion (65). The sludges contained straw-pulp, waste paper, white water and bark and were treated by thermophilic and mesophilic digestion. The raw sludge contained 50 to 70% crude fibre in the volatile matter. In ten days of batch-wise digestion, these sludges were destroyed, producing 150 to 600 ml of gas per gm of volatile matter. For continuous digestion of volatile matter, however, nutrients were required. It was found that activated sludge was the most effective nutrient tested. Doses of 2 and 4% activated sludge were added to raw sludge containing 2,5% volatile matter. After digestion, 40 to 70% of the crude fibre had been destroyed, while 300 to 500 ml of gas containing 70% methane were produced per gm of crude fibre destroyed. The treated sludge settled rapidly,

the settled volume being reduced to 1/2 to 1/3 of that of the raw waste. Thermophilic digestion was found to be better than mesophilic for the destruction of volatile matter and for gas production.

2.2.4. Fish Stickliquor

Borchardt and Pohland (2) treated the stickliquor resulting from the recovery of oil and protein from the alewife fish found in Lake Michigan. The stickliquor is particularly strong with an unpleasant odour and did not respond to treatment with the usual coagulants. Anaerobic digestion was able to treat the waste satisfactorily if the loading of volatile solids was maintained at less than 0,8 kg/(m^3day), and if sufficient time was allowed for acclimation. Digestion was also satisfactory if the stickliquor was mixed with at least an equal amount of sewage sludge. The observed pH during digestion, however, appeared higher than normal, and this, or the accumulation of excessive amounts of inhibitors such as ammonia or sulphide, led to eventual failure of the process. Internal pH adjustment with hydrochloric acid appeared beneficial, however.

2.2.5. Phenolic Wastes

Anaerobic digestion has also been used to treat waste waters containing phenol. Chmielowski and Kusznik (6) carried out laboratory experiments on the anaerobic digestion of various types of phenolic waste waters, including those from the synthesis of phenols, from the coal-tar chemical industry and from coke works. The digestion units were maintained at mesophilic temperatures (32°C) and a solids concentration of 1 000 mg/l. After a period of acclimation to the digestion of pure phenol, the seed of digested sewage sludge was decomposing 90% of the phenol present in waste waters from the phenol synthesis process, but only 50 to 65% of the phenol in the waste waters from the coke industry. The latter waste contained other substances inhibitory to methane fermentation, and this accounted for the low degree of decomposition observed.

2.2.6. Simulated Cheese Wastes

In laboratory experiments by Harishchandra et al (7) simulated waste waters from cheese production were digested at 37°C after a long acclimation period. The experiments showed a BOD reduction of 86% at a loading of 2,92 kg/(m^3day), while for lower loadings, the BOD and volatile solids reductions were greater.

2.2.7. Monosodium Glutamate Waste

That anaerobic digestion can be used to treat very concentrated industrial wastes has been proved by Niles and Frook (41) who used the process to treat what is probably the strongest of all industrial wastes in terms of BOD : the end liquor from the manufacture of monosodium glutamate (MSG). This waste has a BOD varying between 250 000 and 400 000 mg/l. The raw materials for MSG production are wheat gluten or concentrated Steffen's filtrate (CSF) from beet sugar manufacture. The waste produced by the process is almost completely soluble, and attempts to evaporate and incinerate the waste were reported as unsuccessful. Alternatively, digestion was tried. Laboratory experiments on the digestion of the end liquor from the wheat gluten process revealed that 98,7% reduction in BOD was possible at a loading of 0,165 kg BOD/(m^3 day). When this loading was doubled, digestion failed due to chloride toxicity. The methane content of the gas produced was 58%. The end liquor from the CSF process gave a 96,9% reduction in BOD at a loading of 0,68 kg BOD/(m^3day). High chloride concentrations again caused digestion problems. In view of this chloride problem, digestion of the end liquor by itself did not seem feasible, but in admixture with sewage sludge, no problems were foreseen.

2.2.8. Starch-Gluten Waste

In a short pilot scale experiment on the anaerobic digestion of the tailing stream from a starch-gluten plant, Ling (25) showed that it was possible to obtain at least 80% removal of volatile solids at a loading of 1,6 kg volatile matter/(m^3day). The waste had a BOD of

12 000 mg/l and total volatile solids of 14 000 mg/l. The most practical methods of treating the waste were anaerobic digestion and lagooning. Aerobic treatment or evaporation and incineration would have been impractical, either requiring too much supervision or being too expensive.

2.2.9. Brewery Waste

Further applications of anaerobic digestion have taken place in the treatment of brewery wastes. Newton et al (40) operated a 1 900 litre digester receiving wastes from a brewery in Frankenmuth, Mich. Nearly two years of operation revealed that the brewery wastes were amenable to anaerobic digestion provided that the raw waste was supplemented with nitrogen and phosphorus to give concentrations in the feed of about 100 and 15 mg/l respectively. The ratio of BOD to total nitrogen in the feed ranged between 65 : 1 and 5 : 1. At these levels nitrogen generally built up in the digester. The operation of the pilot plant revealed that loadings of up to 2,9 kg BOD/(m^3day) could be handled with a removal expectancy of 92 to 97%. Also the digestion system could adapt to brewery shutdowns of two or more days without serious difficulties. The optimum mixing arrangements were shown to be intermittent mixing by a propellor stirrer for approximately 15 seconds every 2 hours, with feed introduced near the bottom of the digester. This gave a sludge with the best settling characteristics. The final effluent would need tertiary treatment before discharge to a water-course, however. Gas productions indicated that considerable supplementary heating would be required in the cold climate of Frankenmuth. Bosch et al (3) found in laboratory scale digestion experiments on strong and dilute waste waters from breweries that 85 to 90% reduction in organic matter could be expected in both cases with a retention time of 9 to 11 days. The strong waste, containing 75% beer, produced sufficient gas to maintain the digestion temperature, but this was not the case with the dilute wastes from the filter presses, making digestion of this stream uneconomic.

2.2.10. Cane-Sugar Factory Effluent

Cane-sugar factory effluents have been successfully treated by anaerobic digestion as shown by Sinha and Thakur (62) in laboratory experiments. The waste waters were seeded with digested sewage sludge and maintained at about 36°C. BOD reductions of 89 to 96% were achieved for retention times of 2 to 6 days at BOD loadings of 0,26 to 1,78 kg BOD/(m^3day).

2.2.11. Wine Distillery Wastes

Stander (67) has described the operation of a full-scale clarigester treating wine distillery wastes at Paarl, South Africa. The clarigester achieved consistently greater than 96% reduction in BOD of a feed with a BOD of 12 000 mg/l and a Chemical Oxygen Demand (COD) of 22 400 mg/l. The maximum organic loading attainable was 3,2 kg COD/(m^3day) at an operating temperature of 30°C, but this loading was limited by the hydraulic characteristics of the clarigester. This loading was equivalent to a retention time of 7,2 days. At any retention time less than this, excessive loss of sludge occurred. The volatile acids concentration in the digester compartment averaged 50 mg/l as acetic acid and did not exceed 100 mg/l at any time, while the gas produced had a heating value of 5 340 k cals/m^3. The clarigester was operated both on fresh spent wine and on spent wine that had been stored for up to three months in a lagoon. The fresh spent wine gave gas productions of 14 volumes of gas per volume of feed, while the production from the lagooned spent wine varied between 2 and 5 volumes per volume. It was found that although the digester was dormant for some five months per year, it could be reactivated by feeding spent wine only and that re-inocculation was not necessary.

Sonoda and Seiko (64) digested at thermophilic temperatures (54°C) an alcohol distillery waste diluted to contain 1 and 2% volatile matter in two separate digesters. The sludge concentrations were adjusted to 20 to 30 centrifuged volume per cent and tests were continued

for three months. The maximum loadings reached for the two dilutions respectively were 5 and 18 kg/(m^3day) as volatile matter and 70% reduction of BOD was obtained. Radhakrishnan et al (45) determined in laboratory experiments that it was better to treat raw molasses distillery waste in a diluted form, rather than in the concentrated (30 000 mg/l) form, since the high volatile acids and low pH generated with the concentrated waste slowed down digestion. They also determined that two-stage digestion was better for treating high organic wastes than single stage digestion with longer retention times.

Basu (1) studied the treatment of beet molasses distillery waste waters. He found that anaerobic digestion at 35°C with a BOD loading of 3,2 kg/(m^3day) reduced the BOD by 96%, producing a gas containing 59 to 64% methane, but that secondary treatment of the supernatant liquor would be desirable. Parthasarthy et al (42) found in laboratory scale investigations that the waste waters from the molasses distillery of a sugar factory at Nellikuppum, India, could be treated by anaerobic digestion. 90 to 95% BOD reduction was achieved at 40°C in 8 to 12 days retention time with optimal BOD loadings almost proportional to the retention times. The gas produced contained nearly 60% methane.

2.2.12. Molasses Distillery Waste

Sen and Bhaskaran (61) carried out a set of laboratory experiments on the digestion of liquid wastes from a distillery fermenting cane-sugar molasses in India. The spent waste investigated had total solids concentrations of from 70 000 to 120 000 mg/l. A BOD of 18 000 to 37 000 mg/l and COD of 40 000 to 90 000 mg/l while the total Kjeldahl nitrogen concentration was between 600 and 900 mg/l. The first phase of the experiments was carried out in two stages under quiescent conditions and resulted in BOD removals of about 95% at loadings of up to 3,02 kg/(m^3day) It was thought that the high BOD : N ratio of 40 : 1 to 50 : 1 of the waste might have been limiting digestion, but the addition of nitrogen had no significant effect on performance. Different methods of agitating the digesters were then tried. Mechanical agitation and recirculation of

all the digester gas had little, if any, effect on digester performance. Agitation by recirculation of carbon dioxide only was then tried and this had a marked effect, increasing the BOD removal at a loading of 3,05 kg/(m^3day) from 91,2% to 96,5% and increasing the proportion of methane in the gas from 49% to 58%. This was explained by postulating that the carbon dioxide in the gas acted as a hydrogen acceptor, and thus an increase in partial pressure of carbon dioxide caused an increase in proportion of methane in the gas, e.g.:

$$4\,H_2A + CO_2 \longrightarrow 4A + CH_4 + 2H_2O \quad .....(2.1)$$

where A is any oxidised substrate. In a series of laboratory experiments designed to determine the effects of nitrogen and carbon dioxide on anaerobic digestion, Hartz and Kountz (18) agitated a digester with carbon dioxide alone and nitrogen alone. A control digester was agitated mechanically by sludge recirculation and the deviations from the control observed in the digesters agitated by gas recirculation. The gas streams were sufficiently strong to ensure complete mixing of the digester contents, and their respective effects were to provide a saturation of carbon dioxide and to strip out carbon dioxide and methane as fast as they were formed. In this way the effect of carbon dioxide on digestion could be observed. The results showed that carbon dioxide recirculation had no beneficial effect on the digestion rate compared with mechanical agitation, but should the carbon dioxide recirculation become high enough, it could have an inhibitory effect, by altering the ratio of oxidising agents to reducing agents. Further, it was found that the presence of carbon dioxide in a measurable quantity is required for methane production and solids breakdown in anaerobic digestion. This leads to the conclusion that there is an optimum level of carbon dioxide in the sludge solution, somewhere between zero and saturation, but not at either of these values. In the light of these findings it becomes clear that Sen and Bhaskaran (61) were operating initially at a carbon dioxide level below the optimum, and that by agitating with carbon dioxide only, they approached the optimum more closely, and hence better digestion was obtained.

2.4 TREATMENT OF YEAST WASTES

2.4.1. Introduction

The local regulations governing the discharge of industrial wastes usually allow an effluent below a given strength to be discharged free. This minimum level allows the free discharge of domestic sewage, but most industrial wastes are stronger than this minimum level and so are subject to a treatment fee. In factories with large labour forces, e.g. fruit canneries, the volume of domestic sewage can be considerable, in some cases sufficient to dilute the industrial waste discharged by the factory to a strength at which it would not be subjected to a municipal treatment charge. Yeast factories, however, have such a strong effluent that the sewage from their relatively small labour force is totally insignificant in diluting the waste. Hence there is a powerful incentive for the development of a process which will treat yeast wastes satisfactorily.

Rudolfs (49) has looked at the overall problem of what to do with the effluent from yeast factories. He came to the obvious conclusion that in the first place, the treatment of the waste should be looked upon as part of the manufacturing process, and so the cost of the treatment should be charged against the product. At the time of writing (1944) Rudolfs said that the possibilities of utilizing the waste for some other purpose have not been fully investigated. Since this survey has revealed no economic means of utilizing the waste, it seems that this is still the case at the present time. It is possible to recover various constituents of the waste by evaporation but this is usually impracticable from an economic point of view. Hence it is necessary to treat the waste purely to reduce its pollution load and then to discharge the effluent to the local sewer or watercourse if it is of a high enough standard. Various methods of treating the yeast waste have been tried. These include physico-chemical and biological processes.

2.4.2. Physico-Chemical Treatment

Federov and Golod (14) treated the waste waters from yeast plants using beet sugar molasses as substrate for the yeast by flocculation with ferrous sulphate and lime (200 mg/l as FeO and 600 mg/l as CaO respectively). The terms of their report are difficult to reconcile with practice, however, but the authors say that after coagulation the water could be discharged directly into the watershed.

Drublyanets and Nesterenko (12) have tested a number of sorbents for removing the residual colour from biologically purified effluents from yeast manufacture. Sand and lignin were ineffective. The 1 to 2 mm fraction of coal ash removed the colour completely when used in a volumetric ratio of 1:3,5 and the BOD of the effluent was reduced by 40%. It was not possible to determine what original substrate was used for the yeast growth but beet sugar molasses is the most likely. Stander et al (68) carrying out adsorption tests on untreated yeast waste from cane sugar molasses found ash from a chemical plant to be totally ineffective, while ordinary coal was effective in removing COD, but the quantities of coal required were completely impracticable - of the order of 3 kg per litre of effluent.

Zawonda (76) has used soil filters to purify yeast wastes from beet sugar molasses. A 5 cm dosage of waste every second or third day was purified by 79% on soil filters in the laboratory. In practice a 5 cm dose was applied every third or fourth day and the field allowed to dry and ventilate for 7 to 10 days every month, since the field soil particles were finer (0,01 to 0,12 mm) than the optimum (0,2 to 0,5 mm).

The above reports indicate that some degree of success has been obtained with physico-chemical treatment of wastes arising from yeast growth on beet sugar molasses, but that little such success was evident for wastes from the cane-sugar molasses process.

2.4.3. Biological Treatment

Londong (26) has described the effluent problem existing at a German plant producing bakers' yeast from beet sugar molasses. Under present conditions, the waste is piped from the factory a distance of 21 km to the municipal sewage treatment works at the town of Ham on the Lippe River. On arrival at the sewage works, the waste, with an average BOD of 10 000 mg/l is first aerated for 45 hours in contact with return sludge at a BOD loading of 5 kg/(m^3day) and sludge loading of 0,67 kg BOD/kg Mixed Liquor Suspended Solids (MLSS). Average BOD removal in this tank is approximately 65% and power consumption about 0,3 kWh/kg BOD. The effluent from this tank passes directly into a second aeration chamber where it is mixed with the domestic sewage treated at the plant and aerated for a further 2 hours. In this second aeration tank, the BOD loading is 2,6 kg/m^3 and sludge load 0,65 kg BOD/kg MLSS, and a yearly average of 80% of the BOD is removed. The operation of the plant, although sensitive to temperature, has shown no difficulties from sludge bulking or foaming, with an average sludge volume index of 68 ml/g. Further experiments have been conducted and have shown that the yeast wastes are amenable to treatment in combination with other industrial wastes, including those from a large chemo-pharmaceutical plant. Experiments on the aerobic treatment of yeast wastes alone showed that it was possible consistently to remove greater than 80% of the BOD and occasionally greater than 90% with aeration times varying between 18 and 51 hours and sludge loads between 0,2 and 0,95 kg BOD/kg MLSS. The effluent still had a brown colour, however, and a characteristic yeast waste odour with a BOD of approximately 1 000 mg/l. Slight tendencies to bulk and foam were noticed, especially during periods of nutrient (phosphorous) deficiency. Londong concluded by giving an estimate of the cost of aerobic treatment of yeast waste alone of between 4% and 10% of the production cost of the yeast in Germany.

Rudolfs (49) recommends anaerobic digestion of the waste followed by aerobic treatment on a trickling filter to remove up to 95% of the BOD. The digestion period recommended is 2,5 days in two-stage

reversing digesters for waste with an average BOD of 7 000 mg/l. The effluent after 70% of the BOD has been removed is applied to a 1 metre deep trickling filter with 100% recirculation at a load rate of 10 000 l/m^3 of filter media. The gas produced during digestion contains approximately 70% combustibles and may be used for its fuel value, while the sludge amounts to some 500 litres per million litres waste and drains easily with no objectionable odours.

Tatlock (73) has described the treatment process used to treat the wastes from two yeast factories in Illinois - one at Pekin and the other at Crystal Lake. The Pekin plant has six digesters operating in three stages of 2 tanks each. The overall BOD reduction is 80 to 85% while volatile solids are reduced by 50%. It was necessary to add dried sludge to the tanks on start-up to provide some surface for the active sludge to grow on. The Crystal Lake plant also uses digestion to treat its waste, but in this case two stages are used followed by high-rate trickling filtration, settling and finally chlorination after mixing with condenser water. The final effluent is discharged directly into a drainage ditch which showed no ill effects, apart from a caramel colour. The average BOD of the waste treated in this plant is 4 250 mg/l and Tatlock points out the fallacy that anaerobic digestion had been considered suitable only for very concentrated wastes up to that time (1947).

Sonoda and Seiko (64) have also successfully digested yeast wastes containing 1,6% volatile matter, and determined maximum loadings of volatile matter at 37°C of 4,8 kg/(m^3day) and 8,8 kg/(m^3day) in 10 and 20 volume per cent sludge respectively. Popescu et al (44) have treated wastes from the manufacture of compressed yeast by anaerobic digestion. They achieved 70% reduction in COD in a single stage plant with a load of about 2 kg volatile solids/(m^3day). The relatively low efficiency is attributed to high nitrogen concentration, giving rise to pH values near 8,0 and volatile acids concentrations occasionally higher than 10 000 mg/l. The proportion of volatile solids transformed to gas was inversely proportional to the organic loading. Very little, if any sludge was formed.

Rudolfs and Trubnick (50) have carried out extensive tests over a period of approximately 5 years on the treatment of wastes from compressed yeast manufacture at Old Bridge, N.J., U.S.A. Laboratory tests (50) revealed that electrodialysis could remove up to 40% of the oxygen consuming material. Normal coagulants showed no material precipitation or clarification at practical dosages. Biological tests (51) revealed that both anaerobic digestion and trickling filtration could treat the waste economically and were expanded to pilot plant size. Activated sludge also treated the waste satisfactorily, but bulking sludge was obtained and long aeration periods would be necessary. Accordingly the pilot plant tests were limited to digestion and trickling filtration. The digestion studies (52) were carried out over a period of 5 years in a 106 m^3 capacity two-stage pilot plant and revealed that two-stage operation produced greater BOD reductions per unit BOD loading than did single stage operation. Loadings attained in terms of kg/m^3day) were 5,4 kg volatile matter or 2,1 kg BOD, while average removals were 68% volatile matter and 85% BOD. Total gas productions were 470 l/kg volatile matter added, while the gas contained on average 25% carbon dioxide and 2,5% hydrogen sulphide. Observations on the sludge during this period (54) indicated that a minimum quantity of sludge was required for efficient operation, but that too much sludge was detrimental to the treatment efficiency since conditions given for quiescent operation are that the sludge should occupy between one-eighth and one-half of the digester volume ; under agitated conditions, however, the loadings to the same amount of sludge can be increased greatly. The trickling filtration tests (53) were carried out in two pilot scale filters 1,2 m deep and 4,5 m in diameter filled with crushed rock 2,5 to 6,25 cm in diameter and fed by rotating distributors. Five years of tests indicated that 50% of the BOD applied was removed, irrespective of whether the load applied was in the form of raw waste or anaerobic digester effluent, or mixtures of raw and pre-digested material. Loadings of up to 0,25 kg BOD/(m^3day) to 0,28 kg BOD/(m^3day) were possible without material retardation of purification. The quality of the effluent depended on

the raw BOD concentration, while recirculation appeared to be of value only as a means of diluting concentrated materials.

An extensive research programme on the treatment and disposal of yeast wastes from cane-sugar molasses has been carried out by workers of the National Institute for Water Research of the South African Council for Scientific and Industrial Research (68). A survey of the waste liquids produced by the yeast factories investigated revealed that the first separation waste liquor carried about 65% of the total organic load while constituting only 20 to 30% of the total effluent flow. Treatment methods investigated were anaerobic digestion, activated sludge treatment and physico-chemical treatment. Previous experience indicated that anaerobic digestion would probably be the most successful and this method was investigated both in the laboratory and in a pilot scale plant. The pilot plant used was a reversed flow "Dorr-Oliver" clarigester with a digestion compartment of 6 300 l capacity situated underneath a settling section. Mixed liquor is displaced from the digestion section by raw feed entering, and sludge returns by gravity after settling in the clarifying compartment. The maximum load rate attained in the pilot plant digester was 4,0 kg COD/(m^3day), corresponding to a load ratio of 0,26, at a temperature of 35°C. This was equivalent to a retention time of 6 to 9 days. This maximum loading in the clarigester was limited by physical sludge behaviour rather than by overloading of the metabolic capacities of the organisms. Laboratory digesters were able to accept loads up to three times that placed on the clarigester. This indicates that a conventional stirred digester followed by an efficient settling tank need be only 1/3 the size of an equivalent plant using a reversed flow clarigester. No decline in activity was noted over a period of nearly three years, indicating that yeast waste by itself is a suitable substrate for supporting anaerobic metabolism. Throughout the period of study reported on it was found that only 70% of the applied COD could be decomposed while some 88% of the BOD was removed. This is indicative of the presence of a biologically intractable residue, confirmed by the persistence of the characteristic brown colour of the yeast waste

throughout the whole treatment process. Gas produced by the digestion was some 70% of the consumed COD. The ratio of the volume of gas produced per volume of feed varied between 6:1 and 8:1, depending on the strength of the feed. Hydrogen sulphide constituted about 2% of the gas. General conclusions drawn about the clarigester were that while the loading was limited by mechanical design, the clarigester provided a satisfactory unit for anaerobic treatment of yeast wastes in that it was easily controlled and operated by normal sewage works personnel. Laboratory experiments indicated that separate digestion of the first separation liquor is desirable in view of the increased load rates and purification efficiencies possible when digesting this material alone.

The activated sludge process was also investigated by Stander (68) to determine whether the aerobic organisms could effect any further reduction of the COD remaining in the effluent from the anaerobic process, or whether the activated sludge would be more effective for treatment of raw yeast waste. Laboratory scale experiments were carried out and the results indicated that both wastes were amenable to activated sludge treatment. 65 to 70% COD breakdown for raw waste was accomplished while 35 to 40% could be achieved for digester effluent. Difficulties were experienced with the sludge as wild yeasts tended to cause bulking and protozoa were absent. With regard to treatment of raw yeast waste, high operating costs and long retention times (of the same order as for anaerobic digestion) made the process economically unattractive. Its feasibility for the treatment of digester effluent, however, needs to be evaluated in terms of existing trade effluent charges. Physical treatment of the wastes was also investigated. Flocculation with regular flocculants was unsuccessful in that excessive dosages of flocculants were required for small decreases in COD. Adsorption tests were run with coal and smokeless fuel (soft coke). These two adsorbents were capable of reducing the COD of the effluent, but the quantities required were completely unworkable. The final conclusion drawn from the report is that the strong yeast wastes (COD 20 000 mg/l) should be separated and treated by anaerobic digestion, the effluent from this process being

combined with the weaker factory effluents and discharged to the municipal sewer or irrigated.

2.5. ANAEROBIC FILTER

2.5.1. Development

McCarty (32) built the first anaerobic filter consisting simply of a glass bottle filled with stones, through the voids of which waste was passed while micro-organisms growing on the stones purified the waste. This prototype was then developed into the anaerobic filter as described by Young and McCarty (75). This consisted of a 15,2 cm diameter plexiglass tube 2 m high packed with 2 to 3 cm diameter round quartzite stones. A synthetic waste was fed to the bottom of the filter and flowed upwards through the packing, completely submerging it and thereby ensuring anaerobic conditions for the sludge growing on the surface of the stone packing. The aim of the experiments was to prove that the filter could treat efficiently at ambient temperature waste of a low strength not normally treatable anaerobically. To this end, the filters were maintained at 25°C while a synthetic protein - carbohydrate waste with a COD varying between 1 500 and 6 000 mg/l was fed at rates sufficient to give loadings of 0,43 to 3,40 kg COD/(day m^3 of total filter volume). These loading rates corresponded to theoretical liquid retention times of 72 to 4,5 hours while COD reductions obtained varied between 93 and 60% respectively. Suspended solids in the effluents from the filters were very low : only at retention times of 4,5 hours did the suspended solids in the effluent rise to 250 mg/l and these were easily settleable. Sludge growth in the columns was also very low: for the protein-carbohydrate waste, some 85% of the applied COD appeared as methane, the remaining 15% going to form biological solids; while with a volatile acid feed, the conversion of COD to methane was almost 100%. In terms of COD profiles up the filter, at the low loadings 90% COD was removed in approximately 0,7 m, while at the higher rates, the whole filter height was required to achieve 60% reduction. The remarkable success

2.6. CONCLUSION

Despite the many variables affecting the process, anaerobic digestion has been shown to be capable of treating a wide variety of wastes, both domestic and industrial. The type of treatment system chosen depends largely on the characterists of the waste, particularly with regard to its strength and solids content: those wastes with large quantities of suspended solids being treatable in a completely mixed digester; but wastes with few solids require sludge recycle or an anaerobic filter to maintain a sufficiently high sludge concentration for economic treatment. Various chemicals can upset the balance between the complicated biological processes that go to make up the anaerobic digestion process, and the reduction of these inhibitory effects has been the subject of much study. The treatment of yeast wastes has been reviewed by several investigators, most of whom come to the conclusion that biological treatment is necessary and that anaerobic digestion is the most suitable, aerobic treatment requiring too much aeration and producing too much sludge for subsequent disposal. The anaerobic filter has been shown to be well suited to the treatment of soluble wastes since high sludge concentrations can be maintained by physically holding the sludge in the filter. The logical conclusion is that yeast wastes, being almost entirely soluble, would be admirably suited to treatment on the anaerobic filter.

The data presented during this survey is summarised in Table 2.1 which lists the type of waste treated; the treatment method; the scale of the investigation; the loading applied and the reduction obtained, as well as giving the name of the principal investigator and the reference.

TABLE 2.1. SUMMARY OF LITERATURE SURVEY DATA

TYPE OF WASTE TREATED	TREATMENT PROCESS	SCALE	LOADING APPLIED	REDUCTION OBTAINED	MAIN INVESTIGATOR	REF.
Meat Packing	Anaerobic Lagoons	Pilot & full	1 100 mg/l BOD	81 - 95%	Sollo	63
Meat Packing	Anaerobic-Aerobic Ponds	Pilot	0,26 kg BOD/(m^3 day) (Anaerobic)	58% BOD (Anaerobic)	Rollag	47
Meat Packing	Anaerobic Lagoon	Full	-	80 - 90% BOD	Stanley	70
Slaughter & Packing House	Anaerobic Contact	Pilot	1,35 kg BOD/ (m^3day)	95 - 96%	Fullen	15
Slaughter & Packing House	Anaerobic Contact	Pilot	3,2 kg BOD/ (m^3day)	95%	Schroepfer	59
Slaughter & Packing House	Anaerobic Contact	Full	7 320 kg BOD/day	91%	Steffen	71
Wool Scouring	Anaerobic Digestion	-	25 days for 9 000 to 22 000 mg/l BOD_{20}	90% BOD_{20}; 67% Fat, 45% Volatiles	Nevzorov	39
Wool Washing	Filtration and Digestion	Pilot	20 000 mg/l BOD_{abs}	99,9% BOD	Grishina	16
Paper Mill Waste Sludge	Batch-wise Digestion	Lab.	50 - 70% Crude Fibre in 10 days	40 - 70% Fibre Destroyed	Sonoda	65
Alewife Stickliquor	Anaerobic Digestion	Lab.	<0,8 kg Vol.Solids /(m^3day)	Satisfactory	Borchardt	2
Phenolic Wastes: Coal Tar	Anaerobic Digestion	Lab.	-	90% Phenol	Chmielowski	6
Coke	Anaerobic Digestion	Lab.	-	50-65% Phenol	Chmielowski	6
Simulated Cheese	Anaerobic Digestion	Lab.	2,9 kg BOD/ (m^3day)	86% BOD	Harishchandra	17

TABLE 2.1. SUMMARY OF LITERATURE SURVEY DATA (Contd.)

TYPE OF WASTE TREATED	TREATMENT PROCESS	SCALE	LOADING APPLIED	REDUCTION OBTAINED	MAIN INVESTIGATOR	REF.
M.S.G. Production	Anaerobic Digestion	Lab.	0,17 kg BOD/(m^3day) (Wheat Gluten Source)	98,7% BOD	Niles	41
			0,7 kg BOD/(m^3day) (C.S.F. Process)	96,9% BOD	Niles	41
Starch-Gluten	Anaerobic Digestion	Pilot	1,6 kg Vol. Solids/(m^3day)	80% Volatile Solids	Ling	25
Brewery	Anaerobic Digestion	Pilot	2,9 kg BOD/(m^3day)	92-97%	Newton	40
Brewery	Anaerobic Digestion	Lab.	Strong & Dilute Wastes, 9-11 Days	85-90% Organic Matter	Bosch	3
Cane Sugar Factory	Anaerobic Digestion	Lab.	0,26 to 1,8 kg BOD/(m^3day)	89-96% BOD	Sinha	62
Wine Distillery	Anaerobic Digestion	Full	1,7 kg BOD/(m^3day), 3,2 kg COD/(m^3day)	96% BOD	Stander	67
Distillery	Anaerobic Digestion	Lab.	18 kg Vol. Matter/(m^3day)	70% BOD	Sonoda	64
Molasses Distillery	Anaerobic Digestion	Lab.	-	-	Radhakrishnan	45
Beet Molasses Distillery	Anaerobic Digestion	Lab.	3,2 kg BOD/(m^3day)	90% BOD	Basu	1
Cane Molasses Distillery	Anaerobic Digestion	Lab.	8-12 days Retention time	90-95% BOD	Parthasarthy	42

TABLE 2.1. SUMMARY OF LITERATURE SURVEY DATA (Contd.)

TYPE OF WASTE TREATED	TREATMENT PROCESS	SCALE	LOADING APPLIED	REDUCTION OBTAINED	MAIN INVESTIGATOR	REF.
Cane Molasses Distillery	Anaerobic Digestion	Lab.	3,0 kg BOD/ (m^3day)	96,5% BOD	Sen	61
Yeast	Anaerobic Digestion & Trickling Filtration	-	2,5 days for 7 000 mg/l BOD	70% BOD 95% Total	Rudolfs	49
Yeast	Flocculation ($FeSO_4$ + CaO	-	200 mg/l $FeSO_4$ + 600 mg/l CaO	Satisfactory	Federov	14
Biologically purified Yeast	Adsorption on Coal Ash	Lab.	Volumetric Ratio 1:3;5	40% BOD; Total Colour	Drublyanets	12
Yeast (Cane Molasses)	Anaerobic Digestion	Pilot	4,0 kg COD/ (m^3 day)	70% COD 88% BOD	Stander	68
Yeast	Anaerobic Digestion	Lab.	12,0 kg COD/ (m^3 day)	70% COD 88% BOD	"	"
Yeast	Activated Sludge	Lab.	-	65-70% COD	"	"
Digester Effluent	Activated Sludge	Lab.	-	35-40% COD	"	"
Yeast	Physical Treatment	-	-	Unsatisfactory	"	"
Yeast	Soil Filter (Irrigation)	Lab.	5 cm dose every 2 - 3 days	79%	Zawonda	76
		Pilot	5 cm dose every 3-4 days; 7-10 days/month down		"	"
Yeast (Beet Molasses)	Aeration with Sewage	Full	5 kg BOD/(m^3 day) (first aeration	65% BOD	Londong	26

TABLE 2.1. SUMMARY OF LITERATURE SURVEY DATA (Contd.)

TYPE OF WASTE TREATED	TREATMENT PROCESS	SCALE	LOADING APPLIED	REDUCTION OBTAINED	MAIN INVESTIGATOR	REF.
Yeast (Beet Molasses)	Aeration with Sewage	Full	2,6 kg BOD/ (m^3day) (Second Aeration)	80% BOD	Londong	26
	Activated Sludge	Pilot	0,2-0,9 kg BOD/ kg MLSS	80-90% BOD	"	"
Yeast	3-Stage Anaerobic Digestion	Full	-	80-85% BOD; 50% Volatile Solids	Tatlock	64
Yeast	Anaerobic Digestion	-	4,8 kg Vol.Matter (m^3day) 10 vol.% Sludge	Satisfactory	Sonoda	64
			8,8 kg Vol.Matter (m^3day) 20 vol.% Sludge	Satisfactory	Sonoda	64
Yeast	Anaerobic Digestion	-	2 kg Vol.Solids/ (m^3 day)	70% COD	Popescu	44
Yeast	Electrodialysis	Lab.	-	40% COD	Rudolfs	50 to 54
	2-Stage Anaerobic Digestion	Pilot	2 kg BOD/(m^3day); 5,4 kg Vol.Matter/ (m^3day)	85% BOD; 68% Vol. Matter	"	"
	Trickling Filtration	Pilot	0,25-0,28 kg BOD/ (m^3 day)	50% BOD	"	"
Synthetic Protein Carbohydrate	Anaerobic Filter	Lab.	0,4-3,4 kg COD/ (m^3day)	93-60% COD	Young	51

TABLE 2.1. SUMMARY OF LITERATURE SURVEY DATA (Contd.)

TYPE OF WASTE TREATED	TREATMENT PROCESS	SCALE	LOADING APPLIED	REDUCTION OBTAINED	MAIN INVESTIGATOR	REF.
Synthetic Ammonia	Submerged Filter	Lab.	20 mg/l NH_3-N @ 30 mins. retention	90% NH_3-N	Haug	19
Saline Agricultural Water	Anaerobic Filer	Pilot	20 mg/l NO_3-N @ 30 mins. retention	90% NO_3-N	Tamblyn	72
Saline Agricultural Water	Anaerobic Filter	Pilot	-	-	St. Amant	55
Carbohydrates	Anaerobic Filter	Lab.	2,4-15,2 kg COD/(m^3day)	93,5-41% COD	Plummer	43

CHAPTER 3

APPARATUS AND OPERATION OF THE FILTERS

3.1. APPARATUS

3.1.1. Introduction

The apparatus used in this investigation into the treatment of yeast waste with the anaerobic filter will be described below. Diagrams and photographs will be included to clarify the description where necessary. A discussion of the suitability of the equipment is given in Chapter 4, Section 4.5., but it is as well to mention at this stage that the major difficulty of the whole investigation was the fluctuating flow rates of the various devices used to feed the filters. This accounts for the wide variety of feeding devices used, as attempts were constantly being made to obtain steady flow rates.

3.1.2. Filters

The anaerobic filters as constructed for this study were modelled on those described by Young and McCarty (75). They consisted of plexiglass tubing 9,4 cms internal diameter, two of the filters being 1,87 m high and the third 1,98 m high. (Fig. 3.1). Young and McCarty (75) stated that the sludge tended to adhere to the surface of the packing as well as grow in the voids, and so the packing medium chosen was 1,2 cm porcelain Raschig rings, having a specific surface of 400 m^2/m^3 (27) and a void fraction as packed of 0,62. This gave void volumes in Filters I II and III of 8,0 l, 8,0 l and 8,3 l respectively. During the investigation, however, the interior of these rings became clogged with inert sludge, reducing the effective specific surface to 270 m^2/m^3 and the void fraction to 0,4. All results given, however, were calculated on the

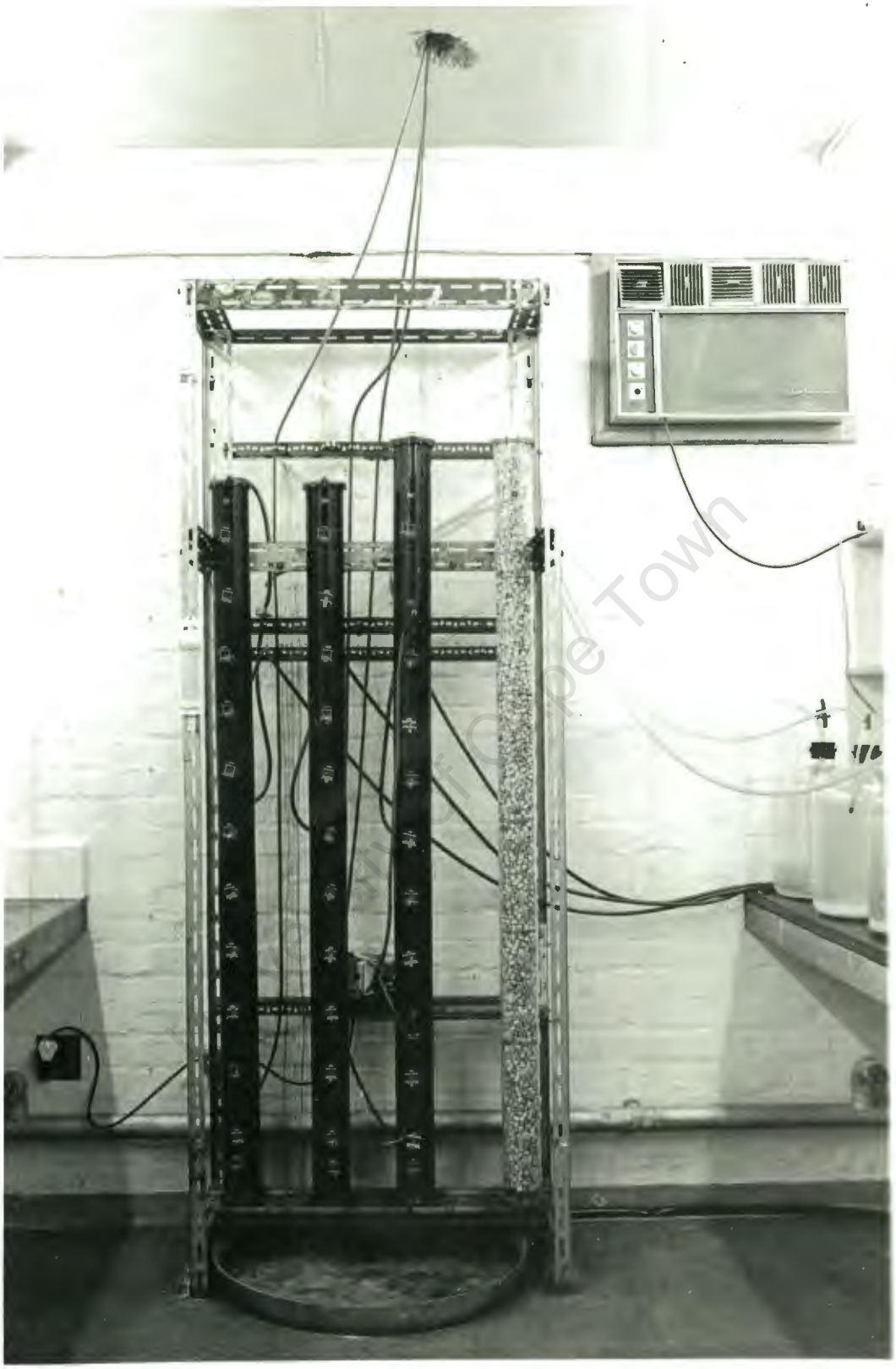

Fig. 3.1 The Anaerobic Filters as used in the Investigation.

figures for clean packing. The filters were wet-packed to within 2 cm of the top and were equipped with dispersion rings 1,9 cm wide spaced every 0,5 m up the filter in order to reduce wall effects, (Fig.3.2.) The packing was supported by a stainless steel grid 1,9 cm from the bottom of the filter to distribute the waste evenly across the packing. Sample tubes extending to the centre were installed every 15 cms up the filter, with an additional tube 7,5 cms from the bottom. The effluent from the filters was withdrawn from the top, gas and liquid passing together to a separating bulb from which the liquid flowed to a drain by way of a U-tube liquid seal, (Fig. 3.3.) The gas was collected over acidified water in graduated bottles, (Fig. 3.4.) (The same water was used throughout the experiments to ensure saturation of the water with digester gas at all times.) The filters were kept in a room maintained at 30 $\pm$ 1°C and the volume of the gas produced was measured at this temperature and atmospheric pressure. Filters I and II were operated on a plug-flow basis, but Filter III was equipped with a pump to circulate the middle two fourths of the filter as shown in Fig. 3.3. A small peristaltic pump was used for this circulation.

Because of the types of feeding device used, the feed tanks in their refrigerator (Fig. 3.5) were mounted with the feed pumps in a room directly above the laboratory containing the filters. The feed pipes were passed through a hole in the floor to the filters below. (Fig. 3.1.), while the refrigerator kept the temperature of the feed at 4 $\pm$ 2°C. By the time the feed reached the filters, however, it had warmed up to 30°C.

3.1.3. Pumps

Methods of feeding the filters caused major problems during the investigation. Various types of feed pumps and devices were tried, with little success in obtaining constant day-to-day flow rates. The main problem with all the feeding devices was the sludge growth which took place in the feed lines and which tended to block all the feed systems used, (Fig. 3.6.).

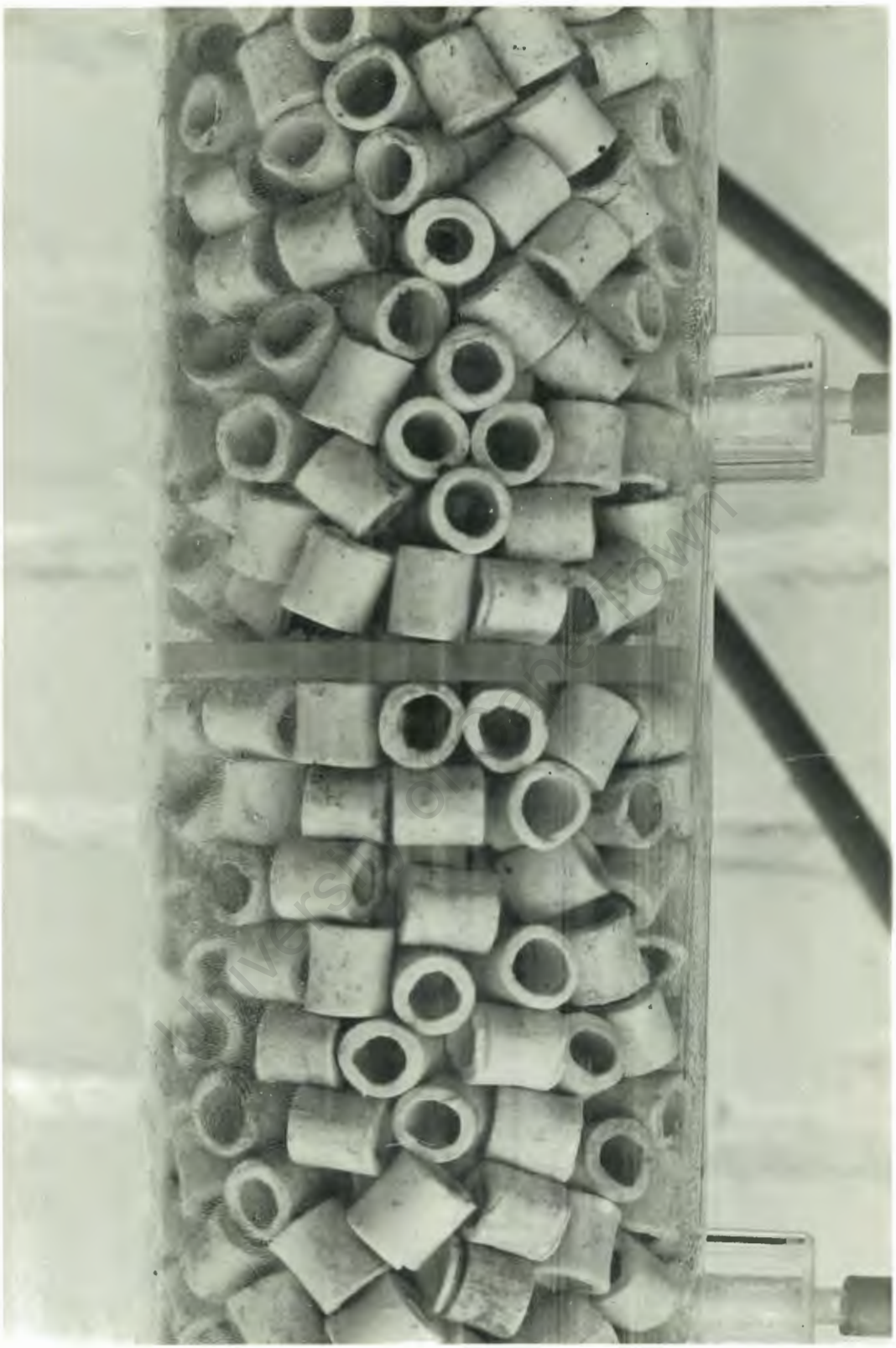

Fig. 3.2 The Raschig Ring Packing and a Dispersion Ring.

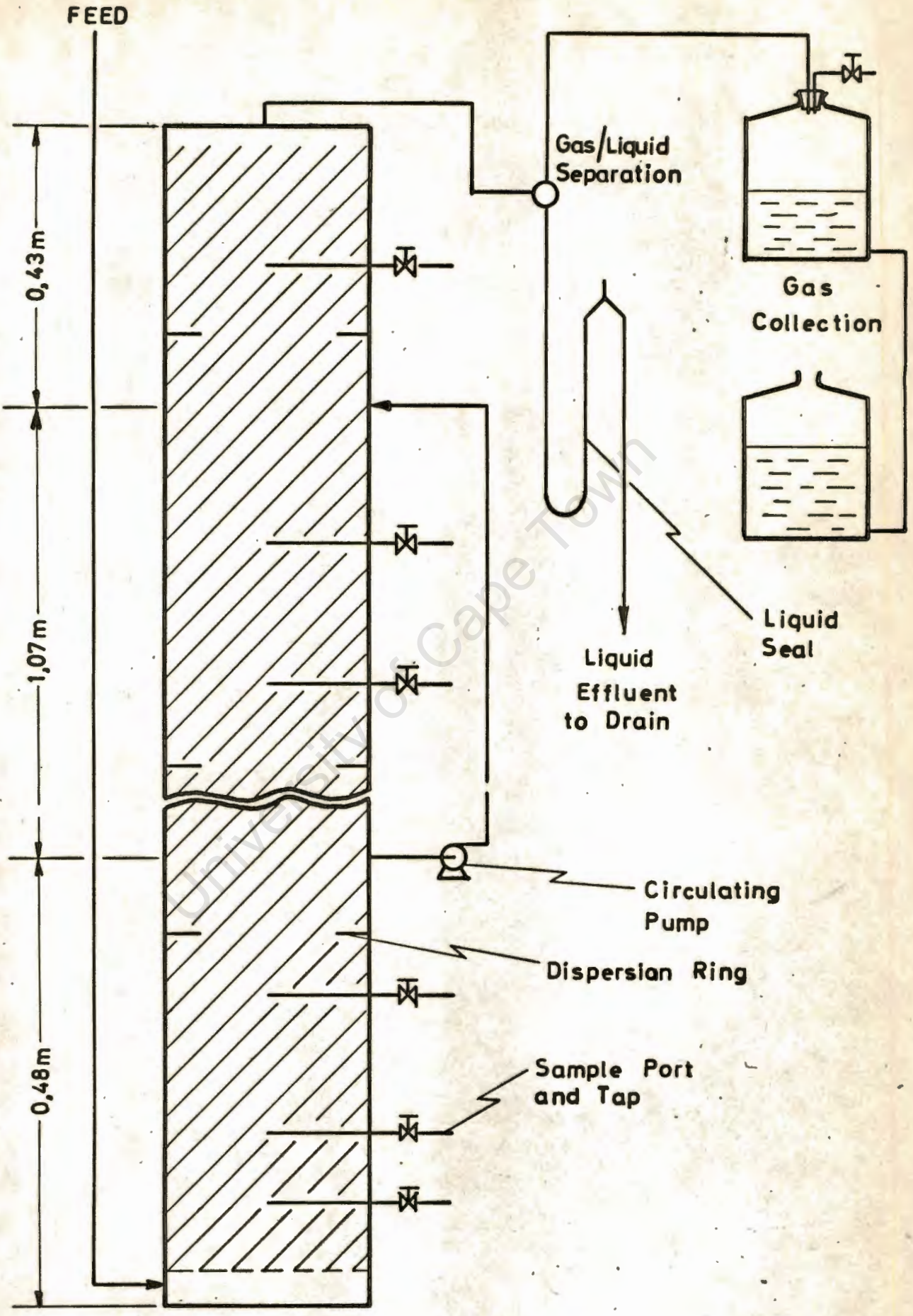

Fig 3.3 CIRCULATED ANAEROBIC FILTER WITH APPURTENANCES (not to scale)

Fig. 3.4 The Gas Collection Bottles Used.

Fig. 3.5 The Refrigerator housing the Feed Tanks and the Chemical Metering Pump.

Fig. 3.6 Sludge Growth (light-coloured) in Feed Lines.

The first pump used was the so-called "kinking tube pump", shown in Fig. 3.7. The action of this pump may be seen from Figs. 3.8.(a) and (b). The height to which the liquid rises in the chamber, and so the volume delivered per stroke, is governed by the position of the capillary tube, the liquid rising in the chamber until it reaches the bottom of the capillary tube and then rises up this until it reaches the height of the liquid in the feed tank.

The second pump tried was a peristaltic "finger" pump, or sigma-motor type pump. A positive displacement chemical metering pump fitted with back pressure valves for constant flow was also used.

The fourth feeding device used was based on a restriction on the inlet side of an aspirator controlling the flow rate of the liquid feed leaving the aspirator. The inlet tube passed through an air-tight rubber stopper and extended to the bottom of the aspirator bottle in order to give a constant pressure at a reproducible level as the level "H", (Fig. 3.9.) of the liquid in the aspirator dropped. The restriction on the air flow was provided by a capillary tube of 1 mm bore attached to the top of the inlet tube and carrying a varying length of wire with a diameter fractionally less than 1 mm, allowing a snug fit into the capillary tube. The rate at which air is drawn through this restriction, and hence the liquid flow rate out of the aspirator, is controlled by the distance "h", (Fig. 3.9.), by which the outlet weir, open to atmospheric pressure, is below the bottom of the inlet tube. Both the length of wire in the capillary tube and the depth of the outlet weir may be varied to give the required flow rates and sensitivity, (Fig. 3.10.)

The liquid flow rates were measured at all times by noting, at known intervals, the liquid levels in the feed tanks, as indicated in calibrated sight tubes on the outside of the refrigerator housing the feed tanks, (Fig. 3.11.)

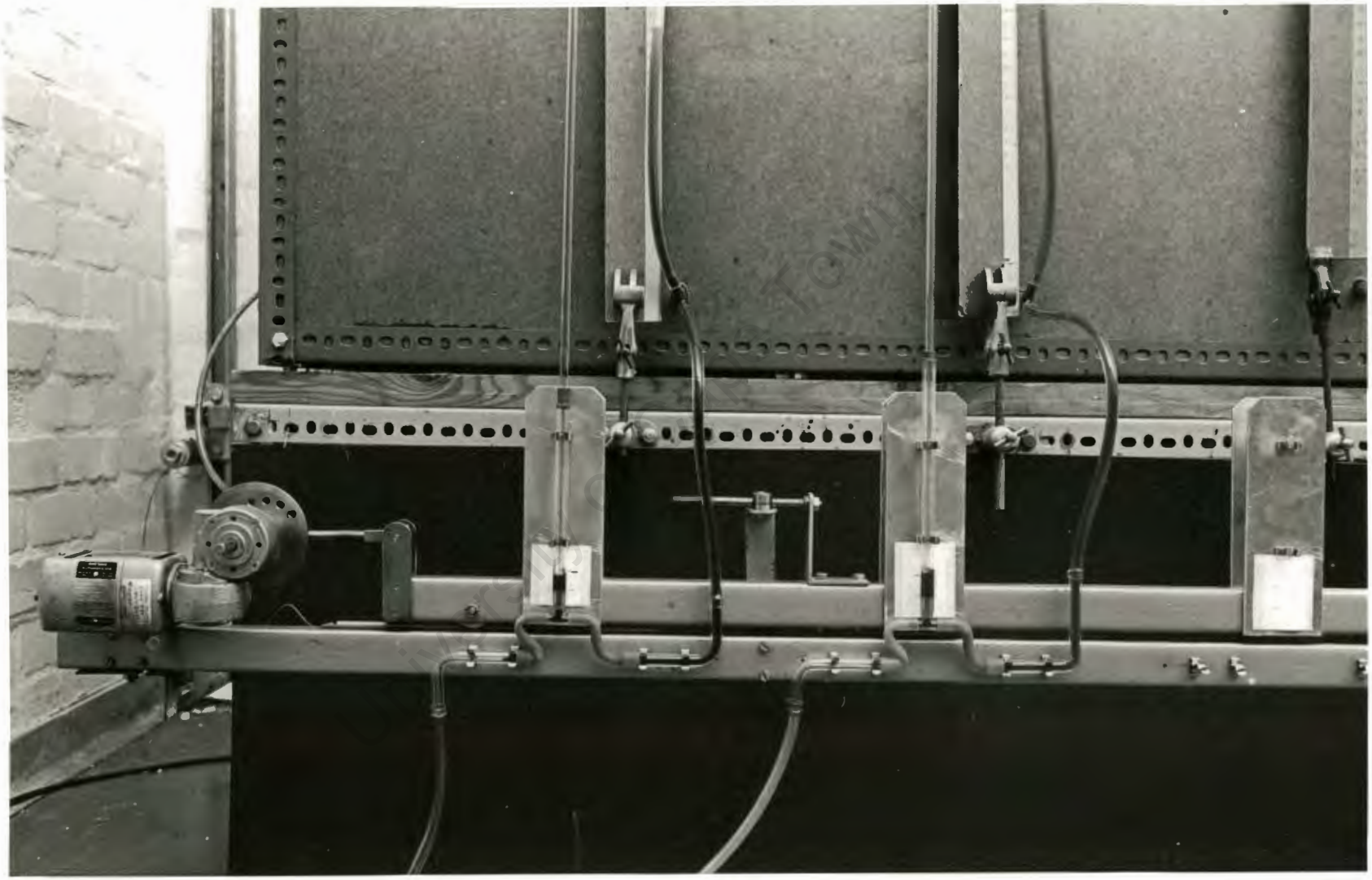

Fig. 3.7 Overall View of the "Kinking Tube" Pump.

Fig. 3.8(a) "Kinking Tube" Pump with Feed Line Open.

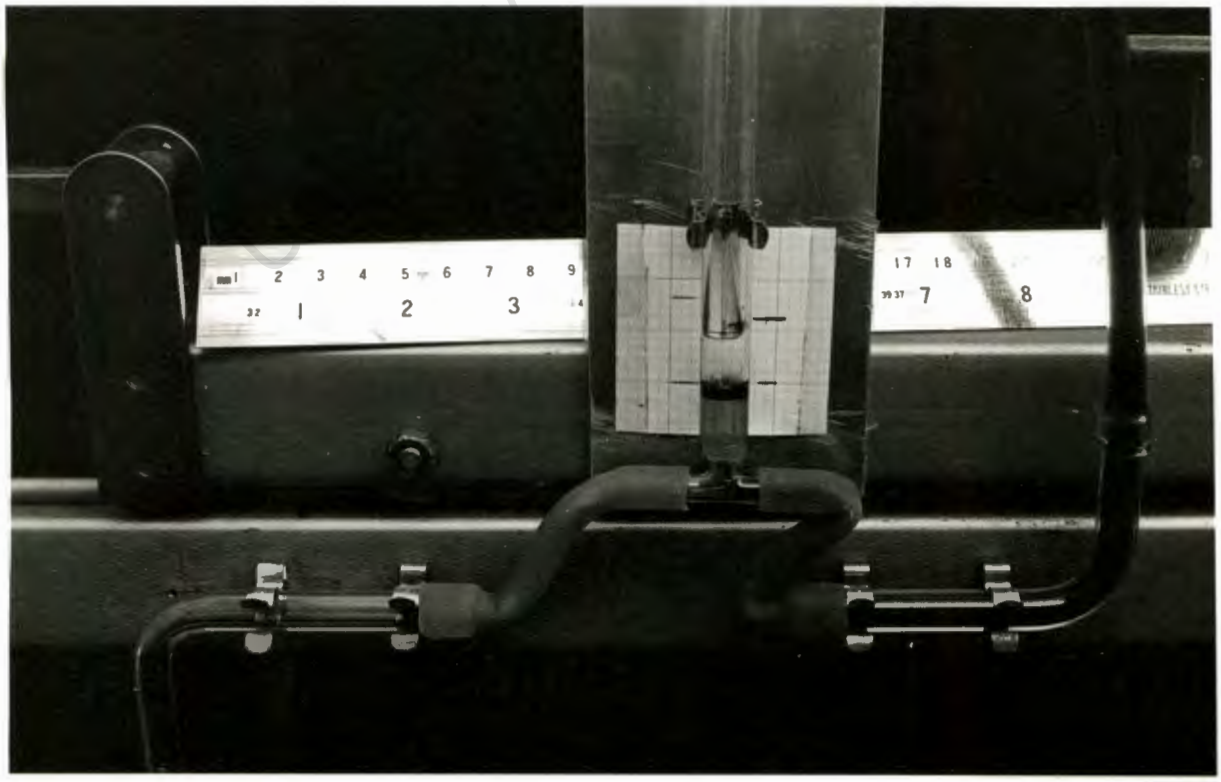

Fig. 3.8(b) "Kinking Tube" Pump with Delivery Line Open.

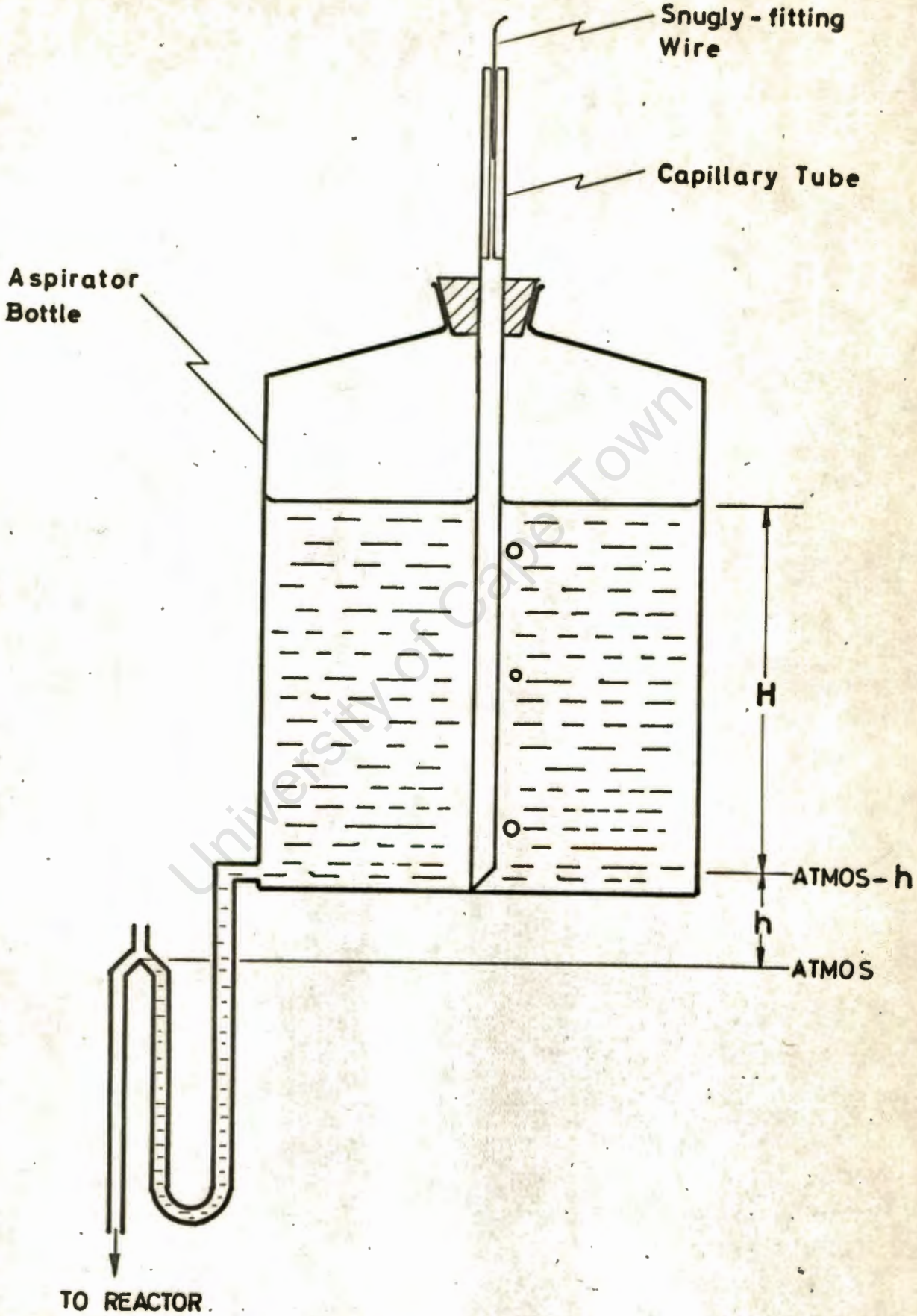

Fig 3.9 ASPIRATOR FEEDING DEVICE

Fig. 3.10 The Aspirator Feeding Device as Used in the Investigation.

Fig. 3.11 Sight Tubes Indicating Liquid Level in the Feed Tanks.

Standard laboratory apparatus was used for chemical analyses, with pH being measured on an Electronic Industries Limited direct reading pH meter. A detailed description of analytical techniques is given in Appendix A.

3.2 OPERATION OF THE FILTERS

3.2.1. Introduction

This section gives a summary of the main patterns in the operation of the filters. A detailed description of the daily performance of the filters is given in Appendix B, while Tables of all operating results are contained in Appendix C. This section also deals with the major difficulties encountered during the investigation, nearly all of which stemmed from variations in the feed flow rates.

3.2.2. Outline of the Operation of the Filters

Two anaerobic filters, constructed as described in Section 3.1.2. above, were seeded with sludge from laboratory digesters treating wine waste and placed in a room at 30°C. Feeding commenced with pure wine waste, but yeast waste was soon added to the feed to start acclimating the sludge to the new substrate, as this was thought to be necessary. The quantities of yeast waste added initially were too large, causing overloading of the filters' capacity with the small quantities of sludge present, as was evidenced by very high acids concentrations. In an attempt to reduce these concentrations, a 4:1 effluent to feed recycle was set up, but was not successful, as the gas rate - one of the main indicators of the amount of methane fermentation taking place - continued at a low level. At this stage (day 31) a shock load of some 10 l of feed passed through one of the filters overnight, and this filter was then operated subsequently on pure wine waste. The feed to this filter had the pH adjusted to 7,0 by adding sodium bicarbonate and this extra alkalinity also kept the pH of the filter within an acceptable range. From day 40 onwards, effluent was again

recycled in the ratio of 4:1 with feed and this time was more successful in reducing the buffer needed for the feed. Some 60% of the OA was being removed by passage through the filter at this stage. For the next 50 days, loading continued at a low level, fluctuating considerably due to pumping difficulties, however. Recycle of effluent was kept at about 2,5:1 and about 70% of the OA was removed.

From day 30 onwards, the other filter kept operating on a mixture of yeast and wine wastes, with gradually increasing proportions of yeast waste. The loading also increased generally, but many fluctuations were caused by pumping difficulties. The acids concentration gradually dropped from its very high levels of 7 000 mg/l near day 30 to 1 500 mg/l on day 94. Once the acids concentrations had dropped, the gas rates followed the load rates predictably, while reductions of 60% in OA were effected. Recycle of the effluent was maintained at between 4:1 and 2:1.

On day 94 the feed to both filters was stopped in preparation for a vacation, the temperature allowed to fall to ambient, and the filters were left dormant for 60 days. After this time, the temperature was raised to 30°C and tests showed the acids concentrations to be approximately 400 mg/l and the pH 7,3. The filter that had been treating mixed yeast and wine waste - the final proportion had been 75% yeast waste - was then started up using pure yeast waste feed at a very low loading rate. This was gradually increased with no signs of ill effects from the filter until the loading had trebled after 10 days to about 1 kg COD/(m^3day).

The other filter that had been treating pure wine waste was flushed and reseeded with digesting sewage sludge and fed pure yeast waste. The initial loading rate proved to be far too high, as the acids concentration rapidly increased, proving that no acclimation period was necessary. After about 5 days during which fluctuations in the load rates were interspersed with periods of no feed to allow the acids concentration to fall, this filter was loaded at the same level as the other. The operation of the two filters was then maintained in parallel.

From day 165 through to day 220, the loadings to both filters were kept between 1,0 and 1,7 kg COD/(m^3day). The loading did fluctuate widely between these values, however, due to pumping difficulties, but the gas rates followed the loading rates predictably. The reductions in OA averaged 40% at the beginning, increasing to 50% by day 220. During this period, one of the filters received a large shock load of feed. The acids concentrations were monitored and the bottom of the filter recovered within 12 hours of the end of the shock, with no further feed, but the top of the filter required more than 24 hours.

After this period of steady operation, the load rates to both filters were gradually increased, reaching about 4 kg COD/(m^3day) by day 240. The gas rates also increased correspondingly, following the fluctuations in the load rates. At this time a finger pump was brought into service to replace the kinking tube feed pump which had been used up to this time. After starting this pump, however, a joint in the feed line to one of the filters failed and the sludge from the filter was lost. This was replaced with fresh sewage sludge and feeding recommenced with pure yeast waste buffered with sodium bicarbonate. As before no acclimation period was necessary and the sludge rapidly started gassing at a rate proportional to the loading. For the next 17 days, the feeds to both filters fluctuated considerably about a mean of near 2 kg COD/(m^3day) while about 45% reduction in COD was effected. During the following 14 days, the loads to both filters were increased significantly up to three-fold for the one filter and two-fold for the other. There were several stoppages during this period, however, caused by fractures in the feed lines, but the gas rates followed the feed rates closely. The COD reductions achieved averaged 55% (70% OA).

The 25 days from day 275 to day 300 saw large increases in feed concentration and loading rates to both filters, but many fluctuations occurred in the loading rates. The feed concentrations doubled to approximately 6 000 to 7 000 mg OA/l (16 500 to 20 000 mg COD/l) and the reductions effected were about 70% and 55% respectively for OA and COD while loadings were about 10 kg COD/(m^3day).

For the next 42 days operations were very erratic. Initial high load rates caused the acids concentrations in both filters to reach near 5 500 mg/l. A stoppage of feed allowed the filters to recover but operation continued to be erratic. A chemical metering pump was brought into service during this period, but sludge tended to block the valves, further opsetting the flow rates. After this period of very erratic operation, the flow rates steadied out a little when an aspirator feeding device was used for one of the filters, but the flow rates still fluctuated too widely for COD or OA reductions to have any meaning, however. For the next 36 days, loads to both filters fluctuated considerably, but the general trend in the loading was upward as the concentrations of both feeds were increased to some 10 000 mg OA/l (30 000 mg COD/l).

By this time both filters were badly clogged with sludge and short-circuiting of liquid was taking place. The filters were flushed with water and loading resumed at the old levels, but these proved to be too high, as the acids concentrations immediately rose to very high levels and digestion failed. At this stage the investigation was ended.

A third filter was started on day 213, and this incorporated a pump to circulate part of the contents of the digester as described in Section 3.1.2. above. This filter was seeded with fresh sewage sludge and was fed with pure yeast waste. The pH of the circulated section was monitored and lime water added as necessary to control the pH at 7,0. The feed was not buffered at all and considerable quantities of lime were required. Problems were experienced with the circulating pump as it frequently fractured the rubber tubing used, resulting in loss of sludge. The filter was not digesting properly as the gas rate was relatively low.

On day 231 the filter was effectively divided into three sections - a plug flow acid-forming section followed by a mixed methane-forming section and a quiescent settling/polishing section. Also about two-thirds of the sludge in the filter was drained and replaced with

fresh sludge. This seed sludge was very poor, however, and after 2 days gassing had all but ceased. Fresh seed sludge was obtained and buffering continued with lime water. The gas rate was low initially, but dropped rapidly after feeding and buffering started. This indicated that the lime was inhibiting the sludge and so the addition of lime was stopped. The gas rate continued to drop, but not as rapidly as before. On day 238 a fresh batch of good seed sludge was obtained and the feed was buffered with 1,25 g/l of sodium bicarbonate with provision for adding more if necessary. At the same time the "finger" feed pump was brought into service and loading commenced at a slightly reduced rate. Problems did arise with the new pump, in that one of the feed pipe joints failed and approximately half the sludge leaked out. This was recovered and replaced in the filter with no ill effects, but then a further fault caused a large shock load on the filter. After these faults were rectified, the filter operated as desired in three stages.

From day 260 for the next 13 days, the loading rate was gradually increased by increasing the feed concentrations to 3 600 mg OA/l (1 000 mg COD/l), from 2 500 mg OA/l (7 000 mg COD/l). After a shock load on day 277, the load rate was further increased over the next 21 days with increases in the feed strength. The load rate at this stage was just less than 10 kg COD/(m^3day) with a feed strength of 6 500 mg OA/l and a COD of 18 000 mg/l. The circulation rate during the whole period was kept at about 80:1 and after several days at these operating conditions some 70% of the OA and 55% of the COD were removed.

For the next 54 days, very erratic loadings occurred, with very high acids concentrations, caused by high initial load rates (more than 12 kg COD/(m^3day)). The chemical metering pump was installed during this period, but did little to stabilize flows. On day 353, an aspirator feeding device was installed and for 6 days gave constant feed rates of 4,8 kg COD/(m^3day) while effecting reductions in OA and COD of 58% and 51% respectively, with feed strengths of 5 300 mg OA/l (14 700 mg COD/l). For the following 13 days, feed continued with the aspirator device and

increasing feed strengths. Loadings were erratic, however, but a feed of 9 000 mg OA/l (23 300 mg COD/l) was being delivered when a reduction gearbox became available for the metering pump. With a feed of 10 600 mg OA/l (37 300 mg COD/l) this gave steady loads around 19 kg COD/(m^3day) with 64% reduction in OA and 39% in COD. Acids concentrations during this time were near 5 000 mg/l, however, so this cannot be regarded as stable operation of the filter.

At this stage it was obvious that the filter was badly clogged with sludge, even in the circulated section where the circulation ratio was 100:1, and so the filter was flushed. On restarting, loading was reduced to 7,5 kg COD/(m^3day) but the acids concentrations had still risen to 3 500 mg/l in the circulated section when the investigation ended on day 393.

3.2.3. Some of the Main Difficulties encountered during Operation

The main difficulty encountered during the investigation was that the feed flow rates fluctuated randomly from day to day. The average daily fluctuation was between 10 and 15% of the mean flow rate, but variations much larger than this were also encountered, as well as shock loads when large quantities of feed were delivered within a few minutes by pumping faults. This made it extremely difficult to operate under constant conditions for long enough to reach a steady state in the filter in which exit conditions could have been related to inlet conditions with a high degree of certainty. The difficulties associated with each of the pumps used, as well as their advantages are discussed in detail in Chapter 4, Section 4.5.3.

A further difficulty occurred with gas analyses. An Orsat apparatus gave the only immediately available method of analysing the digester gas. The results obtained with this apparatus were reproducible to within 0,5%, but the overall analysis could have been in error. The analysis was carried out by observing the volume of gas

absorbed by concentrated potassium hydroxide solution. This was taken to be carbon dioxide, while the remaining gas was assumed to be methane. The analytical procedure used is described in detail in Appendix A, Section A.2.3. Hydrogen sulphide, identified in the gas by its smell, was reported as carbon dioxide since it is absorbed by potassium hydroxide. Any nitrogen present from air leaks or any other sources was reported as methane. These two gases, together comprising not more than about 10% of the gas, should not have greatly affected the ratio of methane to carbon dioxide, but could have caused errors in the measurement of the actual concentrations of methane and carbon dioxide. These errors could account for some of the discrepancy between the observed and theoretical gas productions in the results given in Chapter 4, Section 4.3. Gas analysis by means of a gas chromatograph would have been preferable, since it would then have been possible to determine accurately carbon dioxide, methane, hydrogen sulphide and nitrogen. In this way the fraction of the COD stabilized appearing as methane could have been determined and this would have allowed an estimation of the sludge growth rate, since the remaining COD is used for the growth of new micro-organisms.

Despite these main difficulties outlined above, valuable experience was gained in the operation of the anaerobic filter, and various recommendations have been proposed based on this experience. These experiences and recommendations have been discussed in detail in Chapter 4, and the recommendations proposed have been summarised in Chapter 5.

CHAPTER 4

D I S C U S S I O N

4.1. INTRODUCTION

The discussion presented in this chapter covers the results of the investigation, the aims of which were to determine the applicability of the filter to the treatment of yeast wastes and the establishment of an operating procedure for a laboratory scale anaerobic filter. The applicability of the filter to yeast wastes is discussed in detail in Section 4.2. below, while an attempt at characterising the filter statistically from operating results is discussed in Section 4.3. The operating procedure developed is discussed in detail in Section 4.4. and it is hoped that this procedure will expedite the progress of future investigations in this field. Conclusions drawn from the discussion and recommendations proposed for future work have been incorporated in this discussion, but are also summarised in Chapter 5.

4.2. APPLICABILITY OF THE FILTER

In Chapter 1 it was established that anaerobic digestion was more suitable for treating yeast waste than aerobic treatment. Briefly, the advantages stated for treating strong wastes by anaerobic digestion were: low sludge growth for subsequent disposal; low nutritional requirements because of the low sludge growth; no costly air blowers are needed and the methane formed is a useful end product. These factors all combine to make anaerobic digestion more economical than aerobic treatment for wastes with a COD greater than 4 000 mg/l (7). The main disadvantage of anaerobic digestion is a lower quality effluent than that from the activated sludge process. A further disadvantage for the anaerobic

treatment of yeast waste in particular was the soluble nature of the waste and the requirement of a solid vehicle to support the sludge - even if this is provided merely by suspended solids in the waste. As concluded in Chapter 2 the anaerobic filter with the sludge supported by the packing would appear to offer an excellent digestion system for yeast wastes.

The results of this experimental investigation show that it is possible to treat yeast wastes with the anaerobic filter. The detailed results given in Appendix C indicate that the maximum laoding which could be applied for extended periods was 10 kg COD/(m^3day) while the reduction in COD effected by the filter at this loading varied between 40% and 60% with a liquid retention time of 40 hours. Another worker in the Chemical Engineering Department of the University of Cape Town, H.I.H. Richter (46) is at present treating the same yeast waste as used in this investigation with an anaerobic contact type system. This is being loaded at 13 kg COD/(m^3day) with a 48 hour retention time, and is consistently giving between 62% and 67% reduction in COD. In comparing the performance of these two systems, it should be borne in mind that only approximately 70% of the applied COD appears to be biologically degradable. The yeast waste has some 30% of the COD present as what are believed to be caramels from the molasses and broken cell walls of Saccharomyces cerevisiae from the growth of the yeast. This proportion of the COD is not degraded by extended aerobic or anaerobic treatment and the brown colour of the waste persists through both treatment systems. In terms of degradable COD applied, the anaerobic filter and the contact type system give COD reductions respectively of 57 - 85% and 88 - 95%.

No reason is immediately obvious for the poor performance of the anaerobic filter. As stated above and in Chapter 2, the anaerobic filter should provide a nearly ideal digester for the treatment of soluble wastes, as a high sludge concentration can be maintained permanently in the filter with little fear of washout. This is because the micro-organisms are physically held in the voids of the packing and adhere to the surface. Also, by virtue of the plug-flow nature of the flow

system, the degree of stabilization achieved in a given time in the filter should be greater than that achieved in the completely mixed reactor for the same concentrations of sludge and feed. Further experimental work is recommended in order to try to find the reason for this poor performance of the filter.

In considering further the applicability of the anaerobic filter to the treatment of strong yeast wastes, the effect of shock loads on the filter should be discussed. These are considered in detail in Section 4.4.7. below, but general effects will be considered here. The feed rates to the filters during this investigation continually fluctuated by between 10% and 15% of the mean load. The filters were capable of accepting these variations with no adverse effects, and indeed, operating experience showed that fluctuations of up to 20% were acceptable. If the feed rate suddenly increased by more than about 20%, however, the acids concentration increased sharply at the bottom of the filters and this caused a wave of high acids and low pH to pass up the filters operated in the plug flow manner. This could cause digestion to fail throughout the whole filter if feed were to be continued, but a rapid recovery was possible if the feed was stopped immediately.

In this susceptibility to shock loads, the filter would seem to be at a disadvantage compared with the conventional stirred tank digester in view of the inherent stability of the backmix reactor to shock loads. No definite answer can be given on this question, however, as the author has had no experience of operating conventional digesters. The circulated filter would seem from theoretical considerations to be much less susceptible to shock loads than the plug flow type filters, but this was not obvious from operational experience - in fact the circulated filter seemed equally susceptible to shock loads. No real explanation can be given for this apparent anomaly, except that possibly the degree of mixing caused by the rise of gas bubles in the plug flow filters was greater than was obvious from the observed flow patterns.

The loading of 10 kg COD/(m^3day) given above was that loading which the experimental results indicated was the maximum which could be applied for extended periods without the acids concentrations rising over 2 000 mg/l as acetic acid. Loadings of up to 16 kg COD/(m^3day) were applied for short periods, but these caused the acids concentrations to rise sharply to values up to 6 000 and 8 000 mg/l at which stage complete failure of digestion seemed imminent. Consequently 10 kg COD/(m^3day) must be considered the maximum loading applicable for extended periods.

For the whole duration of the investigation the feed rate fluctuated daily by about 10 to 15%. The possibility does arise that steadier operation, or indeed a different operating procedure, may increase the loadings applicable. The operating procedures used during the investigation were: plug flow; plug flow with a small recycle of effluent, and circulation of part of the digester contents. Visual observations on the sludge and general operating experiences lead to the conclusion that loadings on the filter can only be increased if the activity of the sludge can be increased. Because of the clogging that occurred in the filters at the end of the investigation, it is obvious that sludge concentrations cannot be increased significantly, and hence the active fraction of the sludge must be increased. There are two obvious procedures by which the sludge could possibly be made more active: heating and backflushing.

(i) Heating: Fig. 2.1 shows that the rate of metabolism of anaerobic micro-organisms doubles when the temperature is raised from 35°C to 55°C Hence by heating the filters to the thermophilic operating range, the loading could be doubled. Approximate calculations reveal that under the present conditions - 10 kg COD/(m^3day) with an average of 70% reduction of the applied biodegradable COD and a feed temperature of 25°C - some 11 000 Kcals/(m^3day) of excess heat are available for use in the plant, after the heat requirements of the feed have been deducted. If it is assumed after heating to 55°C that the loading can be increased to 15 kg COD/(m^3day) and the reduction of the biodegradable COD increased to 90% (a doubling of the amount of COD metabolized), then although the

heat requirements of the feed increase considerably, the excess heat available is increased to some 15 000 Kcals/(m^3day). These calculations do not take into account heat losses or inefficient heating. The anaerobic contact process should produce similar, or greater, quantities of methane in view of the better performance of this unit. The running costs involved would probably be higher, however, since this process would require more supervision than the filter because of the settling tank necessary. These conclusions and calculations should still be verified experimentally.

(ii) Backflushing: (A detailed discussion of sludge growth and clogging is given in Section 4.4.8. below). The advantage to be gained from instituting a regular backflushing programme has not been proved since this was beyond the scope of this investigation, but it is possible that regular flushing would preferentially remove inert solids from the filter, allowing a more active sludge to develop. Whether in fact this will occur can only be verified by experiment.

With these possibilities in mind, it is recommended that further investigation be undertaken to determine the maximum loadings applicable while heating the filter and with a regular programme of backflushing in operation.

The presence of sulphate in the feed and its reduction to sulphide during digestion was confirmed by the odour of hydrogen sulphide in the digester gas as discussed below. McCarty (30) has stated that under certain conditions sulphides can be inhibitory to digestion. No obvious inhibition was noticed during this investigation, however, and Stander et al (68) reported that excess sulphide added to laboratory digesters had no deleterious effect on digester efficiency. In the light of this observation and in the absence of any evidence to the contrary noticed during the investigation, sulphide in the filters was not considered to be a problem, although its effects were not investigated, since this was beyond the scope of this project. It is recommended, however, that

The condition of low temperature for weak wastes means that the loadings applicable will not be as high as those at higher temperatures, but the temperature range of operation will depend on economic considerations.

In conclusion it can be said that unless the recommendations proposed above, coupled with those recommended modifications to the operating procedure described below, can significantly improve the performance of the anaerobic filter, it cannot be recommended for the treatment of strong yeast waste over the anaerobic contact type process shown in Fig. 2.4. This recommendation must also apply to the treatment of other strong soluble wastes, but the filter should be well suited to the treatment of weak soluble wastes, with a COD of less than about 5 000 mg/l.

4.3. STATISTICAL TREATMENT OF RESULTS

One of the aims of the investigation was to provide the information necessary to predict the performance of an anaerobic filter treating yeast waste for possible future use in the design of a large scale process. Although the fluctuations in feed rates and other variables discussed below detract to some extent from the value of the results obtained, these are presented below.

Since it is difficult to see the overall pattern of operation from the tables of results in Appendix C, a summary of those results obtained during the closest approaches to steady state observed during the operation of the filters is given in Table 4.1. It should be emphasised that these results were obtained when operating conditions had been steady for only one theoretical time in most cases. In order to draw valid conclusions and obtain results for theoretical purposes, it is imperative that the results be obtained under proper steady state conditions. This usually means that operating conditions must be steady for at least 5 retention times before the results can be considered valid. Since it was not possible to obtain steady-state

TABLE 4.1. RESULTS USED IN THE STATISTICAL ANALYSIS

FILTER No.	DAY No.	FEED CONC. F mg COD/1	FEED RATE Q 1/hr	FEED ALKALIN B mg/1	LOAD RATE $\frac{kg\ COD}{m^3 day}$	EFFLUENT CONC. E mg COD/1	% COD REDUCTION	METHANE PRODUCTION 1/hr	METHANE PRODUCTION* $\frac{1\ CH_4}{kg\ COD}$ (Stabilized)
I	196	5 970	0,085	1 620	1,67	3 580	40,0	0,111	496
I	200	6 210	0,093	1 675	1,81	3 900	37,2	0,112	495
II	200	6 120	0,098	1 675	1,88	3 540	42,2	0,121	457
I	203	6 210	0,093	1 620	1,25	4 130	33,5	0,091	651
II	203	6 120	0,095	1 620	1,58	3 770	38,4	0,112	550
I	237	5 600	0,206	1 025	3,42	3 290	41,0	0,201	427
II	237	5 600	0,200	1 025	3,36	3 000	46,3	0,214	410
II	248	5 820	0,114	945	2,00	3 330	42,8	0,149	518
I	267	7 350	0,140	1 300	2,91	3 480	52,7	0,252	489
II	267	6 560	0,180	1 300	4,23	3 270	50,2	0,330	463
I	273	8 710	0,175	1 520	4,57	3 860	55,7	0,349	409
I	280	9 130	0,211	1 710	5 72	3 650	60,1	0,400	347
II	280	10 200	0,242	1 790	6,90	4 260	58,3	0,439	326
I	294	12 400	0,200	1 690	9,58	6 320	48,9	0,538	343
II	313	23 200	0,179	2 960	12,50	12 200	49,8	0,509	245
I	350	12 200	0,154	2 560	6,64	5 830	52,4	0,326	279
II	350	11 900	0,170	2 600	7,28	6 730	43,5	0,291	247

* Theoretical methane production = 390 1 CH_4/kg COD stabilized at 30°C, 1 atm. (28), (36).

results, it was decided to carry out a statistical analysis of the results available. This analysis was to determine which parameters were significant in determining the strength of the effluent, and the appropriate results are given in Table 4.1.

The dependent variable in the analysis was taken to be the effluent concentration, E mg COD/l, while the independent variables considered were: the feed strength F mg COD/l; the liquid flow rate, Q l/hr; and the alkalinity of the feed, B mg/l as $CaCO_3$. The cross products, squares and reciprocals of these independent variables were also included in the analysis. A preliminary analysis showed that B was, in fact, dependant on F, and so its effect on E is incorporated in that of F on E. A further analysis showed that over the range of flow rates considered, Q was insignificant in determining E, although the range of flow rates covered was very low. This left F as the only independent variable. The programme used for the analysis was the standard I.B.M. Multiple Linear Regression Program (20) modified to read in data from cards. A listing of the programme as used is given in Appendix E, together with a sample print-out of results. The analysis showed the following equation to be the most significant in describing E in terms of F:

$$E = 2\,880 + 1{,}79 \times 10^{-5} F^2 \qquad .....(4.1.)$$

where E and F are measured in mg COD/l. The standard error of the regression coefficient was $0{,}11 \times 10^{-5}$, while the correlation between F^2 and E was 0,973, with a standard error of the estimate for the 17 sets of data used of 535 mg COD/l. The F-value for the regression of 265,7 shows that equation (4.1.) is highly significant since the F-value for 1% random chance with the appropriate numbers of degrees of freedom is 6,2 (13). This means that the effluent strength is determined only by the square of the feed strength within the range of operating conditions covered. It does seem anomalous that the liquid flow rate was found to be insignificant, as the product of the flow rate and the feed strength

is the loading rate, which was found from operating experience to be the variable most important in governing the operation of the filters. This anomaly is explained by the very narrow range of flow rates represented in the analysis (from 0,085 1/hr to 0,242 1/hr). Since the statistical analysis was considered only after all the results had been recorded, no attempt could be made to cover a wider range of flow rates which would have shown up the relationship between E and Q. A further investigation covering a much wider range of flow rates would be desirable from the point of view of gaining a more accurate description of the filter for prediction purposes.

Coupled with this, further work of a more fundamental nature would be extremely useful. This work should be aimed at evaluating the kinetic growth constants for anaerobic microbial films, using both pure substrates and yeast waste under accurately known conditions so that sludge growth and gas productions can be measured. Measurements of the dispersion and the degree of axial mixing occurring during flow through the filter would allow the application of the fundamental reactor design equations developed by Levenspiel (24),p.279 and Coulson and Richardson (9), p.71, or the model of the filter developed by Haug and McCarty (19). In this respect, the gas flow rates play an important role in determining how much axial mixing occurs, and measurements should be taken for a wide range of the ratio of gas flow rate: liquid flow rate. The measurements should be aimed at verifying the application of these equations and models and so the performance of the filter should be carefully monitored.

The last column in Table 5.1 gives the volume of methane produced per kilogram of COD stabilized by the filter. The theoretical value of this quantity is 390 1 CH_4/kgCOD stabilized, as measured at 30°C and 1 atmosphere (28), (36). The first eleven values in Table 5.1. are all greater than this theoretical value, however. Since McCarty (28) and Malina (36) have both arrived at the same value, and

and since this value has been calculated stoichiometrically, it is clear that the experimental results given in Table 5.1. are in error. There a are several possible sources of error which could account for the excessive methane productions observed:

(i) errors in measuring the COD of the effluent caused by suspended solids not removed by the small laboratory centrifuge available;

(ii) prevalence of non-steady state conditions at the times of sampling;

(iii) errors in gas analysis caused by the use of an Orsat apparatus rather than a gas chromatograph. These errors are caused by the presence of nitrogen and hydrogen sulphide in the gas which would be reported as methane and carbon dioxide respectively, as discussed below and in Appendix A, Section A.2.3.

Probably no single one of these sources is solely responsible for all the error, but a combination of errors from all these sources would be sufficient to explain the discrepancy between the measured and theoretical methane productions. This does cast some doubt on the veracity of the other experimental results given in Table 4.1. and hence on the relationship determined between E and F. Despite this doubt, however, it is felt that the variables given in equation (4.1.) are the only significant variables within the operating range covered by the investigation, although the actual values of the regression coefficients may have a relatively large error associated with them.

4.4. OPERATION OF THE FILTERS

The original plan for the investigation was to operate the filters at a given feed concentration and retention time until steady state was reached, determine the operating parameters for this loading and then increase the loading. This was to continue until the maximum loading acceptable by the filters was reached. As described in detail in Appendix B, however, the actual operation of the filters consisted of attempts to obtain steady state conditions at various increasing

loadings. These attempts were thwarted by the large variations in flow rates of the feeding mechanisms used. This made it extremely difficult to maintain steady state conditions for longer than one or two days and led to the necessity for the statistical analysis of the available results as described above. The following discussion covers some of the more practical aspects of operating an anaerobic filter and is presented in the hope that it might be of use in guiding any further experimental work on similar equipment.

4.4.1. Source of Sludge and Acclimation

The original sludge dosed into the filters on day 1 came from laboratory digesters treating wine distillery waste. The high acids concentrations observed initially when the yeast waste content of the feed was increased were at first thought to be due to the need for acclimation of the sludge to yeast waste. Later it was recognised that these high concentrations were in fact due to loadings higher than those which the small quantity of sludge present could handle, and that no acclimation was necessary. The acid formers present rapidly converted the yeast waste to acids, but the few methane forming bacteria present were insufficient to convert these acids to methane and carbon dioxide. Further experience with sewage sludge confirmed that acclimation was unnecessary and that the acid formers in the sludge readily accepted pure yeast waste.

4.4.2. Indications of Failure of Digestion

When operating a digester of any kind, it is obviously highly desirable to have operating parameters which can indicate impending failure of digestion, and allow timely remedial action to be taken. The anaerobic filter is no exception, but the operating parameters can be a little more difficult to define. The volatile acids concentration is one of the most widely used operating parameters to monitor digestion - any sudden rise in the acids concentration is a sure sign that the digestion is failing, and that remedial action is necessary. Usually

accompanying this rise in acids concentration is an increase in the carbon dioxide content of the digester gas. This, too, is a widely-used method of monitoring digestion and can give early warning of impending failure.

The application of these tests in this investigation, however, was hampered by the variations in the feed flow rates, as well as by the plug flow type of operation of the filters. These flow variations caused corresponding fluctuations in the acids concentration and consequently in the carbon dioxide content of the gas. Hence it was extremely difficult to interpret correctly an early warning of impending failure of digestion, and it was necessary for large changes in the operating parameters to occur before these could be recognised as indications of failure, rather than as being due to variations in load rates, and remedial action taken. By the time this action was taken, it had to be drastic, and this usually meant stopping the feed altogether to allow the filters to recover, as discussed below.

4.4.3. Routine Operation of the Filters

In order to keep as close a check as possible on the operation of the filters, both for theoretical purposes and to detect impending failure as early as the fluctuating loadings would allow, the following tests were carried out on samples from the filters:

(i) Loading Rates: These were measured daily in order to eliminate as much error as possible in reading the levels in the feed tanks from which the flow rates were calculated. The frequency of these readings must be a compromise between the desire to know the flow rate from hour to hour and the degree of accuracy by which the flow rates can be measured. In addition to the volumetric flow rate, the concentration of the feed should be known as accurately as possible.

(ii) Gas Productions: These were measured twice daily in order to record fluctuations in digestion, e.g. response to an increased load

that might otherwise have been missed. Once again the frequency of this measurement is a compromise between the desire for a continuous recording and the degree of accuracy with which the measurement can be made.

(iii) Gas Analyses: This test was usually carried out daily or whenever the gas collection bottles (see Fig. 3.4.) were full, as these sometimes filled up in less than 24 hours. As mentioned above, this test is a good indicator of the condition of digestion and so frequency of analysis and accuracy are most desirable. In this respect, analysis by gas chromatography would be more useful than analysis by Orsat apparatus as used in this investigation. The Orsat apparatus requires a large sample of gas which must be accumulated over several hours at least, and so the advantage of knowing the condition of digestion at a particular time is lost. Further the gas chromatograph can give a quick reliable reading of all the components of the gas mixture, which would require long and tedious analysis by the Orsat apparatus. A suitable gas chromatograph was not available during the investigation, however, and so the Orsat apparatus was used.

(iv) pH: This was measured every time a sample was taken from the filters - usually about three times per week. The pH was measured at about 3 or 4 points up the filters in order to check that the initial low pH was recovering to within the range 6,8 to 7,4 needed for optimum digestion.

(v) Volatile Acids and Alkalinities: These tests were usually performed twice a week or whenever changing gas compositions indicated that digestion might be failing. The direct titration method of DiLallo and Albertson (11), described in Appendix A, Section A.2.1., was used, as this gave both alkalinity and volatile acids concentrations rapidly and easily. A series of tests on samples from several points up the filters gives a good indication of the progress of digestion.

samples are withdrawn from a filter with 8 l of void volume, this can be the equivalent of ½ to 1 hour's flow. The actual order of sampling should be from the top downwards, so as not to affect the liquid around the subsequent sampling ports. Samples from near the bottom of the filters will contain much suspended sludge, and, if this is wasted, up to 1 gram of sludge can be lost per set of samples. The effect of this on sludge densities is discussed in Section 4.4.8. below.

4.4.4. Buffering of Feed

From the beginning of the investigation it was realised that it would be necessary to add base to the digestion system to maintain the required pH. The raw undiluted yeast waste has an alkalinity of some 4 300 mg/l as $CaCO_3$ and this would be sufficient as such, but for a feed diluted to less than half its original strength, it would be necessary to add base (29). The first attempts at buffering occurred when an untreated feed of low pH had been used and the pH at various points up the filters had fallen to very low values. Lime water was added to these points in an attempt to correct the pH, but large quantities were required and a small overdose resulted in a rapid rise in pH to values near 10 and 11. This is discussed in Appendix B, Section B.2.1. Later it was decided to buffer the feed to values near pH 7,0. Since the carbonate-bicarbonate system is the natural buffering system in anaerobic digestion, and sodium bicarbonate is recommended by McCarty (29), this was chosen as the buffering agent. This was used throughout the investigation at dosages of up to 2,0 g/l to give alkalinities in the feed of greater than 2 000 mg/l or pH values near 7,0, except for the instance detailed below.

When Filter III was started up with provision to monitor the pH of the circulated section it was decided to use lime water again in view of the cost of bicarbonate for a large-scale process. (This use of lime is described in detail in Appendix B, Sections B.3.2. through to B.3.5.) Provision was made in the mixing box where the pH was monitored for the carefully controlled addition of lime water. Initially the system worked

well, and it was possible to control the pH closely, but the pH tended to drop rapidly, requiring frequent additions of large quantities - up to 1,5 l - of lime water to maintain the pH near 7,0. When the gas rate from the second batch of seed sludge started declining rapidly, the addition of lime water was stopped, to see whether this would improve digestion. The rate of decline decreased after the lime additions were stopped, indicating that the lime was having a detrimental effect on digestion, and so when the new batch of seed sludge was dosed into the filter, sodium bicarbonate solution was used in the same way to control the pH. Because the pH tended to drop to very low values overnight when no additions of buffer could be made, buffering of the hitherto untreated feed was resorted to. This method of adding the required base worked well for the rest of the investigation.

In view of the conclusion reached in Chapter 2, Section 2.1.3. that lime was one of the most suitable chemicals for pH control, it is surprising that the use of lime in this investigation was unsatisfactory - indeed from the results it appeared to be inhibitory. No definite explanation can be given for this strange behaviour, but it is thought that although Ca^{++} has been shown to be less toxic than Na^{+} (30), (34), it is possible that other cations present in the waste exert an antagonistic effect on Na^{+} toxicity or a synergistic effect on Ca^{++} toxicity, resulting in an inhibition by lime but not by sodium bicarbonate.

Summarising, it was necessary to add base to the digestion system. Lime water was found to be inhibitory and inconvenient. Sodium bicarbonate added to the feed to give an alkalinity greater than about 2 000 mg/l as $CaCO_3$ proved to be the most successful method of adding the required base.

4.4.5. Recycle of Effluent and Circulation of Digester Contents

The main advantage to be gained from operating a plug flow system is the greater degree of conversion attainable in a plug flow system than in a completely mixed reactor of the same size. This is

a well-known principle of reactor design and arises from the fact that the concentration of reactants in a completely mixed system is equal to the effluent concentration, whereas in a plug flow reactor the concentration is everywhere greater than the effluent concentration, resulting in higher reaction rates for any reaction of order greater than zero, (9), p.61. Since biochemical reactions usually have an order between zero and one (9), p. 356, this principle applies to biological waste treatment systems as well. The main disadvantage of a plug flow system is instability, particularly in the case of anaerobic digestion, where the products of the first, rapid, stage are inhibitory to the second, rate-limiting, step. Hence in the practical application of digestion, it is necessary to stabilize the plug flow system in some way. This can be done most easily by the addition of large quantities of buffer to the feed in order to keep the pH high and so reduce inhibition, but this can be very costly. Another method is to compromise between the high conversion of the plug flow system and the stability of the completely mixed system by recycling effluent to the feed. The amount of recycle used must depend on the stability required.

At the beginning of the investigation, low pH values were observed at the bottoms of both Filters I and II. In an attempt to try to stabilise the filter, the second method referred to above was used, and effluent from the filters, with a pH between 7,0 and 7,3 was recycled with the feed in a ration of about 4:1. The results of this recycle were not encouraging, however, as, apart from a slight increase in the gas rate due to the extra load imposed, little was gained. It was possible to stop buffering the feed, however, and this could represent a considerable saving in operating costs for a large filter, although no definite results were obtained as to the amount of recycle needed. At one time during the investigation, the gas rate from both filters dropped for no obvious reason. It was thought that an inhibitor might be building up in the system because of the recycle, but an increase in the recycle ratio caused an increased gas production disproving the hypothesis.

The operation of Filter III with continuous circulation of part of the contents of the filter revealed no significant gain over the plug flow type of operation of the other two filters, in terms of COD removal or maximum load applicable. The circulation ratio employed with Filter III - some 100:1 - was sufficiently large that the circulated section was completely mixed, but the liquid flow rate through the voids of the packing - some 4 cm/min - was insufficient to prevent clogging and channelling. Also it was still necessary to add sodium bicarbonate to the feed to give an alkalinity greater than about 2 000 mg/l. Further work needs to be done on the minimum alkalinity needed by the filter for satisfactory operation, since this was beyond the scope of this investigation.

During the periods of regular operation, the three effective stages in this filter were readily apparent. The lowest, acid-forming section, consistently had acids concentrations up to 2 to 3 times those in the circulated, methane-forming, section, Fig. 4.1., while there was usually a distinct, albeit small, drop in COD from the middle section to the final effluent through the quiescent polishing section. This indicates that the two stages of digestion can be successfully separated. That the acid formation stage of digestion is rapid was shown by the high acids concentrations reached by the time the liquid had risen as far as sample point 3, 30 cms up the packing after an average of about 6 hours. The circulated section was responsible for most of the methane formation, since the pH in the acids section was frequently at values below those at which methane inhibition had been noted in the other filters - this usually occurred at pH values below 6,6 to 6,8. The uppermost, settling section ensured that the sludge stirred up by the circulation flow was not carried over into the effluent. Near the end of the investigation, when the filters were badly clogged, the same level of effluent suspended solids was observed from this filter as from the other two. The pH, acids concentration and COD of the filter effluent were in general very similar to those of the circulated section, implying that the settling section did little but capture suspended solids.

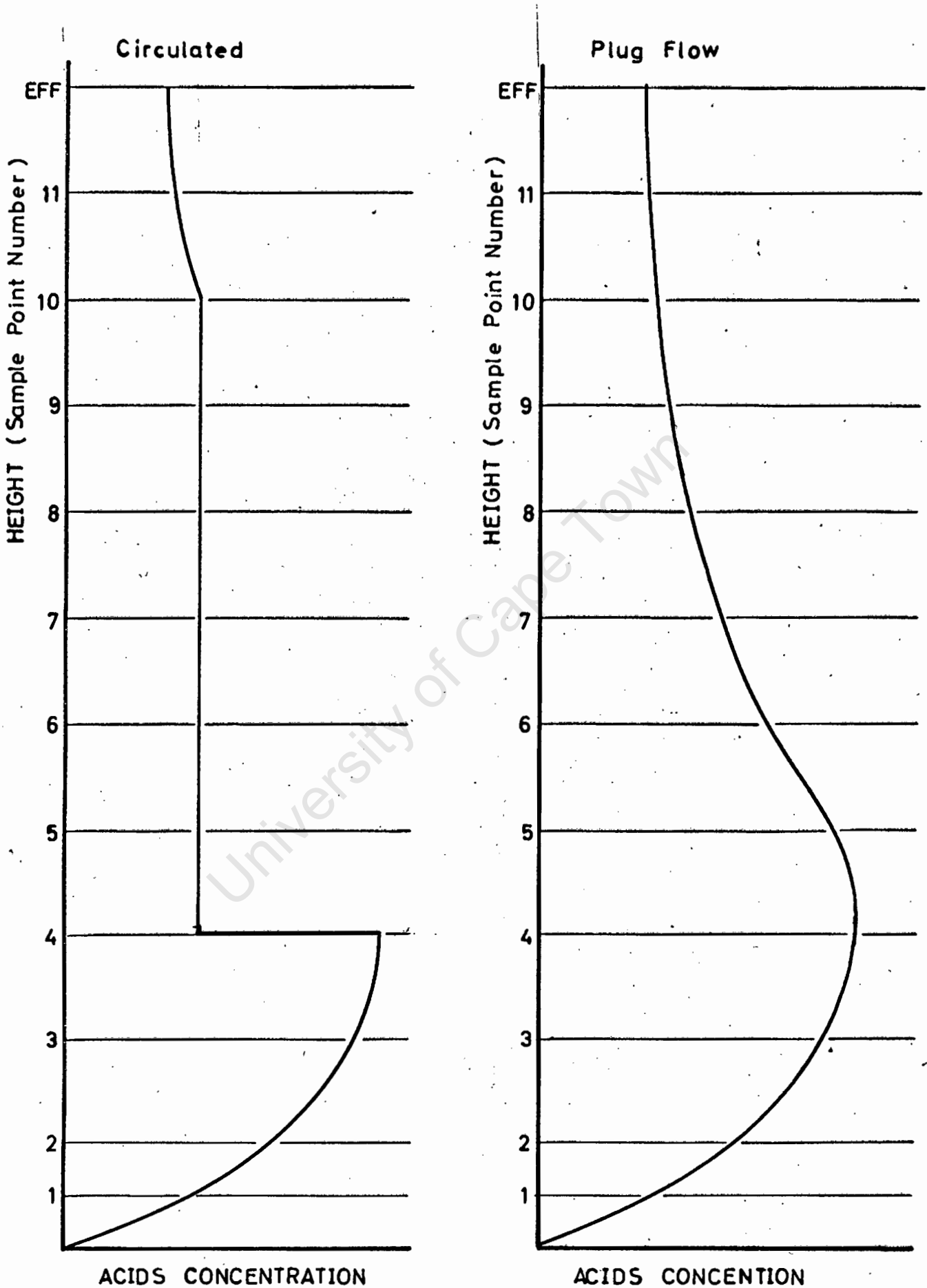

Fig 4.1 DIAGRAMMETRIC REPRESENTATION OF ACIDS CONCENTRATIONS IN CIRCULATED AND PLUG FLOW FILTERS

It is obvious that a circulated filter as described above is a logical extension of a plug flow filter with recycle of effluent, in which the recycle has been increased to a large valve. The optimum recycle ratio needs to be determined experimentally, and will be a compromise between the advantages of plug flow - high concentrations and therefore high efficiencies in the use of the volume of the digester - and the advantages of completely mixed operation - provision of the required alkalinity and stability to shock loads. The main disadvantage of completely mixed operation, viz., an effluent concentration equal to that in the whole of the digester, could be overcome by polishing the effluent with, e.g. a trickling filter. It is recommended that further work be carried out to determine the optimum recycle ratio, with the main factors to be borne in mind being the cost of the chemicals needed for buffering the feed, the cost of circulating the filter by pumping and also the cost of the final polishing of the effluent.

4.4.6. Rate of Increase in Loading

The rate at which the loading on a filter can be increased without constituting a shock load depends on the sludge concentration in the filter, with the higher concentrations able to accept faster load increases. After operating for some 50 days at loads averaging about 1,2 kg COD/(m^3day), the loading to Filter I was trebled within 3 days. This was accompanied by a rise in acids concentrations from about 600 mg/l to about 900 mg/l, and a slight drop in the methane content of the gas. At the low original loading rates, this relatively high rate of increase was possible, but at higher loadings, a lower rate was necessary. At an original load rate of 5,7 kg COD/(m^3day), the loading was almost doubled over a period of 20 days to reach 9,5 kg COD/(m^3day). It is doubtful whether the loading rate could have been increased faster over this range without causing excessive acids concentrations.

4.4.7. Shock Loads

Because of the plug flow operation of two of the filters and the inherent instability of anaerobic digestion, the anaerobic filter is

very susceptible to shock loads. The daily fluctuations of 10 to 15% in the flow rates were handled easily by the filters, but fluctuations of 20% or more appeared to constitute a shock load and required remedial action as discussed below. The rapid metabolism of the feed into acids (see below) caused excessive acids concentrations which depressed the pH, thereby inhibiting digestion. As this high acids concentration passed up the filter, so the inhibition was carried up until the digestion failed completely. The circulated filter, contrary to theoretical expectations, appeared equally susceptible to shock loads.

Several times during the investigation the filters were subjected to shock loads when pumping faults caused large quantities of feed to flow through the filters within a short time. The maximum shock load which can occur is when all the liquid in the filter is replaced by raw feed within a few minutes. This happened on several occasions, a typical example of which is the shock load received by Filter II on day 208. On this day, some 12 l of feed flowed rapidly through the filter, replacing all the liquid with fresh feed. With no further feed, pH and acid analysis were performed at intervals after the discovery of the accident. These results are given in Fig. B.2. and show that the acids concentrations at the bottom of the filter rapidly increased and then dropped again, reaching its normal operating level within some 12 hours. The acids concentration at the top of the filter, however, while following the same pattern, took twice as long to return to normal levels. This time lag can be ascribed to the higher sludge concentrations existing at the bottom of the filter, resulting in more rapid metabolism of feed and acids.

This rapid recovery from a serious shock load is encouraging, since it means that merely by stopping the feed until the acids concentration has dropped - a maximum of 24 hours is required - the effects of a shock load can be neutralized. This is important in possible industrial applications where the dumping of a contaminated fermentation broth is sometimes necessary. The filter's recovery capability from high

acids concentrations was further demonstrated over days 315 to 318 when the acids concentrations in all three filters dropped within 48 hours of the feed being stopped from values between 5 300 and 8 900 mg/l to values about 900 mg/l.

4.4.8. Sludge Growth and Clogging

At the beginning of the investigation after the filters had been dosed with some 3 l of sludge each, this was dispersed lightly through the whole packing, with a small region of dense sludge at the bottom of the filters not more than 5 cms high. During the start-up phase and until day 180, whenever a sample was withdrawn for analysis, the accompanying sludge was wasted. This procedure could have caused the loss of up to 1 gm of sludge per set of samples taken, as discussed above. The seriousness of this loss was not appreciated until it was noticed that the sludge in Filter II - which had been heavily seeded with sewage sludge on day 162 - was steadily becoming less dense, revealing packing which had initially been well covered. After day 180, any samples withdrawn were centrifuged, the sludge resuspended in deoxygenated water and replaced in the filters. This had an immediate effect on the sludge densities and these gradually increased until by day 310 the first indications of clogging were noticed, although these were not identified as such until later. Firstly, large particles of agglomerated sludge started appearing regularly in the effluents from all three filters. Up to this time visual observation had shown the effluents to have negligible suspended solids. The practice of returning sludge withdrawn during sampling was suspended when the solids in the effluent were noticed, but this had little effect on the effluent suspended solids, and on day 388 these were measured at between 500 and 575 mg/l for all the filters. Secondly, it was noticed that the COD profiles up the filters no longer decreased steadily, but each had a minimum - see Fig. 4.2. This indicated that clogging was occurring in the filters as discussed above. Finally it became obvious that the filters were badly clogged with sludge and on day 389 they were flushed as described in Appendix B, Section B.2.30.

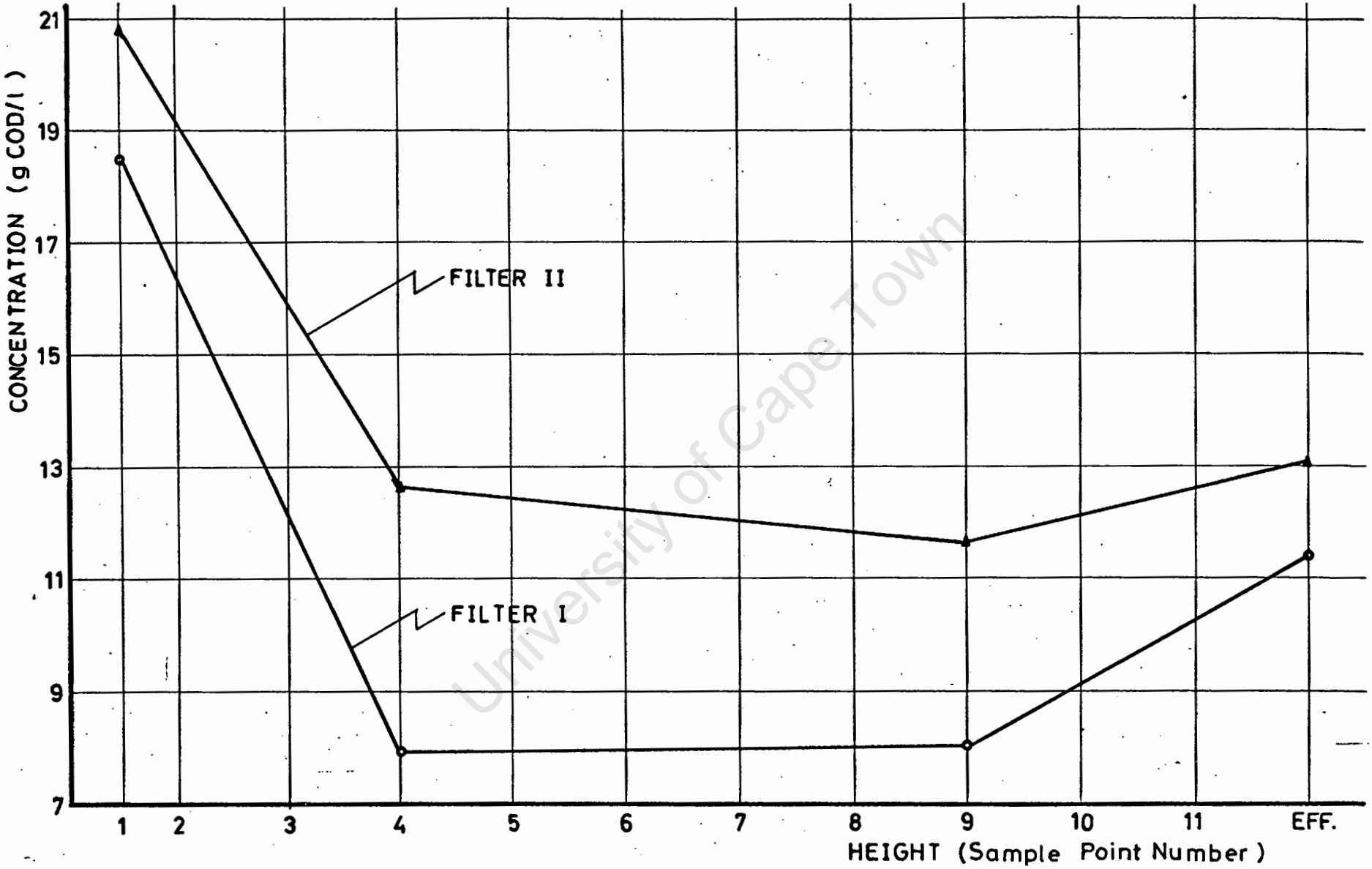

Fig 4.2 COD PROFILES ON DAY 372

Haug and McCarty (19) also experienced problems with clogging. In their investigation into the nitrification of agricultural wastewater with a submerged filter, liquid retention times used were as low as ½ hour, but clogging still occurred. This was demonstrated by the presence of excess solids in the effluent, peaks in ammonia profiles up the filters, and by tracer studies. Anticipating this problem because of their earlier work in this field, Haug and McCarty had run residence time distribution tests on the clean unseeded filters, using the alkalinity of tap water as the tracer. During the investigation, they were able to measure the residence time distribution by the same procedure, and comparison with the results of the run using the clean filter indicated whether short-circuiting of liquid - and hence clogging - was occurring and whether backflushing was necessary. Haug and McCarty used regular weekly backflushing with a gentle stream of tap water flowing down the filter to wash out excess suspended solids. It is clear that a similar programme will be necessary with the anaerobic filter, in order to prevent a recurrence of the badly clogged state which existed on day 388 in this investigation. A regular gentle backflushing should also prevent the washout of large quantities of methane-forming organisms as occurred with the violent flushing necessary on day 389. That this washout occurred is obvious from the high acids concentrations which existed in all three filters on starting at the same loading rates as before flushing.

4.4.9. Dormant Periods

For 62 days Filters I and II were allowed to stand dormant. The temperature of the filters was lowered to ambient and no load was applied. On restarting, low loadings were applied for the first two to three days, but no difficulties were encountered and loading after this was able to continue normally. This implies that the anaerobic filter can be used to treat seasonal wastes, where it would be required to stand dormant between seasons, and could be started up at the beginning of each season with only a short "awakening" phase.

4.4.10. Operation on Pure Wine Waste.

The operation of Filter II on pure wine distillery waste shows that this, too, is a suitable substrate for anaerobic growth. Some 70% reduction in OA was achieved with 80 to 90% methane content of the gas. This implies a high heating value, and the gas could be a useful fuel. The relative weakness of the waste - between 2 000 and 3 000 mg OA/l - means that a relatively short retention time may be used while feeding undiluted waste. The fact that during operation of this filter loadings of about 300 mg OA/hr for the 8 litres of void volume in the filter, with a retention time of 80 hours, appeared to be the maximum, can be explained by the low sludge concentrations in the filter at that time.

4.5. APPARATUS

4.5.1. Introduction

In addition to the discussion of the results obtained and the operating procedures for the filters it is felt that a discussion of the apparatus used in the investigation would be of use to other workers wishing to build similar apparatus. Chapter 3 gives a detailed description, including photographs, of the equipment used, and so the following will be limited to a discussion of the apparatus.

4.5.2. Filters

The filters as constructed proved to be satisfactory research tools. The 70 cm^2 cross section, while still ensuring that the model adequately represented a full scale filter, allowed chemical and feed usage to be kept to a minimum. The results given in Fig. 4.3. show that the full 2 m height of the filters was unnecessary and that essentially all the reduction took place within the first 1,2 m. The ancillary equipment - gas/liquid separator, liquid seal, etc. - all worked well and the same layout can be recommended for future work.

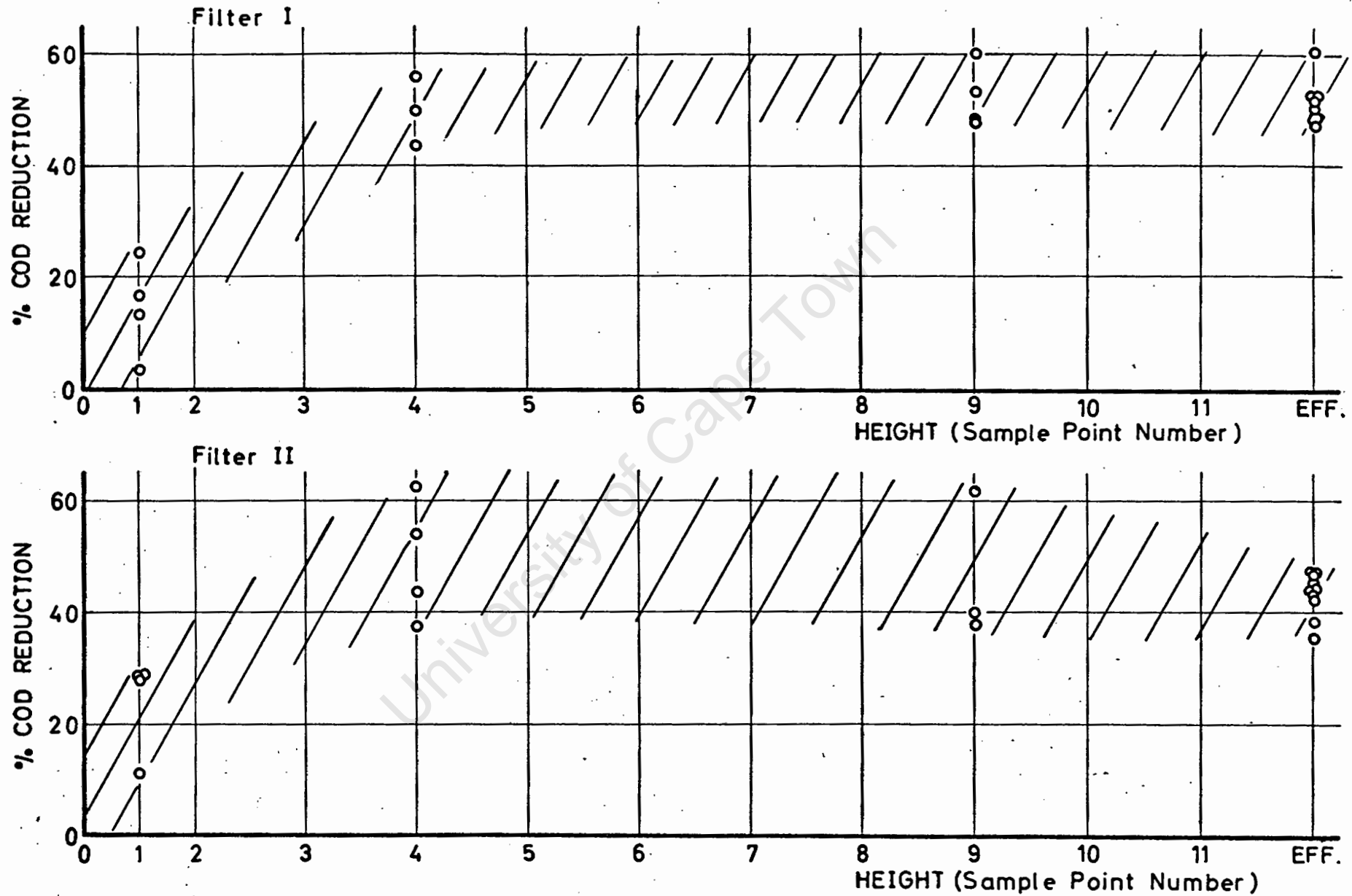

Fig 4·3 COD REDUCTION vs HEIGHT IN PLUG FLOW FILTERS

Some discussion is needed on the gas collection apparatus, however. During this investigation, the gas produced daily was collected in large graduated glass jars over acidified water, Fig. 3.4. Because gas analyses were carried out using an Orsat apparatus as described above, and in Appendix A, Section A.2.3., this method of measuring gas production was satisfactory, since large volumes of gas - up to 200 ml - were required for each analysis. If a gas chromatograph were available for analysis, however, it would probably be advantageous to use a wet type gas meter to measure productions, as this can be read as frequently as desired. Also by using only up to 1 ml per sample, accumulation of gas for analysis will not be necessary and analyses can show the state of digestion at the time of sampling, rather than accumulated samples being used.

The Raschig ring packing used - see Fig. 3.2 - was not satisfactory, however. The insides of the rings tended to block up rapidly with sludge which then became effectively inactive. The packing was also susceptible to clogging because of the relatively small void spaces between the rings. Raschig rings were originally designed for gas/liquid contact, and unless very large rings - greater than about 3 to 4 cms diameter - are used, this type of packing will almost certainly have large inactive volumes of sludge inside the rings. The rings were used in this investigation since they were readily available and little was known about the characteristics of sludge when the investigation was started. Tamblyn and Sword (72) in field studies on the denitrification of agricultural wastewater using an anaerobic filter, found that sand clogged rapidly, while the optimum packing appeared to be rounded stones of 2,5 cm diameter. This packing was also used by Young and McCarty (75) and on the basis of these results and operating experience gained from this investigation, this packing must be recommended for any future work on anaerobic filters. Use of this medium in a laboratory filter would require a filter diameter of at least 15 cms to minimise wall effects, however, but the advantage to be gained from using this type of packing - minimum clogging - outweigh the disadvantage of greater feed and chemical use.

4.5.3. Pumps

The task of feeding the filters at a constant, controllable rate was first regarded as being the simple engineering problem of feeding a liquid into a reactor at a known rate. Several different types of pumps were known to be capable of performing such a task on a laboratory scale under favourable conditions, and so the simplest and cheapest was chosen first. This was the "kinking tube" pump.

The main advantages of this pump are its flexibility and cheapness. One small low speed motor can drive as many feed chambers as desired, and each is individually variable over an extremely wide range. Under ideal conditions, the pump can give constant flow rates, but its unsuitability for this application resulted from the fact that air is drawn through the capillary tube and chamber with every stroke. Under non-sterile conditions, excessive sludge growths occur and these block the capillary or change the volume of the chamber, thereby altering the flow rate and necessitating frequent dismantling for cleaning. Operating continuously at 1 stroke per minute, the pump gave daily flow rates fluctuating by 10 to 15% about a mean. It would be possible to set the pump to deliver larger volumes of feed less frequently, but although this would largely eliminate the errors caused by changing chamber volumes, the flow of feed would become discontinuous. This would mean that the feed would be a series of small shock loads rather than a continuous flow and as such would be undesirable in a plug flow system. When it became obvious that the kinking tube pump was incapable of delivering constant feed rates under the conditions of the investigation, the peristaltic "finger" pump was used.

This operates on a completely closed system, thereby eliminating much of the sludge growth, but flow rates still fluctuated by between 5% and 15%. Anaerobic sludge growth still occurred in the closed lines, and the gas produced by these growths tended to affect the flow rates. Further, although the pump could accept up to 5 individual feeds, these were not separately variable. An added

disadvantage of the particular pump used was its tendency to break the rubber tube being squeezed. When this peristaltic pump proved to be unsatisfactory, an expensive positive displacement metering pump was used.

In principle, the chemical metering pump is capable of extremely accurate metering of liquids, but despite the fact that the system was closed, sludge growth caused blockages in the valves, resulting either in no flow or excessive flows and use of this pump had to be discontinued.

At this stage it was realised that it would be necessary to have the flow control of the feeding device completely isolated from the liquid being fed, as without sterilising the feed, sludge growth would always remain a problem. This condition was met by the aspirator feeding device, described in Chapter 3, Section 3.1.3., but 10 to 15% variations in daily flow rates were still encountered. In searching for a reason for these variations it was observed that temperature changes of $\pm$ 2°C on either side of 4°C at which the feed was stored caused the pressure in the feed tanks to fluctuate. These fluctuations were sufficient to cause either a complete stoppage of feed for up to 10 minutes as the tanks cooled, or to cause increased flow rates as the temperature rose. The daily fluctuations arose because the volume of air on which these pressure changes occurred was continually increasing as feed flowed out of the aspirator, and so the fluctuations grew in size. For this reason it will be necessary to see that temperature changes in the aspirator are kept to a minimum in any future application of this device.

The conclusion to be drawn from operating experience with the four types of feeding device discussed above is that for any application in which a non-sterile organic waste, or any waste containing suspended solids, is to be metered to a reactor on a laboratory scale, the control of the flow should be isolated from the liquid. This implies that an aspirator feeding device, or some similar device, should be used. In view of the simplicity of the aspirator device, this is recommended for future work in this field.

4.6. CONCLUSION

In concluding this discussion of the results of the investigation a summary of the major points raised will be appropriate.

The anaerobic filter was found to be capable of treating strong yeast waste at loadings of up to 10 kg COD/(m^3day) with a retention time of 40 hours, and a COD removal between 40% and 60%. This performance is recognised as being poor, but no reasons for this were obvious. It was necessary to add sodium bicarbonate to the feed to give an alkalinity greater than about 2 000 mg/l in order to buffer digestion capacity adequately. Although very susceptible to shock loads, the filter recovered rapidly if the feed was stopped. Sludge growth in anaerobic systems is low, but the filters still clogged and flushing was necessary. Before the filter can be recommended for large scale use in the treatment of yeast, or any other similar strong waste, attempts should be made to improve the activity of the sludge by, amongst other factors, heating and regular backflushing. Further experimental work to investigate these and other possibilities is recommended. The filter should be the most suitable method of treating weak wastes at ambient temperatures, however.

The statistical analysis of the results obtained during approaches to steady state operation showed that under the conditions of the investigation, the effluent concentration is determined only by the feed strength, and that the liquid flow rate and the alkalinity of the feed are insignificant in this determination. Certain spurious gas productions were observed, and these cast some doubt on the results, but possible sources of error were considered. Before the performance of the filter can be predicted with confidence, however, future work of a fundamental nature is needed. This work should be aimed at both describing the operation of the filter empirically and measuring the kinetic growth constants of sludge and the degree of dispersion occurring in the filter, so that the applicability of the standard reactor design equations can be verified.

It was concluded from the operation of the filters that acclimation of anaerobic sludge is unnecessary. Two of the better indicators of impending failure of digestion were found to be gas composition and volatile acids concentration. Routine tests were proposed with which to monitor the operation of the filters in order to detect failure and to gain useful information for design purposes. The buffering of the feed and the unsuitability of lime for this purpose were discussed, although no satisfactory reason was found for the latter. The operation of the circulated filter was found to offer few advantages over the plug flow type operation. The filters were found able to recover from bad shock loads within 24 hours of stopping the feed, depending on sludge concentrations. The onset of clogging and its symptoms were described, so that the condition can be detected before it becomes chronic. It was also discovered that the filters could operate readily on wine distillery waste and that they could be left dormant for long periods.

The Raschig ring packing used in the filters was found to be rather unsatisfactory and rounded stones of 2,5 cms diameter were recommended for all future work. If the gas chromatograph is available for gas analysis, this should be used in conjunction with a wet type gas meter rather than the Orsat apparatus and gas collection bottles used in this investigation. Of the different feeding devices used, the aspirator device was found to be the most suitable for feeding organic wastes, but it must be kept at constant temperature with no small fluctuations.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. INTRODUCTION

This chapter gives a summary of the conclusions reached and the recommendations proposed during the discussion given in Chapter 4. These are first presented in detail in Sections 5.2. and 5.3., respectively and then itemised in Section 5.4.

5.2. CONCLUSIONS

The major conclusion which can be drawn from this investigation is that yeast waste can be treated by the anaerobic filter. The filter can accept for extended periods a loading of 10 kg COD/(m^3day) based on void volume of the packing, and gives a reduction in COD of between 40% and 60%. It was hoped that the anaerobic filter would be a most successful means of treating yeast waste, since the packing provides a means by which a high sludge concentration can be held in the reactor. The results of this investigation as given above are rather disappointing, however, compared with those of a contact type process at present being loaded at 13 kg COD/(m^3day) and giving an average of 65% reduction in COD. There was no obvious reason for the poorer performance of the filter, since both systems were treating the same waste, but possible causes were low sludge activity caused by large quantities of inert solids in the sludge, and inhibition of digestion, either by sulphide toxicity or nutrient deficiency. Of these possible causes, the former was felt to be the more likely, and so recommendations were made for operation with regular backflushing, but investigation of the latter possibility was also recommended. Because of this poorer performance, the anaerobic filter

cannot be recommended as it stands for application on a large scale to the treatment of yeast wastes. Some recommendations for changes in the operating procedure are given below and it is hoped that these will significantly improve the activity of the sludge, which is at present limiting the loading which can be applied to the filter. If these changes in procedure are successful in improving the performance of the filter, so that it equals that of the contact system, then the former is recommended for development into a full-scale process. This recommendation arises because of the operating problems usually associated with the sludge settling and separating unit of the contact process, which is not required for the anaerobic filter. The application of the filter to the treatment of other industrial wastes must depend on the nature of the waste. The operation of one of the filters for some 60 days on wine distillery waste showed that this waste may be successfully treated on the anaerobic filter. It is felt that the filter will find its best application in treating relatively weak wastes with a COD of less than about 5 000 mg/l, and containing very few suspended solids. This is because the sludge retention properties of the filter will allow very short liquid retention times to be used while still maintaining a high sludge concentration, and hence providing economical treatment.

It was discovered from operating experience that an alkalinity in the feed of greater than about 2 000 mg/l as $CaCO_3$ was required to maintain the pH of the filter near the optimum. The most satisfactory method of increasing the alkalinity was found to be the addition of sodium bicarbonate to the feed. Lime was tried on several occasions with little success. The method used in these cases was to add lime water to parts of the filter where low pH values were observed, or to the circulated section of the mixed filter. This was found to have an inhibitory effect on the digestion and was also inconvenient since large doses were required at frequent intervals. During the initial start-up phase it was found that if effluent was recycled in a ratio of at least 2:1 of feed, it was no longer necessary to add base to the feed in order to maintain the required pH.

The anaerobic filter can be started up rapidly by seeding heavily with sewage sludge. An acclimation period was found to be unnecessary and yeast waste could be fed directly to fresh sewage sludge. The plug flow type filter was found able to accept variations in loading rates of up to 20% with no ill effects, but variations of greater than 20% caused rapid failure of digestion. The circulated filter was operated in the hope that it would be more resistant to such shock loads than the plug flow type filter, but no significant advantage was observed. Once a filter had received a shock load and excessive acids concentrations had caused digestion to fail, it was able to recover within 24 hours of stopping the feed if allowed to stand at the normal operating temperature of 30°C.

The construction of the filters was satisfactory as described, although it was found that little further reduction in COD took place at heights greater than 1,2 m in the plug flow filters. This implies that for future work on a plug flow basis, the filter need be no higher than 1,2 m, but it is felt that a height of about 1,5m would allow some desirable flexibility if operation at retention times of substantially less than 40 hours is envisaged. The Raschig ring packing used was felt to be less than satisfactory, since the interiors of the rings rapidly clogged with sludge, becoming ineffective. Also the small size of the rings used - 1,2 cm - meant that the void spaces between the rings were small, and this led to clogging and short-circuiting of liquid faster than would probably have occurred had 2,5 cm rounded stones been used. The latter is the packing that has been found most satisfactory by other workers.

The method of feeding the filters caused the major difficulties of the investigation, with 10 to 15% variations in the flow rates from all the feeding devices used, but the aspirator device held the most promise for delivering constant flow rates. These fluctuations in flow rates prevented steady state conditions from being reached. The results believed to approach steady state most closely revealed that the effluent strength depended only on the feed strength under the conditions of the

investigation, and was independent of the flow rate, although only a very narrow range of flow rates (from 0,085 l/hr to 0,242 l/hr) was covered. The effects on the effluent of the alkalinity of the feed were incorporated in those of the feed strength, since the alkalinity depended on the feed strength.

In the daily operation of the filters, it was found that routine analysis of samples from the filters for pH, volatile acids and alkalinity and COD as well as measurements of gas productions and analyses was essential. These analyses could reveal increases in acids concentrations and carbon dioxide content of the gas, which are known to be indicators of impending failure of digestion.

5.3. RECOMMENDATIONS

The recommendations proposed for further work are aimed at discovering the reason for the performance of the filter being lower than was expected. These recommendations take the form of proposals for future programmes of operation by which it is hoped to improve the performance of the anaerobic filter by increasing the activity of the sludge, and improving the understanding of the digestion process as it takes place in the filters by studies of a fundamental nature. Recommendations are also given on general operating procedures by which these programmes should be executed.

The recommendations for further work of a fundamental nature stem from the desire to apply the general reactor design equations (24) p.279, (9) p.71, to the anaerobic filter. These require a knowledge of the growth kinetics of anaerobic filters. It is recommended that experiments be designed to measure these constants for anaerobic films treating both yeast waste and synthetic substrates. A comparison of these constants for films and suspended flocs of bacteria would also be of interest. The results of these experiments should also include data on sludge growth and gas productions. The application and

extension of a model of the filter developed by Haug and McCarty (19) requires a knowledge of the dispersion effects caused by rising gas bubbles and liquid eddies in a plug flow filter. These effects should be investigated by residence time distribution tests on a packed column covering a wide range of liquid and gas flow rates. The anaerobic filter should also be operated under a wide range of flow conditions to determine the effect on the effluent concentration of the liquid flow rate.

The first recommendation for improving the performance of the filter is that a programme of regular backflushing be instituted to prevent clogging. It is felt that the filter should be flushed at monthly or even two-weekly intervals, depending on the loading applied, but the actual frequency of flushing required would have to be determined by experiment. It is hoped that this would remove inert solids from the filter and allow a more active sludge to develop.

It is also recommended that filters be operated in the thermophilic temperature range (50 - 55°C) as this should double the metabolic activity of the sludge at 30°C. An aim of this programme of operation should also be to determine whether operation at this temperature range will be more economical than operation in the mesophilic range (30 - 35°C) or at ambient temperatures.

Work should also be done to determine whether any inhibition of digestion is occurring in the filters from sulphide toxicity and whether or not digestion is being limited by nutrient deficiency, and what minimum alkalinity is required. The possibility should also be considered of supplying this alkalinity by recycling the effluent, and, if this is possible, determining the optimum recycle ratio.

In executing these proposed programmes, the following recommendations are given: the filters should be packed with rounded stones 2,5 cms in diameter, and will need to be at least 15 cms in diameter to minimise wall effects. The height of the filters is not important if they are to

be circulated, but larger filters will require larger liquid flow rates which should be easier to control than small flows. The aspirator feeding device should be the most satisfactory and is recommended for use. The operation of the filters should be monitored by regular measurements of feed flow rates and gas production rates, as well as routine analyses for pH, volatile acids, alkalinity, COD and gas analyses. BOD's should also be determined whenever possible. These analyses are necessary in order to observe changes in the operating parameters which give warning of failure of digestion.

5.4. SUMMARY

5.4.1. Conclusions

The four major conclusions reached as a result of this investigation are:

1. Yeast waste can be treated by means of the anaerobic submerged filter
2. The filter can accept loads of up to 10 kg COD/(m^3day) based on void volume, for extended periods
3. This loading is limited by the activity of the sludge
4. An alkalinity of greater than 2 000 mg/l as $CaCO_3$ was required in the feed.

Other conclusions reached were:

5. The filter can successfully treat wine distillery waste and should find its best application in the treatment of weaker wastes
6. Sodium bicarbonate added to the feed was a better method of providing the required base on a laboratory scale than lime water dosed into the filters when required
7. Rapid start-up of the filter is possible if a heavy seed of sewage sludge is used. Acclimation to yeast waste is not necessary

8. The filter can accept shock loads of up to 20% of the average load, but is susceptible to sudden changes greater than this. After receiving a shock load in which all the liquid in the filter is replaced by fresh feed, the filter can recover within 24 hours of the flow being stopped

9. The filters need only be 1,2 m high if operated in a plug flow manner with a 40 hour retention time

10. The 1,2 cm Raschig rings used were not the best packing as the interiors clogged with sludge and the void spaces were small which tended to cause overall clogging

11. The aspirator feeding device was the most satisfactory of those tested, since its flow rates were not affected by sludge growth in the feed lines

12. The effluent strength was shown to be dependent only on the feed strength under the conditions of the investigation. The flow rate was insignificant in determining the effluent strength in the narrow range of flow rates covered, and the effect of the alkalinity of the feed was incorporated in that of the feed strength

13. Routine analysis of samples from the filters can detect changes in operating parameters indicating failure. Two of those found most useful were increases in the volatile acids concentration and the carbon dioxide content of the gas.

5.4.2. Recommendations

The recommendations proposed for fundamental studies are:

1. Determination of the growth kinetics for anaerobic films receiving both yeast waste and synthetic substrates. These results to include observations on sludge growth and gas productions

2. Measurement of dispersion effects in flow through packed beds caused by rising gas bubbles

3. Extension of the model proposed by Haug and McCarty (19) on the basis of the above results, and then verification of the applicability of reactor design equations to the anaerobic filter

Recommendations for work to be carried out on the anaerobic filter are:

4. Operation of the filter under a wide range of liquid flow rates in order to observe the effects of flow rate on effluent quality

5. A regular programme of backflushing be instituted to prevent clogging and remove inert solids

6. The filters should be heated to 55°C and measurements taken to determine whether operation at this temperature will be practicable and economical

7. Investigation of possible sulphide toxicity or nutrient deficiencies inhibiting digestion

8. Determination of the minimum alkalinity required for satisfactory digestion

9. Investigation into the possibility of supplying this alkalinity by recycling effluent, and, if successful the optimum recycle ratio

In executing these proposed experimental programmes the following are recommended:

10. Rounded stones of 2,5 cm diameter should be used as packing medium

11. The operation of the filters should be monitored by routine chemical analyses

12. The filters should be fed by an aspirator feeding device maintained at constant temperature.

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A P P E N D I C E S

A P P E N D I X A

ABBREVIATIONS AND ANALYTICAL PROCEDURES

A.1. ABBREVIATIONS

The following abbreviations have been used in this thesis:

BOD Biochemical Oxygen Demand. This is the oxygen demand exerted in 5 days at 20°C from a wastewater saturated with dissolved oxygen by a seed of micro-organisms (66).

BOD_{20} BOD_{abs} These are respectively the BOD exerted over 20 days and the ultimate, or absolute, BOD.

COD Chemical Oxygen Demand. This is the oxygen equivalent of the material in a sample as determined by refluxing with chromic acid for two hours (66).

MLSS Mixed Liquor Suspended Solids. This is the concentration of suspended solids in the mixed liquor of an activated sludge system (66).

OA Oxygen Absorbed. This is the oxygen equivalent of the material in a sample as determined by oxidation with potassium permanganate at 27°C for 4 hours. This is a similar measure to the COD, but the oxidation is much less severe, giving lower results (38).

Where: V_{acid} = volume of standard sulphuric acid used to titrate to pH 4,0 in ml

N_{acid} = Normality of standard sulphuric acid, usually 0,050 or 0,100

V_{sample} = Volume of sample used, in ml

The volatile acid alkalinity determined by the back-titration was calculated as mg/l $CaCO_3$ according to equation (A.2):

$$\text{VOLATILE ACID ALKALINITY} = \frac{V_{alk} \times N_{alk} \times 50\,000}{V_{sample}} \quad \ldots\ldots \text{(A.2)}$$

Where V_{alk} = Volume of standard sodium hydroxide solution used to titrate from pH 4,0 to 7,0 in ml

N_{alk} = Normality of standard sodium hydroxide solution usually 0,050 or 0,100

V_{sample} = Volume of sample used in ml.

The difference between the total alkalinity calculated from equation (A.1) and the volatile acid alkalinity calculated from equation (A.2) is the bicarbonate alkalinity, in mg/l as $CaCO_3$

The volatile acids concentration in mg/l as acetic acid was calculated by multiplying the volatile acid alkalinity from equation (A.2) by the appropriate factor, determined as follows:

Case 1 $>$ 180 mg/l volatile acid alkalinity

Volatile acids = Volatile acid alkalinity x 1,50

Case 2 $<$ 180 mg/l volatile acid alkalinity

Volatile acids = Volatile acid alkalinity x 1,00

In order to minimise volume effects during the titrations, the strengths of the acid and alkali solutions were adjusted so that not more than 10 ml of the solutions were used for the titrations.

A.2.2. Chemical Oxygen Demand (COD)

As in "Standard Methods" (66).

A.2.3. Gas Analyses

Gas analyses were carried out using an Orsat apparatus with 50% potassium hydroxide solution as the absorbent (74). The analysis was carried out by drawing 100 ml of sample gas into a graduated bulb by manipulating a reservoir of liquid, contacting the gas with potassium hydroxide solution, and observing what volume of gas was absorbed. This was taken to be carbon dioxide and the remaining gas to be methane. The confining liquid used for most of the investigation was mercury, and a correction was made for the water vapour present in the gas, which was collected over acidified water. Late in the investigation the confining liquid was changed to acidified water in order to eliminate the correction for water vapour.

A.2.4. Total Kjeldahl Nitrogen

As in "Standard Methods" (66).

A.2.5. Oxygen Absorbed (OA)

The procedure used for this test was that recommended by the National Institute for Water Research of the South African Council for Scientific and Industrial Research (38). This lists two variations - the British method and the South African Bureau of Standards (SABS) method. The basic procedure is the same for each variation : 10 ml of 25% sulphuric acid are placed in a wide-mouthed stoppered jar, a known quantity of N/80 potassium permanganate solution is added and

V = Volume taken of undiluted sample, in ml.

f = Factor of the sodium thiosulphate solution.

This factor f is the ratio of the actual normality of sodium thiosulphate solution to 1/40, and is determined by the standardization with the primary standard, potassium iodate.

A.2.6. Solids Tests

The total solids and total volatile solids were determined as given by "Standard Methods" (66).

Suspended solids and volatile suspended solids were determined as directed by "Standard Methods", except that Whatman No. 542 filter paper was used with a Buchner funnel in place of the Gooch crucible recommended. Two "blank" determinations were run at the same time to determine weight losses by the filter paper.

A.2.7. Sulphate

As in "Standard Methods" (66).

A P P E N D I X B

DAILY RECORD OF THE PERFORMANCE OF THE FILTERS

B.1 INTRODUCTION

This Appendix gives a detailed chronological report of the day-to-day operation of the three anaerobic filters used in the investigation.

The filters were considered to be operating well when the volatile acids concentration at sample point 4, 45 cms up from the bottom of the filters, was low - less than 2 000 mg/l as acetic acid - and when the pH at sample point 1 was above 6,8. These points were used because nearly all the acid formation took place within the first few centimetres of the filter, giving rise to the lowest pH. If the acid concentration had not dropped below the so-called danger level of 2 000 mg/l by sample point 4 there was cause for concern that the filter might go "sour" due to this wave of high acid concentration inhibiting all the methane-producing bacteria up the filter. Digestion was considered to have failed when the acid concentration rose sharply, this usually being accompanied by a rapid drop in pH and an increase in the carbon dioxide content of the gas produced. A recovery was usually possible if the feed was stopped and the filter allowed to stand.

B.2 DETAILED REPORT OF OPERATION, FILTERS I AND II

B.2.1. Source of Seed Sludge and Start-up

Since the sludge in the filters would be required to treat a strong industrial waste, it was reasoned that a sludge already adapted to such a waste would require a shorter start-up period than ordinary sewage sludge. Accordingly, sludge was obtained from laboratory digesters treating wine distillery wastes at the National Institute for Water Research of the South African Council for Scientific and Industrial Research at Bellville, Cape. At the same time, and whenever necessary afterwards, a supply of the wine distillery waste was collected for acclimation to yeast waste.

Each of the two filters used in the initial stages of the investigation was given a dose of about three litres of sludge containing some 2% solids in a heavy bottom seeding, as recommended by Young and McCarty (75) as being the quickest method of starting an anaerobic filter. The filters were fed initially with pure wine waste, but the pH rapidly dropped to 5,2 to 5,4 and by day 3 gas production had all but ceased. Lime water was added at strategic points up the filters in an attempt to correct the pH, since it was established in Chapter 2 that this was the most suitable chemical for pH control in failing digesters, but the filters did not recover. (The use of lime is discussed in Section 4.4.4.) The liquid was then drained and the filters flushed gently with water so as to retain the sludge, and feeding recommenced on day 6. The feed used was buffered to pH 7,0 with sodium bicarbonate, and had 12% of the OA load contributed by yeast waste. This was satisfactory and the production of gas by the filters increased, indicating improved digestion. On day 16, the proportion of yeast waste in the feed was increased to 70% of the OA load, while the liquid retention time was 70 hours, and the strength of the feed was 8 220 mg/l. This proved to be too great an increase, however, since the volatile acids concentration in the filters rose to about 8 000 mg/l as acetic acid, while the percentage of carbon dioxide (CO_2) in the gas was 73% on day 16. Accordingly the feed rate was reduced to give a liquid retention time of 150 to 200 hours. This reduced the proportion of CO_2 in the gas to 55 to 60% on day 17 but the acids remained high at values between 7 500 and 10 000 mg/l. The total alkalinity was approximately 10 000 mg/l as calcium carbonate up to day 27.

B.2.2. High Acids Concentrations and Effluent Recycle

In an attempt to reduce these high concentrations effluent was recycled in a ratio of 2 : 1 with the raw feed as from day 28. At the same time the proportion of yeast waste in the feed was dropped to 48% of the load while buffering of the feed to pH 7.0 with sodium bicarbonate continued. The net effect was to increase the gas production slightly. It was decided on day 31, after a pumping fault the preceding night had allowed 10 l. of feed to flow through Filter No. II within an hour, to

change this filter to operation on pure wine waste. This was to determine whether or not the anaerobic filter could also treat wine waste.

B.2.3. Filter II : Days 32 - 94 : Operation on Pure Wine Waste

From day 32 to day 40 gas production by this filter remained very low (approximately 0,04 1/hr). This corresponded to a low loading rate of 100 mg OA/hr for the filter. Effluent was recycled overnight between days 37 and 38 and resulted in higher loadings, but the gas production remained low. When the recycle was stopped, the loading decreased but not to the same level as before the recycle, while the gas rate increased. During this period, the pH of samples taken from various points up the filter varied from near 6,2 at the bottom to 6,4 in the effluent, while the gas contained some 60% methane (CH_4).

From day 43, the load rate to Filter II was increased four-fold from approximately 120 mg OA/hr to 460 mg OA/hr as effluent was recycled at a ratio of 4 : 1 of feed. At this stage, addition of sodium bicarbonate to the feed was discontinued since the pH of the combined raw feed and recycle was 6,8. The alkalinity dropped from 6 810 mg/1 on day 42 to 4 150 mg/1 on day 56. The increased load caused a steady increase in gas production from 0,05 1/hr on day 40 to a maximum of 0,48 1/hr on day 47. At the same time the acids concentration remained near 7 000 mg/1 and the gas averaged 78% CH_4. The pH fluctuated quite widely, but tended to steady out over the range 6,8 to 7,0. During this period the OA of the feed combined with the recycle was 1 630 mg/1 while that of the effluent was 700 mg/1., a reduction of 57%. Reasonably steady operation continued until day 53, when the gas rate from Filter II suddenly started dropping rapidly, after a small decrease in loading. This rapid decline in gas rate continued until day 58, at which time gas production had all but ceased. At the same time, the pH of the filter rose to 7,2 and the CH_4 content of the gas to 85%. At this time it was noted that the feed had much mould growing on the surface, and this probably caused a rapid decline in feed strength. The acids concentration in the filter, however, remained near 4 000 mg/1. By day 60, new feed had been procured, effluent recycle was maintained at 4 : 1 and the gas productions rose

rapidly in response to the loading rate reaching 500 mg OA/hr. Pumping difficulties dropped this almost immediately to 200 mg/hr causing a slower increase in gas rates, which, by day 64, had reached a peak of 0,47 l/hr, the CH_4 content, however, having dropped to 71%. The pH at this time varied between 6,4 and 6,8, the acids concentration was slightly over 4 000 mg/l and the total alkalinity was 4 300 mg/l, while a 69% reduction in OA of the raw feed from 2 390 mg/l was effected. Loading rates held steady at between 250 and 280 mg/hr until day 70, but gas productions dropped from the peak of 0,47 l/hr to 0,1 l/hr during day 70. A possible reason for this decline in gas production was that a build-up of some inhibitory substance was taking place because of the continued recycle of effluent. To test this hypothesis, the pump settings were changed to lower the recycle ratio to 2 : 1, but before this could take effect, the raw feed chamber blocked, resulting in an increased recycle ratio of 10,5 : 1. Gas production doubled to 0,13 l/hr with this increase, showing that inhibition was not the cause of the decline noticed earlier, and indicating instead that the feed was very old.

From day 73 to 78 feed rates were virtually nil, because of pump difficulties, but low pH of the feed and a low recycle ratio caused the pH at the bottom of the filter to fall to 6,2. On day 78 loading was commenced with fresh feed with sodium bicarbonate added to pH 7,0, at a rate of 240 mg/hr, and a recycle ratio of 2,25 : 1. Gas productions increased sharply to a peak of 0,27 l/hr on day 79. Loading continued at 290 mg OA/hr to day 82 when it increased to 330 mg/hr. Gas productions only responded on day 84, however, when they increased rapidly to 0,28 l/hr from 0,18 l/hr, while pH remained near 7,0. Acids concentrations averaged 3 000 mg/l for the rest of this phase of operation while the alkalinity increased steadily from 2 400 mg/l on day 78 to 6 500 mg/l on day 94, when the phase ended. For the remainder of the phase, days 84 to 94, loadings varied rather randomly due to various pumping difficulties, and gas ratio followed the load rates predictably, rising when loading increased, with the CH_4 content averaging 90%.

B.2.4. Filter I : Days 30 - 94 : Continued Conversion to Yeast Waste

From day 30 the gas produced by Filter I operating on combined yeast and wine wastes increased steadily from 0,08 1/hr to 0,48 1/hr on day 42 while the CH_4 content of the gas rose sharply from 62% on day 29 to 69% on day 30, dropped to 62% again on day 31 and then rose sharply to 92% on day 38 and then dropped off to 87,5% by day 42. The percentage reduction in OA of the feed during this period was 60% with a feed stength of 3 260 mgOA/1. During the same period, the average load rate increased from 120 mg OA/hr to 420 mg OA/hr on day 41, the total alkalinity increasing from 7 000 to 7 800 mg/1 while the acids concentration dropped from 7 000 mg/1 on day 28 to 3 200 mg/1 on day 42. The recycle ratio varied between 4 and 5 : 1, while the pH increased from near 7,0 to range between 7,5 and 7,9. From day 43, the loading was increased to 520 mg OA/hr and the proportion of yeast waste increased to 80%, but the gas rate, which had dropped to 0,28 1/hr on day 43 due to old feed, continued to drop, till by day 49 it had reached 0,13 1/hr. The CH_4 content of the gas averaged 82% over this period and continued to do so until day 60, while the reduction in OA of the feed dropped to only 25%. The acids concentration on day 47 was 2 500 mg/1 and remained at this level until day 51 when it started dropping steadily over the rest of this phase of the operation until by day 94 the acids concentration was 1 500 mg/1. The alkalinity dropped from 7 800 mg/1 on day 42 to 4 400 mg/1 on day 56. The alkalinity stayed at this level until day 72 after which it dropped steadily to reach 3 400 mg/1 on day 94.

On day 49 it was decided that the sudden change to 80% yeast waste was too rapid and so the load was changed back to 50,5% yeast waste. This caused an immediate increase in gas production to an average of 0,27 1/hr until day 53, after which the gas rate started dropping again to 0,17 1/hr on day 58. During this period the pH had remained between 7,0 and 7,6 and the reduction in OA increased to 57%. On day 59 a fresh batch of feed was made up with 65% yeast waste load, and an attempt was made to increase the loading rate, but the pump blocked after one day, having pumped at 850 mg OA/hr for that time. This caused a sharp peak in gas production on day 60 to 0,46 1/hr but by day 62 this had dropped to 0,18 1/hr with the blocked

feed pipe. On restarting, the load rate was set at 450 mg OA/hr and the recycle ratio at 3,5 : 1. Gas production followed the increase in loading reaching a level of 0,3 1/hr on day 65, but at this stage the recycle line blocked and the loading dropped to 240 mg OA/hr. Gas production decreased to follow this decreased loading, but when recycle was started again on day 69 at 3,5 : 1 the gas rate did not increase, despite the fact that the loading increased to its former level of 450 mgOA/hr. The pH during this time varied from 7,0 - 7,2 to 7,2 - 7,6. From day 71, the load rate decreased due to a pump blockage and reached zero on day 74. Pumping difficulties maintained negligible load rates until day 78. The gas rate had continued dropping and by day 78 was at 0,05 1/hr. On day 78 the load rate was increased to 360 mg/hr with 75% yeast waste load and a recycle ratio of 2,25 : 1. This caused a very sharp increase in gas production to 0,28 1/hr on day 79 with a CH_4 content of 76% on day 80, which had decreased by day 82 to 79,5%. The increase in load rates had caused the pH to drop and by day 80 this was ranging between 6,6 and 7,1. This caused a decline in the gas rate to 0,22 1/hr by day 81, but it held steady at that value, with the CH_4 content steady at 80%. After this, the phase concluded with varying load rates and predictable behaviour of the gas rate.

B.2.5. Shut-Down of the First Phase of Operation

The start-up phase concluded on day 94 when feeds were stopped and the temperature of the room in which the filters were kept lowered to ambient (20 - 25°C) in preparation for a vacation. The filters were left to stand for 53 days until day 147 at which time the temperature was raised to 30°C. Gas production rates from the quiescent filters were measured on day 154. As was to be expected, these were very low indeed, with Filter I giving 0,02 1/hr of gas containing some 97% CH_4 and Filter II producing 0,008 1/hr of gas of similar composition.

B.2.6. Restart of Filter I

On day 155 samples from different levels of Filter I showed the acids concentrations to be 410 mg/l as acetic acid, while the pH was 7,3 and the alkalinity 4 000 mg/l - an encouraging recovery from the operating levels of the previous phase, which were 1 500 mg/l acids and 3 300 mg/l alkalinity. On the afternoon of day 156, Filter I was restarted, using very low loadings of 40 mg OA/hr delivered by the kinking tube pump described in Chapter 3. By the following day (157) the acids had dropped to 350 mg/l and gas production was still at 0,02 l/hr. Loading rates remained low, averaging about 70 mg OH/hr until day 166 when an increase to 180 mg OA/hr occurred. Gas production had increased to 0,05 l/hr while the pH had dropped to 7,1 at the bottom of the filter. Gas productions increased to 0,08 l/hr over days 161 to 164, while the acids concentration increased to 500 mg/l, and the proportion of methane in the gas dropped to 89%. On day 164 the reduction in OA of the effluent (600 mg/l) over the feed (780 mg/l) was 23%. After dropping to 60 mg OA/hr on day 165, the loading rapidly increased again to 170 mg OA/hr on day 166. The gas production reached a peak of 0,15 l/hr on day 164/165 when loading was at a minimum, but then steadied out at 0,13 l/hr over days 166 and 167.

B.2.7. Fresh Start for Filter II - No Acclimation

The remaining wine waste sludge was flushed from Filter II and on day 162, this filter was dosed with 6 l. of actively digesting sewage sludge from the anaerobic digesters at the local Athlone Sewage Works of the Cape Town City Council. It was decided to dispense with the acclimation process practised earlier, and feeding was started on day 162 with pure yeast waste diluted to give an OA of 7 980 mg/l. Sodium bicarbonate was added to give a pH of 6,6 - approximately 1,5 g/l of alkalinity measured as $CaCO_3$ was added - and the load rate started at 1 600 mg OA/hr. The pH of the sewage sludge as it had been in the filter before feeding commenced was 7,3 and gas was being produced at 0,6 l/hr, while the acids concentration was 450 mg/l and the alkalinity 3 000 mg/l as $CaCO_3$. By the morning of day 163, however, the pH at the bottom of the filter had

increased to 800 mg/1. The proportion of CH_4 in the gas during this period was 79%. On day 171, the load rate doubled to 250 mg OA/hr but then decreased steadily until by day 176 the load rate was 130 mg OA/hr. During this period the gas production remained essentially constant at 0,13 1/hr, the proportion of methane decreasing from 79% to 71%, however. From day 176 to 182 the load rate to Filter I fluctuated between 130 and 190 mg OA/hr with a retention time of 85 hrs., and a reduction in OA of 40%, but the gas rate stayed near 0.14 1/hr, with the pH at the bottom of the filter between 6,9 and 7,0, and the acids concentration at 700 mg/1. On day 183 the load rate increased to 180 mg OA/hr and stayed near this value until day 185, after which it decreased to 70 mg/hr on day 190. Gas productions had increased slightly to a peak of 0,18 1/hr on day 186 and thereafter declined to a low of 0,13 1/hr on day 190. At the same time the acids concentration increased to 990 mg/1 on day 190 while the pH at the bottom of the filter remained at 7,0. The proportion of methane in the gas increased from 72% on day 183 to 82% on days 185 and 188.

B.2.9. Filter II : Days 172 - 190 : Fluctuations in Loading

On day 172, the loading rate to Filter II increased to 200 mg OA/hr, but by day 175 this had dropped to 180 mg OA/hr. On day 176 a sharp increase in loading to 240 mg OA/hr occurred, followed by an immediate decline to 160 mg OA/hr on day 177. During this period, the gas production rate remained steady at 0,21 1/hr from day 171 to 176 at which time it declined to 0.16 1/hr and stayed at that level until day 179. The proportion of CH_4 in the gas on day 179 was 83% as compared with 74% on day 176. On days 178 and 179 the load rate dropped to 130 and 140 mg OA/hr, respectively, but on day 180, it increased again to 190 mg OA/hr but then declined to reach 150 mg OA/hr on day 182. From day 179 to day 181, the gas production by Filter II increased steadily from 0,17 to 0,19 1/hr and then rapidly increased to a peak of 0,25 1/hr on day 182. It then declined steadily to 0,15 1/hr on day 184 after which it increased to 0,23 1/hr on day 185 and then dropped right down to 0,06 1/hr on day 187. After another peak of

0,14 1/hr overnight on days 187/188, the production dropped again to 0,08 1/hr on day 188 and then increased to reach 0,16 1/hr on day 191. The load rates had increased to 180 mg OA/hr on day 183, stayed at this level until day 185 and then started an accelerating decline to reach 70 mg/hr by day 190.

B.2.10 Filters I and II : Days 191 - 206 : Constant Loadings

From day 190 to day 206, both Filters I and II operated at loadings that remained between 150 mg OA/hr and 215 mg OA/hr with retention times of 100 hrs. Gas production rates fluctuated rather more than did the load rates, varying between 0,11 and 0,20 1/hr. The acids concentrations at sample point 4 for Filter I decreased from 900 mg/1 on day 190 to 700 mg/1 on days 196 through 202 and then to 500 mg/1 on day 207, while the alkalinity stayed at an average of 2 630 mg/1. The proportion of CH_4 in the gas varied from 80% on day 190 to 77% on day 207. The pH at the bottom of the filters fluctuated considerably, however. In Filter I, the pH remained at 7,0 until day 198 at which time it started dropping to reach 6,7 on day 199 and then increased again to 7,0 on day 203 and then dropped again to 6,7 on day 207. In Filter II the pH started at 7,0 on day 190, increased to 7,1 on day 196 and then decreased to 6,8 on days 198 and 199. By day 203 it had risen to 7,1 and then dropped again to 6,7 by day 207. At the start of this period of constant loading (day 191) the reductions in OA being effected were 33 and 41% for Filters I and II respectively. By the middle of this period (day 199) these reductions in OA had risen to 57% for Filter I and 60% for Filter II with corresponding COD reductions of 37% and 43%. On day 203, OA reductions were 55% and 58% respectively.

On day 199 suspended solids tests were carried out on samples withdrawn from each of the filters at different heights. Filter I showed a suspended solids concentration of 17 300 mg/1 in the liquid withdrawn from sample point 1, decreasing to 380 mg/1 at sample point 11. Filter II showed a similar decrease from 24 000 mg/1 at sample point 3 to 780 mg/1 at sample point 11 (See Fig. B.1)

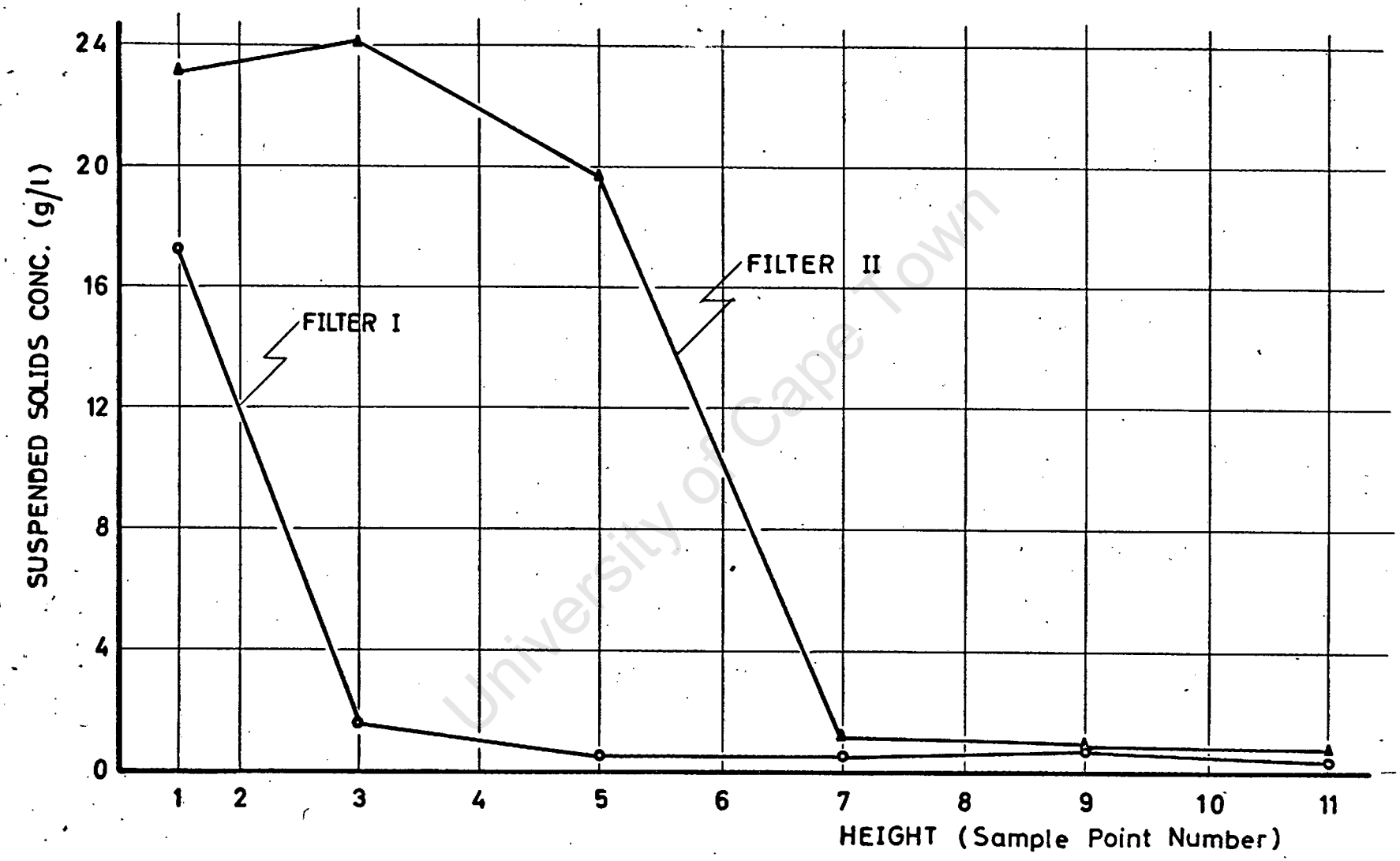

Fig B.1 SUSPENDED SOLIDS PROFILE ON DAY 200

This period, from day 191 to day 206, is the time over which the most constant load rates were obtained for an extended period out of the whole 394 days for which the filters were operated. The reasons for this constant operation can be given as:

(i) dilute feed was being used and so sludge growth in the feed lines was low;

(ii) the kinking tube pump was set to deliver its minimum volume per stroke and this was easily reproducible after cleaning;

(iii) a refrigeration unit to cool the feed was brought into operation on day 190 and this maintained the feed temperature at 4 ± 2^{o} C.

An attempt was made to reproduce the above operating conditions from day 212 to day 219, but this was not successful.

B.2.11. Filter I : Days 207 - 219 : Random Fluctuations in Load

On day 207 the feed rate to Filter I dropped to 140 mg OA/hr and thereafter fluctuated randomly between 100 mg OA/hr and 200 mg OA/hr until day 219 at which time the feed rate was 80 mg OA/hr. The gas productions responded as expected during this time, while acids concentrations appeared to remain constant as the concentration was measured at 450 mg/l at sample point 4 on day 219.

B.2.12. Filter II : Days 207 - 219 : Shock Load and Recovery

The feed to Filter II also dropped on day 207 to a level of 110 mg OA/hr. At approximately 12 noon on day 208 an accident occurred with the feed pump to Filter II causing the remaining 12 l. of feed in the tank to flow through the filter in a few minutes. No further feed was given and the filter was allowed to stand in order to recover. Samples from 4 points were taken at various intervals over the following 24 hours and analysed for pH, acids and alkalinities. These results are presented graphically in Fig. B.2. The feed had been adjusted to pH 7,0 with 2 g/l of sodium bicarbonate and this caused the sharp peak to pH 7,0 at time zero on the graph of pH vs time. The gas production during this period

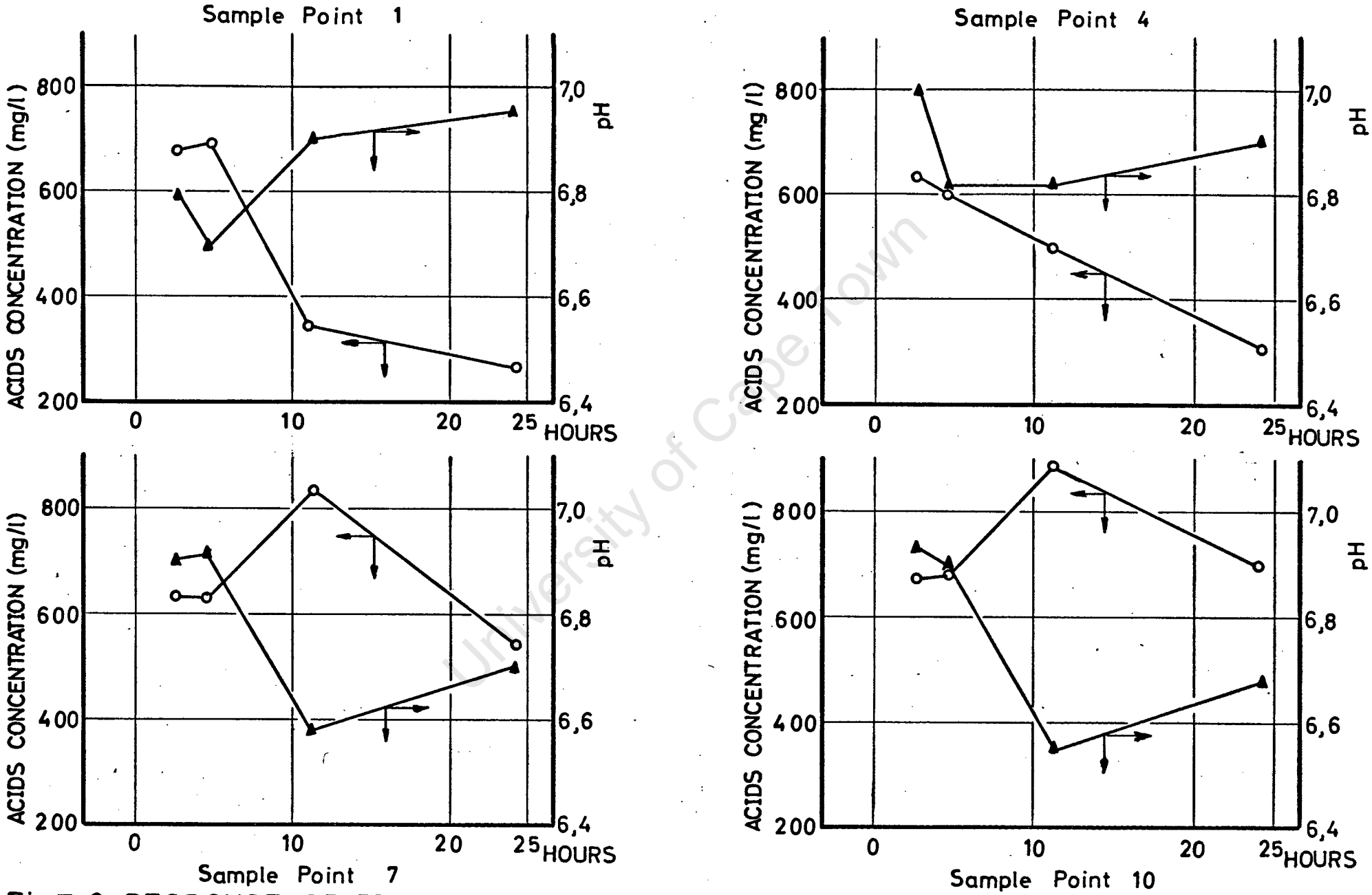

Fig B.2 RESPONSE OF FILTER II TO A LARGE SHOCK LOAD ON DAY 208

rose from 0,14 1/hr on day 208 to a peak of 0,22 1/hr after the shock load and then dropped to 0,09 1/hr on day 210 while the filter was not being loaded. Gas analyses before and after the shock showed 74,5% and 75,5% CH_4 respectively on days 207 and 211.

The rapid recovery of the bottom section of the filter after this shock load can be attributed to the high concentration of sludge existing there as shown in Fig. B.1. Further, these results show that 24 hours are sufficient for a complete recovery of a filter after a shock load of the nature described if the sludge concentration is sufficiently high. Feeding was resumed on day 211 after the acids at the top of the filter had dropped back to 440 mg/1. The loading rate fluctuated between 220 mg OA/hr and 135 mg OA/hr with an average of 200 mg OA/hr until day 219. The gas rates behaved predictably with fluctuations between 0,14 1/hr and 0,19 1/hr. Just before the feed to Filter II was resumed on day 211, the pH at the bottom of this filter was 7,2 and this dropped to 6,8 on day 219. At the same time, the acids concentration at sample point 4 increased from 300 mg /1 to 430 mg/1 on day 219 and the proportion of CH_4 in the gas dropped from 75,5% to 73%.

B.2.13. Filters I and II : Days 220 - 223 : Increased Loads

Up to this stage the feed strength had been maintained at an average of 2 000 mg OA/1 or 5 600 mg COD/1 while liquid retention times varied between 80 and 100 hours. It was felt that little further was to be gained by continued operation at these loading rates and so overnight on days 219/220 the loading rate was increased to 410 mg OA/hr to both Filters I and II by doubling the liquid flow rate. This halved the retention time for both filters to 40 hours. The load rate to Filter I increased still further to 660 mg OA/hr on day 220, but this was reduced to 430 mg OA/hr on day 221 and Filter II was being loaded at the same rate on that day. At this stage the load to Filter II started decreasing steadily to reach 350 mg OA/hr on day 223 when the feed pump broke down, causing the feed to stop. The load to Filter I had increased to 480 mg OA/hr on day 221 but then decreased to 400 mg OA/hr

when the pump stopped. The gas production rates from Filter II climbed rapidly from 0,14 1/hr on day 219 to 0,3 1/hr on day 220 in response to the increased feed rate. The pattern of gas productions followed that of the load rate until day 222, when, with the loading rate decreasing steadily as described, the gas rate increased from 0,29 1/hr to 0,30 1/hr on day 222 and then to 0,34 1/hr on day 223 after which it dropped sharply to reach 0,06 1/hr on day 224, when the feed had stopped. The methane content of the gas was 70,5% on day 221 and this had increased to 73% on day 223.

The gas production from Filter I did not rise as rapidly nor reach the same levels as that from Filter II, despite the fact that the load to Filter I was higher than that to Filter II. The gas production by Filter I increased steadily from 0,13 1/hr on day 219 to 0,31 1/hr on day 223. With the cessation in the feed , the production dropped off to 0,19 1/hr on day 224. On day 220 the acids concentration in Filter I had risen to 900 mg/l at sample point 4, while the pH was 6,9 and the alkalinity was 2 300 mg/l. The methane in the gas from Filter I was 67,7% on day 221 and this increased to 69,5% on day 223.

B.2.14. Filter I : Days 224 - 232 : Fluctuating Load Rates

Feeding of Filters I and II was resumed on day 224 at rates of 280 mg OA/hr for both filters. Until day 233, the feed to Filter I fluctuated about a mean of 350 mg OA/hr with a peak of 410 mg OA/hr on day 229 and a minimum of 260 mg OA/hr on day 230. The gas production pattern again followed that of the feed rate during the whole of the period. The pH at the bottom of the filter dropped from 6,9 on day 226 to 6,5 on day 232, while the acids concentration remained at 850 mg/l, and the alkalinity was 2 530 mg/l on day 226 and 2 050 mg/l on day 232 at sample point 4. On day 226 the reduction in OA of effluent over feed was 58,6% (49,2% COD reduction) while on day 232 these had dropped to 5 7% and 35% respectively. The methane content of the gas on days 228 and 233 were both 71,0%.

B.2.15. Filter I : Days 233 - 242 : Increasing Load Rates

On day 233 the load rate to Filter I started increasing from an average of 350 mgOA/hr on day 233 to an average of 500 mg OA/hr on day 242. The daily fluctuations continued to be about 10% on either side of the mean during this period but the general trend was upward as indicated. The gas rate did not behave as predictably as in the previous period, however. Initially the gas rate increased rapidly from 0,25 l/hr on day 233 to 0,38 l/hr overnight on days 234/235 and then decreased rapidly to 0,3 l/hr during day 235. The gas rate then fluctuated about a mean of 0,33 l/hr until day 241 when it increased to a peak of 0,4 l/hr overnight on days 241/242. The methane content of the gas dropped slightly with the increased load rates. On day 234 the methane content was 67% but this had risen to 67,7% on day 236 and 71% on day 240 but dropped back to 68,5% on day 242. The pH at the bottom of Filter I dropped to 6,5 on day 239 while the acids concentration at sample point 4 also dropped to 650 mg/l from 900 mg/l. on day 232, while the alkalinity was 1 900 mg/l The reduction in OA effected by Filter I during this period was 60,6% as measured on day 235, and 61,6% on day 240 with corresponding COD reductions of 40,6% and 42%.

B.2.16. Filter II : Days 224 - 242 : Increasing Feed Rates

The feed rate to and the gas production rate from Filter II followed essentially the same patterns as those of Filter I. The only major difference was that the gas rate from Filter II increased sharply to 0,35 l/hr on day 225 immediately after the resumption of feed, and then decreased to average 0,27 l/hr until day 232. Another difference between the two filters was that while the load rate to Filter I was consistently higher than that to Filter II, the gas rate from Filter I was less than that from Filter II. The pH of the samples from the two filters were similar as were the methane contents of the gas. The acids concentrations in Filter II were only half those in Filter I, however, averaging 500 mg/l, with the alkalinity in both filters identical at the same sample points and times. The same general similarity between the operation of the filters continued up to day 242 with the gap between the gas productions narrowing as the

concentration of acids in Filter I decreased, thereby decreasing the difference between the acids concentrations in the two filters. The reduction in OA on day 235 was 64,4% and 64,2% on day 240 with corresponding COD reductions of 45% and 45,9%.

B.2.17. Filters I and II : Day 242 : Finger Pump Started

Up to this time the feed concentrations for both filters had been kept at about 2 000 mg OA/hr, and the higher load rates achieved by increasing the volumetric feed rates. During this time the shortcomings of the kinking tube pump became obvious, and it was decided to use a "finger" pump instead, as described in Chapter 3. This was brought into operation on day 242 feeding both Filters I and II. During the night of day 242/243, however, a joint in the feed pipe near the bottom of Filter I failed and all the liquid and suspended sludge in the filter was lost.

B.2.18. Filter I : Day 243 : New Sludge

The filter was redosed with digested sewage sludge from the Athlone Sewage Works and feeding recommenced at 230 mg OA/hr, using yeast waste diluted to 2 000 mg OA/l, and containing 1 g/l of sodium bicarbonate. From day 243 to day 249, the finger pump maintained a feed rate fluctuating by only about 3% on either side of the mean, but by day 250 the fluctuations reached $\pm$ 10%. The loading continued at an average of 240 mg OA/hr from day 250 through day 260, with a peak of 370 mg OA/hr on day 257. During this time the gas production rate dropped from a maximum of 0,45 l/hr on day 244 to 0,23 l/hr on day 246 and then fluctuated about this value until day 260. During this time, the methane in the gas dropped from 82,1% on day 244 to 75% on days 254 and 256 after which it climbed to 73,5% on day 259 and dropped back to 71,5% on day 261. Acids concentrations at sample point 4 in Filter I dropped steadily from 500 mg/l on day 245 to 300 mg/l on day 260 while alkalinities varied between 2 030 and 2 280 mg/l. The pH at the bottom of Filter I on day 245 was 6,4 and this had risen to 6,7 on day 253, but then dropped to 6,5 on day 260. The effluent strength on day 248 was measured at 720 mgOA/l, a reduction of 64,5% over the feed of 2 040 mg OA/l while the COD reduction was 46%.

B.2.19. Filter II : Days 243 - 259 : Fluctuating Loads

Filter II received loadings of approximately the same level as Filter I. There was, however, a decrease in the average loadings from 250 mg OA/hr on day 244 to 200 mg OA/hr on day 252/523. An increase to 300 mg OA/hr occurred on day 254, followed by a decline to 230 mg OA/hr on day 255. For most of the period, the loading rates were about 30 mg OA/hr higher than those to Filter I. The gas rates, however, were about 0,03 to 0,02 l/hr lower than those from Filter I. The acids concentration in Filter II increased from 700 mg/l on day 245 to 1 100 mg/l on day 254 and then dropped again to 480 mg/l on day 260. The alkalinity stayed near 2 000 mg/l during this time, while the methane content of the gas decreased from 71,6% on day 248 to 69,3% on day 254 and increased again to 72,2% on day 256. The pH at the bottom of this filter dropped from 6,7 on day 245 to 6,5 on day 253 and 260. The reduction in OA of the effluent over the feed was 62% on day 248 and 63,7% on day 256, with corresponding COD reductions of 42,8% and 45,2%

B.2.20. Filter I : Days 260 - 273 : Increased Loads and Broken Feed Pipes

On day 260 it was decided to increase the loading rates to both filters in order to determine what maximum loadings the filters could handle. The load rate to Filter I was increased steadily from 230 mg OA/hr on day 259/260 to reach 470 mg OA/hr on day 263. After this peak, however, the load dropped to average 370 mg OA/hr from day 264 to day 268. The initial increase in load rates was effected by increasing the volumetric feed rate of waste with an OA of 2 500 mg/l but on day 263 the concentration of feed to Filter I was increased to 2 600 mg OA/l with 1,5 g/l of sodium bicarbonate, and the volumetric feed rate was reduced to give a 55 - 60 hours retention time. On day 268 the feed tube in the finger pump punctured, and the pump had to be stripped and cleaned. Upon resuming feed late on day 268 the load rate to Filter I was 500 mg OA/hr and the concentration of feed had been stepped up to 2 930 mg OA/l plus 1,25 g/l sodium bicarbonate, until overnight on days 270/271 when the feed pipe again punctured. Upon resuming feed on day 271, the feed strength was increased to 3 100 mg OA/l and the loading was 540 mg OA/hr with a retention time of 45 hours. This

was maintained until day 273 when the feed tube broke for the third time. From day 260 when the increased loadings were started, the gas rate increased steadily from 0,24 1/hr to 0,46 1/hr on day 264 in response to the increase in feed. The gas rate then dropped off to average 0,37 1/hr over days 264 to 267 and on day 268 dropped to 0,25 1/hr because of the cessation of feed. It then increased to average 0,48 1/hr on days 269 and 270 and then dropped again on day 271 to 0,40 1/hr. When feed was started again, the gas rate increased to reach 0,56 1/hr on day 272 and then dropped in response to the stoppage in feed caused by the broken feed pipe. During the period when the gas rate was increasing (days 260 to 265) the methane content of the gas averaged 71,5%, but on day 267 the methane content was down to 68,1%. This increased when the feed stopped, but then dropped to average 70,5% over the period days 268 to 273. The volatile acids concentration at sample point 4 in Filter I increased on day 262 to 640 mg/l from 300 mg/l on day 260, but dropped again to 475 mg/l by day 267. The alkalinity increased from 2 300 mg/l on day 260 to 2 530 mg/l on day 267. The pH also increased from 6,5 at the bottom of the filter on day 262 to 6,7 on day 267. The reduction in OA effected by the filter was 72% on day 268 and 70,7% on day 273, with COD reductions at the same time of 52,7% and 55,7%. These higher percentage reductions reflect the greater efficiency of the filter for a more concentrated feed.

B.2.21. Filter II : Days 260 - 273 : Large Increases in Load

The operation of Filter II over the period days 260 to 273 followed the same pattern except that the changes in load rate were considerably greater. The load rate increased from 200 mg OA/hr on day 257 to reach 450 mg OA/hr on day 261 and 750 mg OA/hr on day 263. After this peak it dropped back rapidly to 470 mg OA/hr on day 264 and 430 mg OA/hr on day 266. A short stoppage occurred on day 268 when the pump was stopped for the first time, after which it increased to 590 mg OA/hr on day 270 when the second pump stoppage occurred, and then reached 700 mg OA/hr on days 271 and 272, and 940 mg OA/hr on day 273, when the third pump

stoppage occurred. These increased loading rates were achieved by increasing the concentrations of waste fed to 2 500 mg OA/l on day 262 and adjusting the volumetric feed rate accordingly. The gas productions followed the same general trends as the loading rates with the production increasing from 0,21 l/hr on day 259 to 0,68 l/hr on day 263. As the load rate declined on days 263 and 264, so did the gas rate, except that the gas rate increased to 0,6 l/hr on day 265 when the load rate had decreased. The variations in gas rate were far greater than those in the load rate, but the gas production reached a peak of 0,77 l/hr overnight on days 273/274 and then dropped to 0,73 l/hr on day 274. The methane content of the gas dropped to 68,8% on day 261 while the gas rate was increasing, from a value of 72,4% on day 259. On day 263 when the peak gas production had been reached, the methane content was down to 66,3%, but this increased to 69,8% the next day when the overall production had decreased. From then until day 273, the methane content averaged 69,5%. The acids concentration at sample point 4 was 450 mg/l on day 262 and then increased to 625 mg/l on day 267, while the alkalinity increased from 1 960 to 2 390 mg/l respectively. The pH stayed constant between 6,5 and 6,6. The OA reductions effected were 67% on day 268 and 68,7% on day 273 with COD reductions of 50,2% and 52,7% respectively.

B.2.22. Filter I : Days 274 - 277 : Decreasing Load

Filter I was started up again on day 274 at a loading of 710 mg OA/hr increasing to 780 mg OA/Hr on day 275 and decreasing to 500 mg OA/hr on day 276, with a retention time of 35 to 40 hours, and a feed concentration of 3 580 mg OA/l. A blockage in the feed line on day 277 caused the feed to drop to zero. The gas rate increased from 0,54 l/hr on day 274 to 0,67 l/hr on day 275 and dropped to 0,22 l/hr on day 277 with the stoppage in feed, while the methane content dropped from 77,2% on day 274 with no feed to 62,3% on day 276 and then increased again to 81% when the feed pipe blocked on day 278. On day 275, the acids concentration at sample point 4 had risen to 1 150 mg/l while the alkalinity was 2 700 mg/l and the pH at the bottom of the filter was 6,2 and 6,7 at sample point 4.

B.2.23. Filter I : Days 278 - 298 : Increased Load by Increased Feed Strength

Filter I was started again on day 278 at a loading rate of 670 mg OA/hr with a concentration of 3 250 mg OA/1 in the feed and a retention time of 40 hours. This loading was steadily increased until by day 298 Filter I was being loaded at 1 150 mg OA/hr with a feed of 5 920 mg OA/1 with 2 g/1 of sodium bicarbonate added, and the retention time still at 40 hours. The fluctuations in the load rates during this time were approximately 10% on either side of the mean, except for days 286 and 287 when the load rate dropped to zero. Loading was resumed on day 287 at the same level as before the stoppage. During this period, the gas rate followed the expected pattern, increasing with increasing load, starting at 0,5 1/hr on day 279 and reaching 1,05 1/hr on day 298. Fluctuations were also of the order of $\pm$ 10% except for the period when the load rate dropped on days 286 and 287 when the gas rate dropped to 0,48 1/hr. The methane content of the gas showed an overall decline from 68% on day 282 to 61,6% on day 299. The decline was reasonably steady, apart from variations when the gas rate decreased appreciably. The acids concentration at sample point 4 was 920 mg/1 on day 281 and this decreased to 875 mg/1 on day 288 immediately after the stoppage of feed, but by day 298, the acids had climbed to 1 870 mg/1. The alkalinity increased from 3 000 mg/1 on day 281 to 3 540 mg/1 on day 288 and 4 350 mg/1 on day 298. The pH at the bottom of the filter decreased steadily from 6,6 on day 281 to 6,4 on day 288 and 6,2 on day 298. The pH at sample point 4 was 6,9 at this time, however. The reductions in OA effected by the filter during this time averaged 70,7% with 73,6% on day 281, 68,7% on day 287 and 69,7% on day 294. COD reductions at the same time varied widely, from 60,1% on day 281 to 52,8% on day 287 and 38,3% on day 294. At these times the feed strengths were 3 480 mg OA/1, 4 400 mg OA/1 and 4 920 mg OA/1 respectively.

B.2.24. Filter II : Days 274 - 301 : Increased Load Rates by Increased Feed Strength

When Filter II was restarted after the third pump stoppage caused by broken feed tubes, the loading was resumed at 880 mg OA/hr on day 274, but

this dropped steadily to 440 mg OA/hr on day 277. From day 277 to day 300, the average load rate increased from 500 mg OA/hr to 1 850 mg OA/hr on day 300, after which the feed dropped to zero on day 301. The fluctuations in feed rates over this period were almost double those of the feed to Filter I, however, with variations of 15% to 20% on either side of the mean, and with a drop down to 75 mg OA/hr on day 297 when a blockage occurred. Retention times during this period varied from 30 hours on day 275 to 60 hours on day 277 and 30 hours on days 290 and 300. During this time, the concentration of feed increased from 3 250 mg OA/l with 1,5 g/l of sodium bicarbonate on day 274 to 7 660 mg OA/l with 2 g/l of sodium bicarbonate on day 296. Gas productions followed essentially the same pattern as the load rate except that the variations during the period days 277 to 292 were substantially smaller than those of the feed rate during the same period. The average gas productions rose steadily from 0,54 l/hr on day 277 to 1,0 l/hr on day 292. On days 292 and 293, a large increase in gas rate to 1,5 l/hr occurred, corresponding to an extra large surge in the load rate after which the gas production decreased to 1,35 l/hr on day 296. Overnight on days 296/297 a maximum gas production of 1,75 l/hr was observed, followed by a very sharp drop to 0,42 l/hr during day 297 when the feed dropped to 75 mg OA/hr. When loading was resumed at a higher level than before the drop, the gas rate only increased back to 1,4 l/hr and then dropped to 0,6 l/hr when the feed was stopped on day 301. The methane content of the gas also fluctuated considerably during this period, averaging 62% during days 275 to 285, increasing to 73% on day 288 and then dropping to 62% on day 289. After this it averaged 63%, gradually dropping to 56% on day 301. The acids concentration at sample point 4 showed an overall rise, with concentrations of 675 mg/l on day 275, 820 mg/l on day 281, 1 100 mg/l on day 288, 2 200 mg/l on day 298 and 2 300 mg/l on day 301. The alkalinites at the same times were 2 650 mg/l, 2 870 mg/l, 3 210 mg/l, 5 110 mg/l and 5 440 mg/l respectively. The pH at the bottom of the filter started at 6,5 on day 275; rose to 6,6 on day 281, 6,8 on day 288 and then dropped to 6,4 on day 298 before rising to 6,7 on day 301. Reductions in OA during this period varied from 67% on day 281 to 68,9% on day 287 and 72,4% on day 294. Corresponding COD reductions were: 56,3% on day 281; 53,2% on day 287 and 58,4% on day 294.

feed stopped until day 353. At these loading rates the hydraulic retention times varied between 60 and 45 hours. The gas productions followed the same pattern as the loading rates, increasing from 0,36 1/hr on day 344 to 0,62 1/hr on day 347, down to 0,56 1/hr on day 349 and finally up to 0,68 1/hr overnight on days 351/352 before dropping to 0,38 1/hr overnight on days 352/353 with the cessation of feed. The proportion of methane in the gas dropped from 60,5% on day 344 to 56,9% on day 347 and remained at that level until day 352 when it increased to 64,2%. The volatile acids concentration at sample point 4 during the same period stayed near 1 750 mg/l over days 344 to 347 and then increased to 2 100 mg/l on day 350. The alkalinities at the same times were 4 710 mg/l; 4 450 mg/l and 3 820 mg/l; while the alkalinity of the feed was maintained at 2 500 mg/l by adding sodium bicarbonate in the required amounts. The pH during this time remained above 6,8, while effluent strengths corresponded to 67,4% reduction in OA (52,4% COD) on day 345 and 64,9% in OA (52,4% COD) on day 350.

B.2.27. Filter II : Days 343 - 353 : Wide Fluctuations in Load

Filter II was still being fed by the metering pump over this period and feed rates fluctuated widely, despite the higher flow rates, which should have allowed better control. The load rate varied from a peak of 780 mg OA/hr on day 344 to 550 mg OA/hr overnight on days 344/345 to average 700 mg OA/hr over days 345 to 350 and then increased to 1 330 mg OA/hr on day 352 after which the feed stopped. The overall level of loading was generally higher over this period than that to Filter I, but the gas production, while following the same pattern as that from Filter I, was some 15% less. The production increased from 0,42 1/hr on day 344 to 0,62 1/hr on day 351 and then dropped to 0,32 1/hr on day 352. Gas analyses showed 58% methane on day 344, 53,6% on day 346, increasing to 57,7% on day 347, dropping again to 56% on day 351 and 53% on day 352. Acids concentrations at sample point 4 stayed at an average of 1 750 mg/l over the whole period, with alkalinities of 4 560 mg/l on day 344, 4 600 on day 347 and 3 230 mg/l on day 350, while the alkalinity of the feed dropped from 2 920 mg/l on day 347 to 2 560 mg/l on day 350. The pH at

the bottom of the filter dropped steadily from 7,0 on day 340 to 6,6 on day 350. With loadings fluctuating so rapidly and widely from steady state, the reductions in OA or COD measured do not reflect true operation at any one level.

B.2.28. Filter I : Days 353 - 389 : Increasing Feed Strengths & Loadings

Filter I continued to be fed by the aspirator feeding device from day 353 through to the end of the period of operation on day 392. Feeding commenced on day 353 at a loading rate of 720 mg OA/hr with a feed of 5 320 mg OA/l, (14 900 mg COD/l) and an alkalinity of 2 500 mg/l, corresponding to a retention time of 58 hours. The volumetric feed rate increased until by day 357, the loading was 1 100 mg OA/hr and the retention time 38 hours. With new feed with a concentration of 6 500 mg OA/l (17 700 mg COD/l) and alkalinity of 2 830 mg/l, loading started at 680 mg OA/hr on day 358, rapidly increasing to 1 340 mgOA/hr by day 360 and dropping again to 1 120 mg OA/hr over days 361 to 363, before dropping to 520 mg OA/hr overnight on days 364/365 . Retention times varied from 80 hours to 40 hours. New feed of 7 500 mg OA/l (20 500 mg COD/l) and 2 030 mg/l alkalinity was used from day 365 with loading starting at 920 mg OA/hr and increasing steadily with small variations to 1 360 mg OA/hr on day 376. The feed strength was increased to 9 170 mg OA/l (25 100 mg COD/l) on day 371. By day 377 the load rate had decreased to 1 180 mg OA/hr and jumped to 1 880 mg OA/hr on day 378 when new feed with an OA of 10 900 mg/l (38 500 mg COD/l) was made up, before dropping back to an average increasing from 1 450 mg OA/hr on day 379 to 1 600 mg OA/hr on day 384. Overnight on days 384/385 the feed dropped to zero, but on day 385 Filter I received a shock load of 10 400 mg OA/hr for 4,75 hours when the feed device leaked. The feed was then stopped until the following day (386) when loading was resumed at 1 600 mg OA/hr, dropping steadily to 1 200 mg OA/hr on day 389.

In general, the gas production pattern followed that of the load rate, starting at 0,62 1/hr on day 353, increased to a peak of 1,06 1/hr overnight on days 374/375. A sharp drop occurred to 0,37 1/hr on day 386 when the feed stopped but the gas rate increased again to 0,86 1/hr

on day 388. The methane content of the gas rose and fell as expected with changing gas rates and varied between 53% and 63%. On day 378 the confining liquid in the Orsat apparatus used for analyses was changed from mercury to acidified water, and this gave a methane content of 48% on day 379, from 53% on day 378. The methane content as measured dropped to 46% on day 382 but increased to 57,5% on day 386 before dropping back to 48% on day 387. The acids concentration at sample point 4 showed very wide fluctuations, starting at 2 020 mg/l on day 354, increasing to 2 950 mg/l on day 361, dropping to 2 480 mg/l on day 365 and 1 930 mg/l on day 367 before increasing to 4 000 mg/l on day 375 and 5 190 mg/l on day 381, while alkalinities at the same times were: 4 360 mg/l, 4 600 mg/l, 4 560 mg/l, 4 730 mg/l, 4 490 mg/l and 3 540 mg/l respectively. The pH at the bottom of the filter also varied considerably. On day 354 the pH was 6,7 and this dropped steadily to 6,1 on day 367 after which it increased to 6,6 on day 372 and then dropped to 5,5 on day 381. Effluent strengths showed reductions of 70,4% OA (53,5% COD) on day 358; 66,3% OA (49,4% COD) on day 367; 65,2% OA (47,9% COD) on day 372 and 54,4% OA (48,7% COD) on day 381.

B.2.29. Filter II : Days 353 - 389 : Fluctuating Loads

The metering pump used to feed Filter II was changed on day 353 for an aspirator feeding device and this started loading at 900 mg OA/hr with feed with an OA of 5 140 mg/l (14 100 mg COD/l) and alkalinity of 2 480 mg/l, while the retention time was 45 hours. By day 357 this had increased to 1 350 mg OA/hr and dropped again to 680 mg OA/hr on day 358 with retention times dropping to 30 hours and increasing again to 62 hours. By day 361 the loading had increased to 1 100 mg OA/hr, but this had dropped back again to 500 mg OA/hr by day 364. At this time the strength of the feed was increased to 5 780 mg OA/l (16 000 mg COD/l) while the alkalinity dropped to 2 040 mg/l. By day 374 the loading rate had increased steadily to 1 100 mg OA/hr with an increase in feed strength on day 371 to 7 740 mg OA/l (20 800 mg COD/l). Retention times during this period averaged 60 hours. After a drop to 970 mg OA/hr on day 375 the load rate increased again to 1 120 mg OA/hr on day 376 before dropping

to 920 mg OA/hr overnight on days 377/378. The feed strength was again increased, this time to 9 050 mg OA/l (38 500 mg COD/l) and loading resumed on day 378 at 1 320 mg OA/hr. This rapidly dropped to 720 mg OA/hr on day 380, however, before increasing to average 1 150 mg OA/hr over days 381 to 386. Retention times at this stage averaged 65 hours. On day 387 the load rate dropped back to 900 mg OA/hr. Once again the gas production pattern followed the loading rate pattern in general tendencies. On day 354 the gas rate was 0,52 l/hr and this increased to 0,65 l/hr on day 356 before dropping to 0,5 l/hr on days 357 to 359. By day 362, the gas rate had increased to 0,58 l/hr, but then dropped again to 0,3 l/hr on day 364 From day 365 to days 373/374, the average gas rate increased from 0,46 l/hr to 0,65 l/hr, but on day 374 the gas rate jumped to 0,86 l/hr and then dropped steadily to reach 0,55 l/hr overnight on days 379/380. From day 380 to days 385/386 the gas rate averaged 0,64 l/hr and then dropped to 0,43 l/hr on day 386, but increased again to 0,52 l/hr on day 387. The methane content of the gas averaged 56,5% over the period days 357 to 378, with a slight increase to 59,5% on day 365 when the gas rate had dropped appreciably. When the mercury in the Orsat apparatus was changed to acidified water, the methane content as measured dropped to 51% on days 379 and 380 and to 49% over days 382 to 387. The acids concentration at sample point 4 dropped at first from 1 750 mg/l on day 354 to 1 350 mg/l on days 365 and 367. By day 375 the acids concentration had increased to just over 4 000 mg/l, but by day 381 the concentration had dropped again to 3 200 mg/l. The alkalinities at the same times were: 4 240 mg/l, 4 850 mg/l, 4 460 mg/l, 4 380 mg/l, 4 000 mg/l, and 3 540 mg/l on day 381. The pH at the bottom of the filter dropped steadily from 6,9 on day 354 to 6,1 on day 381. Effluent strengths during this period reflected reductions of 62,4% OA (43,2% COD) on day 358; 61,1% OA (47,5% COD) on day 367; 60,8% OA (45,2% COD) on day 372 and 47,3% OA (36,4% COD) on day 381.

B.2.30. Filters I and II : Day 389 : Flushing

At this stage it became obvious that both Filters I and II were badly clogged with sludge, resulting in much short-circuiting of waste through channels in the packing, as was shown by low points in the COD profiles

up the filters, as well as excessive carryover of suspended solids in the effluent. The suspended solids in the effluents from the filters were measured on day 388. The effluent from Filter I contained 575 mg/l of which 87% were volatile, while that from Filter II contained 500 mg/l suspended solids of which 87% were volatile. In order to break up the dense pockets of sludge which were causing the short-circuiting and to remove some of the excess sludge in the filters both were flushed on days 388 and 389 with strong flows of tap water and spurts of nitrogen gas. Considerable difficulty was experienced in breaking up the sludge pockets because they had been allowed to settle over a long period, but satisfactory flow patterns were finally obtained. Large quantities of sludge were removed from each filter, but the packing and voids still contained a good covering of sludge when feeding was resumed.

B.2.31. Filter I : Days 389 - 394 : Restart

Filter I was started up late on day 389 at the same loading as before flushing, 1 620 mg OA/hr but this dropped to 1 400 mg OA/hr by day 390, and the feed was stopped on day 392. Gas productions started at 0,52 l/hr late on day 389 and increased to 0,65 l/hr on day 391/392 before dropping to 0,4 l/hr on day 393 after which no further readings were taken. The methane content of the gas started at 47,5% on day 390 but dropped to 36,5% on days 391 and 392 before increasing to 63% on day 393. The pH as measured at sample point 1 on day 392 was 5,7 while the acids concentrations were measured at sample points 1, 4 and 9 on day 392 and these were respectively 6 500 mg/l, 7 410 mg/l and 5 920 mg/l. This was the reason for stopping the feed as it was apparent that very little methane formation was taking place.

B.2.32. Filter II : Days 389 - 394 : Restart

Filter II was restarted on day 389 at a loading of 1 040 mg OA/hr and this increased to 1 100 mg OA/hr on day 390 before dropping to 980 mg OA/hr by day 392. Gas productions started off at 0,5 l/hr on day

389 and this increased to 0,87 1/hr on day 391 and 0,91 1/hr on day 392 while the methane content dropped from 62% on day 390 to 51% on day 391 and 50,5% on day 392. The acids concentrations at sample points 1, 4 and 9 were 6 610 mg/l, 4 490 mg/l and 2 635 mg/l showing better digestion than Filter I, but were still too high. The pH at sample point 1 of 5,4 was a further indication that the filter was being loaded too highly, and so feeding was stopped on day 392.

B.3. DETAILED REPORT OF OPERATION, FILTER III

B.3.1. Filter III : Days 213 - 224 : Start-up

On day 213 a third filter was brought into operation. This filter was identical to Filters I and II in construction, except that it was 0,11 m higher and was equipped with a peristaltic pump to circulate part of the contents of the filter as described in Chapter 3. The purpose of the circulation was to try to determine whether it would be possible to use the alkalinity generated during the digestion process to buffer the liquid in the filter, so that it would not be necessary to add base to the feed. As initially set up, the circulation pump withdrew liquid from sample point 9, passed it through a mixing box which had provision for monitoring the pH and adding buffer if necessary and finally returned the liquid to the bottom of the filter, where it joined fresh feed flowing to the filter. The filter was seeded with approximately 6 l. of digesting sewage sludge from the Athlone digesters and loading started at 570 mg OA/hr late on day 213. The feed used had an OA of 5 400 mg/l (15 200 mg COD/l) with a retention time of 73 hours based on raw feed, while the ratio of the circulation flow to the feed rate was approximately 300 : 1. The quality of the seed sludge was felt to be less than optimum, however, since the initial gas production rate (before commencement of feed) was only 0,17 1/hr, whereas fresh sludge from the same source as dosed into Filter II on day 161 had a gas production rate of 0,55 1/hr. Further, the seed sludge for Filter III had an odour more characteristic of raw sewage solids than digested sludge. The loading rate fluctuated widely

over days 213 to 223, with a maximum of 690 mg OA/hr on day 218 and minimum of 480 and 460 mg OA/hr on days 214 and 217 respectively. On day 217 the feed strength was reduced to 2 720 mg OA/1 (7 630 mg COD/1) and the flow rate increased to give a retention time of 33 hours in an attempt to obtain more constant loading rates. The loading decreased from 690 mg OA/hr on day 218 to 500 mg OA/hr overnight on days 223/224, when the feed pump broke down. Problems were also experienced with the circulating pump during this period. On day 217 the silicone rubber tubing used in the pump fractured and approximately 1 1. of sludge leaked out into a drip tray. This was replaced in the filter and operation resumed. On day 218, however, the tube cracked again, and 3 1. of sludge leaked out. This was again replaced in the filter and the circulation ratio dropped to approximately 100 : 1.

B.3.2. Filter III : Monitoring of pH

During the first few days of operation, the pH of the circulating liquid was monitored at the mixing box and lime water added whenever the pH fell below about 6,9. The pH tended to drop rapidly, however, and overnight dropped as low as 5,0; necessitating up to 1,5 1 of lime water to bring the pH to between 7,3 and 7,4. The feed at this time was not buffered in any way and had a pH near 5,0 with the alkalinity near 300 mg/1 The gas production over the whole period days 213 to 224 averaged 0,16 1/hr with maxima and minima of 0,22 1/hr and 0,12 1/hr on days 215 and 219 respectively. The methane content of the gas fell continuously from 82,7% on day 216 to 81,1% on day 221 to 66,1% on day 226. On day 220 the acids concentrations at several points up the filter were all between 1 320 and 1 380 mg/1 while the alkalinity was between 2 150 and 2 300 mg/1.

B.3.3. Filter III : Days 224 - 231 : No Circulation

The filter was started again on day 224 and the loading averaged 450 mg OA/hr until day 230. The circulating pump tube had broken again on day 223, resulting in approximately 2 1. of sludge leaking out. This was replaced, but the circulating pump was taken out of service for modifications.

The gas rate up until day 230 averaged 0,18 1/hr with a peak of 0,25 1/hr on day 225, but this average rate was only about 0,6 of that from Filters I and II at the same time, which were being loaded at about 350 mg OA/hr.

B.3.4. Day 231 : Effective Division of Filter III into 3 Sections and Fresh Sludge

On day 231 it was decided to change the circulation system so that liquid was withdrawn from sample point 4, passed through the mixing box and was returned to the filter at sample point 9. In this way it was hoped that the bottom section of the Filter - up to sample point 4 - would effectively produce only acids. The liquid leaving this section would then pass through the mixing box where the pH could be adjusted to the optimum for the methane forming bacteria, and in this way the middle, circulated section, would be used for methane fermentation. The effluent would pass through a short section of packing at a low rate, where it would receive a final polishing and excess solids would be trapped. In order to install this system, it was necessary to enlarge sample point 4 and so the filter was drained down to this level. Since the sludge had been gassing so poorly, it was also decided to replace the removed sludge with fresh sludge from the Athlone digesters. The filter was started again late on day 231 at a loading of 450 mg OA/hr, using lime water to adjust the pH to approximately 7,2. The gas rate, however, started at 0,08 1/hr overnight on days 231/232 and dropped steadily to 0,03 1/hr on day 233. Since these low gas rates indicated that the sludge had all but died, it was drained from the filter on day 233 and replaced with fresh sludge from the Athlone digesters. This fresh sludge still had the raw sewage odour noticed with first batch of seed sludge.

B.3.5. Filter III : Day 233 : Fresh Seed Sludge and its Decline

This fresh seed sludge started gassing initially at 0,22 1/hr date on day 233 and this increased to 0,27 1/hr overnight before dropping rapidly to 0,14 1/hr on day 235. Up to this time lime water had been used to adjust the pH, but large quantities were required (of the order

of 1 1.) and these had to be administered every few hours, with the result that the pH fell to very low values overnight when no control could be maintained. On day 235 it was suspected that the lime itself might be inhibitory to the methane formers, so the addition of lime was stopped. (The use of lime is discussed in Chapter 4, Section 4.4.4.) The gas rate continued to decrease, however, but less rapidly than before, reaching 0,055 1/hr on day 238. This further decrease was probably caused by the pH of less than 6,5 existing in the filter, since the loading rate over this period (days 234 to 238) averaged 500 mg OA/hr with a retention time of 41 hours. The extremely low gas rates indicated the necessity for fresh sludge.

B.3.6. Filter III : Day 238 : Fresh Seed Sludge and the Finger Pump Installed

Late on day 238, Filter III was seeded with fresh seed sludge from the digesters at Athlone, and this sludge had an odour more characteristic of digested sludge. The initial gas rate was 0,43 1/hr, confirming that this fresh seed did have a good population of active methane forming bacteria. The load rate averaged 700 mg OA/hr over days 239 to 242, but from then until day 252 it dropped back to average 360 mg OA/hr after the "finger" type peristaltic feed pump was installed on day 243. The feed used from day 238 onwards had an average OA of 2 500 mg/1 (7 000 mg COD/1) and had 1,25 g/1 of sodium bicarbonate added to it to provide the correct alkalinity. If the pH in the mixing box dropped, further sodium bicarbonate solution was added to maintain the pH above 7,0. The gas rate reached a peak of 0,47 1/hr on day 241 and then dropped to average 0,3 1/hr over days 246 to 252. The methane content of the gas started at 70,4% on day 240, dropped to 66,7% on day 242 and then increased to 72,4% on days 244 and 246 before dropping steadily to average 66% near day 270. On day 245, the pH at sample point 3, near the top of the acid-forming section of the filter was 6,6 while the pH of the circulated section was 7,5 and that of the top, clarifying section, 7,4. The corresponding acids concentrations at these points showed that this filter was working as desired, with concentrations of 2050, 540 and 520 mg/1 respectively, while the alkalinities were 2 410, 4 280 and 4 480 mg/1.

When the finger pump and new feed lines were installed on day 242, the same problem occurred as with Filter I - namely one of the joints on the feed lines failed and about half the sludge in the filter leaked out into the drip tray. This was recovered and returned to the filter within a short while.

B.3.7. Filter III : Day 252 : Large Shock Load

Late on day 252 a pump fault caused the contents of all three feed tanks, approximately 40 l in all, to run straight through Filter III. This rapid flow of feed flushed out a quantity of the sludge from the filter but by the following day, with no further feed, the acids concentrations had dropped to 600 mg/l at sample point 3 while the concentration in the circulated section had increased to 900 mg/l. Feeding was resumed on day 253 at an average of 340 mg OA/hr and this was maintained until day 260. Gas rates fluctuated about 0,32 l/hr over days 252 to 256 before dropping to average 0,26 l/hr until day 259. By day 260, the acids concentrations had reverted to their normal profile after the upset caused by the shock load, and the concentrations in the three sections up the filter were 1 600 mg/l in the acids section and 405 and 430 mg/l in the circulated and settling sections respectively, while the corresponding pH's were 6,5; 7,0; and 7,0.

B.3.8. Filter III : Days 260 - 274 : Large Increase in Load Rate

From 340 mg OA/hr on day 260 the loading rate started to increase and by day 263 had reached a peak of 650 mg OA/hr before dropping back to average 500 mg OA/hr on days 264 to 268, after which the load rate increased to 800 mg OA/hr over days 268 to 272 before increasing to 970 mg OA/hr on day 273 and then dropping to zero on day 274. On day 263 the feed concentration to Filter III was increased to 3 170 mg OA/l (8 890 mg COD/l) from the average of 2 500 mg OA/l (7 000 mg COD/l) which had been used up to this time. At the same time the amount of sodium bicarbonate added as buffer was increased from 1,25 g/l to 1,5 g/l. The average retention time was 45 hours, for both feed strengths.

The gas rate increased steadily from 0,26 l/hr on day 259 to 0,49 l/hr on day 262 and then dropped to 0,40 l/hr on day 267. It then increased to 0,70 l/hr on day 269, dropped to 0,52 l/hr on day 271 and finally increased to 0,75 l/hr on day 274 before dropping to 0,16 l/hr on day 275 when the feed stopped. The acids concentration in the acids section decreased gradually from 1 570 mg/l on day 262 to 1 360 mg/l on day 267 and 1 210 mg/l on day 275, while the acids concentration in the circulated section increased from 480 mg/l on day 262 to 635 mg/l on day 275, with the respective pH's fluctuating about 6,6 and 7,0. The reductions in OA effected during this period rose from 60,2% on day 245 to 70,3% on day 261 and 77,2% on day 273, with corresponding COD reductions of 40,0% 55,1% and 65,5%, while the feed concentrations rose to average 3 600 mg OA/l (10 000 mg COD/l) until day 283. The circulation ratio during this period was maintained at near 80 : 1.

B.3.9. Filter III : Days 275 - 298 : Increasing Feed Strengths

After being loaded at only 170 mg OA/hr on day 275 because of a pump blockage, the load to Filter III increased to 1 090 mg OA/hr on day 276 but then overnight on days 276/277 a shock load of some 24 l of feed passed through the filter within half an hour. Loading was stopped after this and resumed again on day 278 at an average of 700 mg OA/hr until day 282. The gas rates and methane content of the gas fluctuated widely with the varying loading rates, but settled down to 0,63 l/hr and 68% respectively over days 280 to 282. The acids concentrations, however, jumped to 2 000 mg/l in the acids section on day 281, while in the circulated section the concentration was 500 mg/l with pH's of 6,4 and 7,0 respectively. The alkalinities in the two sections were 2 680 and 3 250 mg/l respectively. The load rate increased from 700 mg OA/hr on day 282 to 1 000 mg OA/hr by day 290 and 1 150 mg OA/hr by day 298, while the feed concentration was increased on day 282 to 3 950 mg OA/l (11 100 mg COD/l) with 1,5 g/l of sodium bicarbonate added to 4 730 mg OA/l (13 300 mg COD/l) with 1,5 g/l of sodium bicarbonate on day 287 and 5 320 mg OA/l (14 900 mg COD/l) on day 291. On day 294 the feed concentration was increased to 6 430 mg OA/l (18 100 mg COD/l) with 2 g/l

of bicarbonate, while retention times over the whole period averaged 40 hours. The circulation ratio was maintained near 80 : 1 while the gas rate increased from an average of 0,75 l/hr on day 284 to average 0,88 l/hr over days 288 to 294 and finally to average 1,1 l/hr over days 295 to 299. The methane content of the gas dropped steadily from 68% on day 282 to 62,5% on day 299. The acids concentrations in the acids and circulated sections increased overall to 2 750 mg/l and 1 100 mg/l respectively on day 298, while the pH's were 6,7 and 7,2 at the same times. The reductions in OA effected during this period were 67,8% on day 281 and 69,4% on day 294 with COD reductions of 51,4% and 53,8% respectively.

B.3.10. Filter III : Days 299 - 316 : Erratic Loads, Very High Acids Concentrations

From a rate of 1 150 mg OA/hr on day 298, the loading increased to 1 580 mg OA/hr on day 300 and then dropped to zero on day 301. Until day 308 the load rate was very erratic, but averaged 1 100 mg OA/hr. After dropping to zero on day 308, loading recommenced at an average of 1 450 mg OA/hr, dropping down to 1 300 mg OA/hr by day 316. The feed was then stopped because on day 315 the acids concentrations in the acids and circulated sections were 7 500 mg/l and 8 900 mg/l respectively, while the pH's were 6,6 and 6,8. The gas production over days 301 to 308 averaged 0,95 l/hr rising to an average of 1,27 l/hr on day 310 before dropping to 1,15 l/hr on day 316. The methane content of the gas averaged 60%.

B.3.11. Filter III : Days 316 - 353 : Very Erratic Operation

From day 316 to day 356 the load rate to Filter III fluctuated very widely, with many stops and starts. The gas production also fluctuated in accordance with the load rates, while the methane content rose as the gas production fell. The acids concentrations dropped from their extremely high levels of day 315 to near 900 mg/l in both sections by day 318, and the pH increased to 7,5 and 7,6 in the acids and circulated sections. The metering pump was brought into operation on day 332, but the fluctuations in the load rate persisted because of blockages in the valves.

B.3.12. Filter III : Days 353-362: Aspirator Feeding Device, Steady Flows

On day 353, the aspirator feeding device was put into operation and after an initial series of fluctuations it settled down and from day 358 to day 361 delivered an average of 710 mg/OA/hr with small fluctuations. The feed concentration was 5 310 mg OA/l (14 700 mg COD/l) and the alkalinity of the feed was 3 060 mg/l. The gas rate averaged 0,52 l/hr with 61% methane. The acids concentrations on day 359 in the acids and circulated sections were 2 420 and 1 710 mg/l respectively while on day 361 these concentrations were 2 150 and 1 880 mg/l respectively. The alkalinities at the same times were 4 380 and 4 840 mg/l and 4 830 and 5 000 mg/l respectively. The pH of the circulated section stayed at 7,1 while that of the acids section rose from 6,8 to 7,0. The circulation ratio was maintained at about 100 : 1 and the reductions in OA and COD effected were 58% and 51% respectively.

B.3.13. Filter III : Days 362 - 375 : Erratic Increases in Load Rates

From day 362 the load rate was increased by increasing the feed strength to 7 490 mg OA/l (20 400 mg COD/l) and the alkalinity was reduced to 2 000 mg/l in the feed. The load rate increased steadily from 630 mg OA/hr to reach 1 270 mg OA/hr by day 374, except for days 366 and 367. On day 366 a leak developed in the aspirator and all the feed left in the tank (some 13 l) ran through the filter in a short time. The load dropped to zero after this and was restarted again on day 367 with the feed strength increased to 9 180 mg OA/l (23 300 mg COD/l) with 2 000 mg/l alkalinity. The circulation ratio was maintained at about 100 : 1 except during days 371 to 373 when the pump was stopped for further modifications. The gas production rates increased from 0,55 l/hr on day 362 to average 0,95 l/hr on day 374. Considerable fluctuations did occur during this time, however. The methane content decreased from about 60% on day 362 to average 53,1% over days 368 to 374. The acids concentrations in the acids and circulated sections increased to 2 890 and 2 720 mg/l on day 365 and then dropped to 1 030 and 830 mg/l on day 367 after the feed had stopped, but then increased rapidly again

to 3 100 and 3 440 mg/l in the two sections on day 375. The pH of the acids sections dropped from 7,3 on day 367 to 6,5 on day 372 and 6,9 on day 375 while that of the circulated section was 6,8 on day 375. The respective alkalinities on day 375 were 4 810 and 4 330 mg/l while the OA and COD reductions were 64,9% and 40,2% on day 372 respectively.

B.3.14. Filter III : Days 375 - 388 : Metering Pump Installed and Indications of Clogging

On day 375 a reduction gearbox became available for the metering pump, allowing better use of the range of the pump, and this was put into service. After initial fluctuations about 2 000 mg OA/hr on days 376 to 378, the loading settled down to average 1 800 mg OA/hr until day 386, after which it dropped to 1 250 mg OA/hr by day 388. The feed concentration during this period was 10 600 mg OA/l (37 300 mg COD/l) while the alkalinity was about 2 250 mg/l. The gas production increased to a peak of 1,15 l/hr on days 380 and 381 and then declined steadily to 0,85 l/hr on day 389, while the methane content of the gas dropped to an average of 46% with acidified water in the Orsat apparatus. The acids concentrations continued to increase, with the concentration in the acids section reaching 5 000 mg/l on day 381 and that in the circulated section 5 160 mg/l. The pH of both sections was close to 6,7 while the alkalinities were equal at 5 230 mg/l

B.3.15. Filter III : Day 389 : Flushing

As with Filters I and II it became apparent that Filter III was badly clogged, resulting in much short-circuiting of liquid and so on day 389 the filter was flushed with tap water and nitrogen gas, following the same procedure as used for Filters I and II. Before flushing the filter, a suspended solids test was carried out on the effluent, and this revealed 525 mg/l of suspended solids, of which 83% were volatile.

B.3.16. Filter II : Days 389 - 394 : Restart and Final Stoppage

After flushing the filter, loading was started again on day 389 at an average of 950 mg OA/hr. The gas production increased steadily from 0,32 l/hr on day 389/390 to 0,75 l/hr on day 394, after which the filter was stopped. The methane content of the gas between days 391 and 394 averaged 45%. The acids concentrations in the two sections were measured as 4 860 mg/l in the acids section and 3 530 mg/l in the circulated section on day 392. As with Filters I and II, the suspended solids in the effluent after flushing were virtually zero. The pH's of the two sections were 6,3 and 6,7 respectively on day 392. On day 394 the filter was shut down with the investigation at an end.

APPENDIX C

D A I L Y R E S U L T S

C.1. INTRODUCTION

This Appendix gives the daily operating results of the three filters used in the investigation. Tables C.1., C.2., and C.3., give the results for Filters I, II and III, respectively.

The values given in the Tables are the averages of the given quantity over the whole 24 hours from 9.00 a.m. of the day quoted to 9.00 a.m. of the following day. If values given in Appendix B differ from those given in the Tables, this is because the former are peak values measured over periods shorter than the 24 hours of the particular day.

In all of the Tables, two values of the loading rate are given. The first, expressed in mg OA/hr, is the number of milligrams of OA delivered per hour to the whole of the filter, while the second, given in kg COD/(m^3day) is the loading rate expressed as kilograms COD delivered per day per m^3 of void volume of the filter. The gas production rate given in column 4 of all the Tables is the volume of gas produced from the whole filter expressed in litres per hour. In Tables C.1., and C.2., giving the results for Filters I and II respectively, the values given for volatile acids concentration and alkalinity are those measured at sample point 4. The results are given as mg/l as acetic acid and calcium carbonate, respectively. Also in these Tables, the value given for pH is that at sample point 1. In Table C.3., giving the results of Filter III, two values are given for each of volatile acids concentration, alkalinity and pH. The first value in each case is that of sample point 3 in the lower or acid-forming section, while the second value is that of the circulated section. The concentrations are expressed in the same units as those for the other two filters.

TABLE C.1. DAILY RESULTS OF FILTER I

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	GAS Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
1	410							3 600					
2	410												
3	0						5,2						
4	0												
5	0												
6	460							4 000					
7	460												
8	460						6,8						
9	460						5,7						
10	460						5,6						
11	460						7,0						
12	460						6,3						
13	460		0,107										
14	460		0										
15	460		0,084				6,8						
16	950		0,084	26,0				8 220					
17	420		0,021	40,0	7 800	10 450	7,0						
18	420		0,054	43,3									
19	420		0,102										
20	420		0,102										
21	420		0,052										
22	420		0,056	48,5			7,0						
23	420		0,060	55,0	9 000	11 000	7,3						

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA / l	FEED STRENGTH mg COD / l	EFFLUENT STRENGTH mg OA / l	EFFLUENT STRENGTH mg COD / l	% REDUCTION O A	% REDUCTION C O D
24	65		0,032										
25	65		0,021	61,9	7 660	10 200	7,1	2 390		1 460		38,9	
26	65		0,022	59,0	7 580	10 400	7,1						
27	0		0,018										
28	0		0,036										
29	120		0,079	61,8				5 250					
30	133		0,085	69,0	6 860	9 460	7,0						
31	395		0,092	61,6			6,9						
32	535		0,090										
33	400		0,109	75,7	5 850	7 000	7,1						
34	400		0,135										
35	450		0,170	76,2									
36	370		0,211	89,5									
37	320		0,227	91,7	4 910	7 270	7,3						
38	470		0,260	91,7				3 260		1 320		59,5	
39	288		0,320	91,0									
40	274		0,390	83,9	4 020	7 460	7,3						
41	430		0,440	88,3									
42	510		0,460	87,6									
43	460		0,435	87,3	3 120	7 930	7,5						
44	0		0,290	88,1									
45	540		0,290	86,9	3 260	6 840	7,2	3 510		1 180		25,3	
46	465		0,250	83,3			7,2						

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
47	515		0,195	83,7	2 450	6 430	7,3						
48	550		0,172	80,6									
49	550		0,130	80,6									
50	490		0,200	85,1	2 570	6 110	7,4						
51	575		0,282	80,6									
52	545		0,281	81,6	2 790	5 690	7,5						
53	535		0,265	79,6									
54	480		0,270	79,5									
55	500		0,230	83,7									
56	500		0,230										
57	430		0,255		2 480	4 260	7,0	2 620		1 120		57,2	
58	246		0,160	82,1									
59	178		0,170					3 310					
60	740		0,458	84,4									
61	520		0,414	73,6	2 340	4 560	7,2			1 150		65,0	
62	0		0,173										
63	0		0,173										
64	445		0,180	77,0									
65	385		0,299	82,5	2 330	4 520	6,9						
66	410		0,260	79,0									
67	113		0,160	83,0									
68	113		0,160										
69	113		0,160										

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
70	440		0,117										
71	460		0,100	83,7	1 690	4 220	7,2						
72	355		0,084	85,1									
73	315		0,062		1 660	4 170	7,2						
74	315		0,045	85,5				3 300					
75	0		0,150										
76	0		0,150										
77	0		0,150										
78	33		0,048										
79	392		0,210		2 060	4 000	6,8						
80	400		0,283	76,0			6,6						
81	485		0,279	79,3									
82	350		0,212	79,5			6,7						
83	370		0,260										
84	370		0,260										
85	465		0,250	79,0	1 850	3 460	6,9						
86	490		0,230	84,4									
87	385		0,170	84,6									
88	385		0,156										
89	275		0,146	82,5			6,9						
90	300		0,160										
91	300		0,160										
92	330		0,200	81,5	1 430	3 380	6,8						

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA/hr.	RATE kg COD/m³Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA/l	FEED STRENGTH mg COD/l	EFFLUENT STRENGTH mg OA/l	EFFLUENT STRENGTH mg COD/l	% REDUCTION O A	% REDUCTION C O D
93	440		0,250										
94	440		0,232	84,4									
	FILTER DORMANT UNTIL DAY 156.												
156	36	0,29	0,013		410	3 930	7,3	492	1 380				
157	70	0,60	0,022				7,1						
158	105	0,90	0,042		345	2 280	7,1	785	2 200				
159	80	0,61	0,045				6,6						
160	46	0,39	0,043				6,6						
161	74	0,63	0,065	89,3	525	1 330	6,5						
162	78	0,65	0,071				6,7						
163	69	0,57	0,077				6,6						
164	75	0,55	0,120				6,8	785	2 200	605	2 580	22,7	-
165	71	0,59	0,120		440	2 010	6,7	2 000	5 600				
166	173	1,16	0,126				6,6						
167	176	1,18	0,130				6,7						
168	144	0,96	0,090	82,5			6,7						
169	130	0,87	0,103										
170	129	0,87	0,097		840	2 740	6,8						
171	110	0,74	0,098	79,0									
172	250	1,67	0,118					1 600	4 500				
173	200	1,39	0,131										
174	180	1,28	0,129										

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
175	160	1,19	0,128										
176	141	1,04	0,130	71,0				1 580	4 430	975	4 130	38,2	6,77
177	159	1,05	0,135		710	2 560	6,9						
178	145	0,94	0,125										
179	148	0,97	0,125	74,6									
180	192	1,26	0,130										
181	183	1,21	0,146										
182	122	1,07	0,146		635	2 230	7,0	1 510	4 230	905	3 840	39,8	9,23
183	173	1,06	0,153	71,8									
184	190	1,16	0,161										
185	184	1,16	0,165	82,6				1 260	3 530				
186	165	0,87	0,161										
187	155	0,84	0,137										
188	132	0,73	0,140	82,0									
189	130	0,79	0,128										
190	90	0,60	0,150		990	1 940	7,0	2 110	5 910				
191	197	1,69	0,158							850	3 600	32,8	39,0
192	168	1,52	0,135	79,3				1 960	5 500				
193	160	1,35	0,150										
194	187	1,57	0,112					2 130	5 970				
195	187	1,57	0,136										
196	182	1,67	0,145	76,5	700	2 620	7,0	2 210	6 190	845	3 580	60,3	40,0
197	181	1,66	0,140										

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA/hr.	RATE kg COD/m³Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA/l	FEED STRENGTH mg COD/l	EFFLUENT STRENGTH mg OA/l	EFFLUENT STRENGTH mg COD/l	% REDUCTION O A	% REDUCTION C O D
.98	162	1,40	0,148				7,0						
199	218	1,83	0,166	74,6	720	2 640	6,7	2 210	6 210	920	3 900	57,3	37,0
200	216	1,81	0,150										
201	200	1,68	0,165										
202	200	1,68	0,165										
203	160	1,25	0,127		675	2 650	7,0	1 990	5 590	975	4 130	55,1	33,5
204	190	1,65	0,133	71,5									
205	186	1,59	0,147										
206	186	1,60	0,151										
207	140	1,31	0,145	76,8	500	2 600	6,7						
208	177	1,66	0,129					2 120	5 960				
209	135	1,27	0,140										
210	180	1,70	0,152										
211	202	1,68	0,163	75,3				2 500	7 000	1 040	4 410	51,1	25,9
212	205	1,70	0,127					2 000	5 500				
213	151	1,23	0,113	80,6									
214	120	0,98	0,124										
215	187	1,53	0,145										
216	167	1,37	0,137	76,8									
217	180	1,50	0,134					2 110	5 930				
218	100	0,87	0,126										
219	330	2.70	0,153	74,5	420	2 520	6,9	2 100	5 910				
220	500	4,25	0,226		930	2 290	6,8						

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
221	465	3,90	0,260	67,7				2 010	5 630	930	3 940	55,9	-
222	424	3,56	0,306										
223	161	1,36	-	69,5									
224	279	2,35	0,191										
225	365	3,05	0,241					1 710	4 790				
226	363	2,99	0,251	77,0	930	2 530	6,9	1 960	5 500	810	3 440	58,6	49,2
227	350	2,87	0,269										
228	397	3,14	0,266	71,0									
229	366	2,89	0,258										
230	262	2,19	>0,19					2 050	5 750				
231	373	3,11	0,232	79,3									
232	336	2,80	0,263		955	2 050	6,5			880	3 730	57,0	35,1
233	381	3,13	0,297	71,0					1 970	5 530			
234	400	3,25	0,360										
235	372	3,10	0,317	67,0						775	3 290	60,6	40,6
236	417	3,46	0,343					1 990	5 570				
237	412	3,42	0,297	67,7									
238	370	3,10	0,305										
239	498	4,13	0,316	70,0	610	1 910	6,4	1 910	5 340				
240	476	3,98	0,342	71,0						730	3 100	61,6	42,0
241	504	4,15	0,378										
242	250	2,20	0,318	68,5				1 950	5 460				
243	228	1,90	0,440	NEW	SLUDGE								

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
244	220	1,83	0,349	82,1									
245	229	1,91	0,303		515	2 130	6,4			670	2 840	65,2	47,9
246	212	1,77	0,243	74,9				2 040	5 710				
247	216	1,81	0,250										
248	224	1,87	0,223	74,9						725	3 080	64,5	46,2
249	273	2,28	0,230										
250	188	1,57	0,227										
251	222	1,86	0,230	73,2				2 010	5 640				
252	182	1,48	0,220					1 920	5 380				
253	279	2,26	0,228				6,7						
254	209	1,69	0,235	71,8	440	2 030							
255	216	1,75	0,236										
256	361	2,92	0,220	72,0						670	2 840	65,0	47,2
257	258	2,09	0,220										
258	258	2,09	0,225										
259	234	1,95	0,235	73,5				2 530	7 100				
260	316	2,64	0,310		300	2 280	6,5						
261	400	3,25	0,340	71,6						740	3 140	70,5	55,8
262	412	3,44	0,397	71,3	640	2 340	6,5						
263	466	3,90	0,440	72,0				2 620	7 350	845	3 580	66,5	49,5
264	363	3,04	0,393	71,8									
265	376	3,14	0,370	71,2									
266	356	2,97	0,375										

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD RATE mg OA / hr.	LOAD RATE kg COD / m^3 Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
267	349	2,91	0,370	68,1	475	2 530	6,7	2 930	8 210				
268	508	4,24	0,380	71,0						820	3 480	72,0	52,7
269	494	4,13	0,470	70,5									
270	0	0	0,470	69,8									
271	541	4,51	0,500	71,6				3 110	8 710				
272	548	4,57	0,510	69,8									
273	-	-	0,345	69,7						910	3 860	70,7	55,7
274	715	5,98	0,542	77,2				3 580	10 000				
275	780	6,52	0,670	67,7	1 170	2 710	6,2						
276	514	4,43	0,593	62,3									
277	0	0	0,170	68,7				3 250	9 130				
278	510	4,25	0,500	81,0									
279	686	5,74	>0,3										
280	684	5,72	0,640	62,5									
281	634	5,30	0,670	66,7	920	3 010	6,6			860	3 650	73,6	60,1
282	831	6,95	0,670	68,3									
283	810	6,77	0,710	67,3				3 650	10 200				
284	895	7,45	0,740	65,1									
285	895	7,45	0,691	65,1									
286	0	0	-										
287	956	7,67	0,631	75,0				4 400	12 400	1 140	4 830	68,7	52,8
288	937	7,52	0,780	65,7	875	3 540	6,4						

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA / l	FEED STRENGTH mg COD / l	EFFLUENT STRENGTH mg OA / l	EFFLUENT STRENGTH mg COD / l	% REDUCTION O A	% REDUCTION C O D
289	926	7,75	0,820	61,7									
290	887	7,43	0,845	63,8									
291	1 080	9,00	o,874	63,9									
292	1 010	8,43	0,814	63,1									
293	984	8,22	0,829										
294	1 150	9,58	0,838	64,2				5 920	16 600	1 490	6 320	69,7	38,3
295	1 130	9,49	1,09	60,3									
296	1 170	9,80	1,08	62,7									
297	1 100	9,18	1,08	61,6									
298	1 140	9,47	0,998	61,6	1 870	4 350	6,2						
299	2 920	24,5	1,14	61,6				5 970	16 800				
300	2 040	17,1	-										
301	1 690	14,1	0,841	46,9	2 070	4 480	6,7						
302	300	2,50	0,592	59,8									
303	1 370	15,1	0,87	73,4				6 000	16 800				
304	1 200	10,1	0,915	60,7						1 880	7 970	68,7	52,7
305	1 290	10,8	0,93	58,0									
306	1 190	9,92	-										
307	1 190	9,92	-										
308	1 490	12,4	1,00	56,0				7 440	20 900				

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA / l	FEED STRENGTH mg COD / l	EFFLUENT STRENGTH mg OA / l	EFFLUENT STRENGTH mg COD / l	% REDUCTION O A	% REDUCTION C O D
309	1 550	12,9	1,10	54,9									
310	1 900	15,9	1,15	54,9									
311	650	5,25	0,910	54,9									
312	1 170	9,50	1,09	56,9									
313	1 400	11,6	1,12	53,0				7 300	20 300	2 870	12 200	61,2	48,4
314	1 420	11,8	>0,8										
315	1 370	11,3	1,12		5 800	5 870	6,4						
316	0	0	0,410	53,0									
317	0	0	0,161	73,2									
318	165	1,40	0,240		940	7 000	7,5						
319	1 120	9,32	0,525	69,1									
320	1 120	9,32	>0,4										
321	0	0	0,240	51,5									
322	0	0	0,240										
323	685	5,78	0,386	73,0				7 620	21 600				
324	980	8,29	0,469	58,0									
325	1 110	9,39	0,850	49,5									
326	851	7,20	0,549	47,4									
327	788	6,64	-	50,5									
328	788	6,64	-										

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
329	0	0	-										
330	0	0	-										
331	0	0	-										
332	386	3,13	0,27					6 770	18 300				
333	180	1,45	0,455	56,9	1 870	6 350	6,5						
334	40	0,35	0,416										
335	0	0	0,130										
336	197	1,59	0,126	63,3									
337	800	6,45	0,495		2 360	4 960							
338	141	1,14	0,362										
339	219	1,80	0,220	65,2				1 990	5 490				
340	830	6,78	0,350		1 020	5 050	7,3			1 140	3 610	43,0	34,4
341	270	2,20	>0,4										
342	0	0	-										
343	380	3,20	0,358					3 940	11 100				
344	553	4,65	0,432	60,5	1 760	4 710							
345	608	5,12	0,470										
346	746	6,28	0,550	58,0						1 290	5 300	67,4	52,4
347	780	6,56	0,590	56,9	1 780	4 450	7,2						
348	660	5,83	0,559					4 150	12 200				
349	639	5,62	-										
350	755	6,64	0,570		2 100	3 820	6,9			1 460	5 830	64,9	52,4
351	823	7,14	0,670	57,1						1 490	6 390	64,0	47,9

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA/hr.	RATE kg COD/m³Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA/1	FEED STRENGTH mg COD/1	EFFLUENT STRENGTH mg OA/1	EFFLUENT STRENGTH mg COD/1	% REDUCTION O A	% REDUCTION C O D
352	789	6,93	0,388	64,2									
353	710	5,90	0,622					5 320	14 900				
354	780	6,60	0,580	63,0	2 020	4 360	6,8						
355	900	7,55	>0,55										
356	1 030	8,65	>0,66										
357	1 110	9,24	0,794	56,9									
358	770	6,24	0,740					6 500	17 700	1 920	8 230	70,4	53,5
359	939	7,59	0,740	56,9	2 880	4 620	6,6						
360	1 340	10,8	0,766										
361	1 110	8,95	0,799		2 950	4 600	6,5			2 280	8 440	64,7	52,2
362	1 140	9,20	>0,6	56,5									
363	1 140	9,20	>0,6										
364	550	4,59	0,582					7 510	20 500				
365	922	7,49	0,762	59,5	2 480	4 560							
366	990	8,04	0,793	56,5									
367	1 060	8,58	0,791	54,9	1 930	4 730	6,2			2 530	10 400	66,3	49,4
368	1 090	8,83	0,790	56,0									
369	1 060	8,60	0,780										
370	1 080	9,59	0,790										
371	1 270	10,3	0,832	56,5				9 170	25 100				
372	1 340	10,0	0,880	23,9			6,6			3 200	13 100	65,2	47,9
373	1 290	10,5	0,840	53,0									
374	1 270	10,3	1,04	52,0									
375	1 370	11,1	0,923	53,0	4 010	4 490	6,1						

TABLE C.1. DAILY RESULTS OF FILTER I (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
376	1 330	10,8	0,930										
377	1 180	9,57	0,846										
378	1 570	16,6	0,885	51,5				10 900	38 500				
379	1 520	16,0	0,870	48,0*						4 480	17 800	58,9	53,8
380	1 560	16,4	0,903	47,0									
381	1 550	16,3	0,888		5 190	3 540	5,6			4 960	19 700	54,4	48,7
382	1 510	15,9	0,865	46,0									
383	1 600	16,9	>0,82										
384	980	10,4	>0,74										
385	10 400	87,3	0,492					10 600	29 900				
386	1 600	13,4	0,80	57,5									
387	1 400	11,7	0,82	48,0									
388	1 210	10,2	-										
389	FLUSHED FILTER												
390	1 410	11.9	0,521	47,5									
391	1 300	11.0	0,62	36,5									
392	0	0	0,513	36,5	6 500	4 540	5,7			3 410	17 100	67,9	42,8
393	0	0	0,40	63,0									

* Acid in Orsat Apparatus

TABLE C.2. DAILY RESULTS OF FILTER II

Day No.	LOAD mg OA / hr.	RATE kg COD / m³ Day	GAS Rate 1/hr	% CH_4	ACID Conc mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
1	410							3 600					
2	410												
3	0						5,4			550		84,6	
4	0												
5	0												
6	460							4 000					
7	0												
8	0						6,2						
9	460						5,8						
10	460						6,2						
11	460						7,1						
12	460		0,406				6,7						
13	460		0										
14	460		0										
15	460		0,490				6,8						
16	715		0					8 220					
17	410		0,099	26,8	8 550	11 000	7,0						
18	410		0,130	47,4									
19	410		0,130				7,1						
20	410		0,099										
21	410		0,072										
22	410		0,052	51,5			7,2						
23	410		0,028	55,0			7,3						

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3Day	GAS Rate 1/hr	% CH_4	ACIDS Conc mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
24	410		0,015										
25	0		0,023	61,8	10 200	10 200	7,1	2 170		1 630		24,7	
26	0		0,010	62,5	8 650	9 950	7,0						
27	0		0.004										
28	0		0,004										
29	590		0,033	62,0				5 250					
30	490		0,041	56,0	9 450	9 230	6,7						
31	730		0,229	55,4			6,7						
32	194		0,170					3 600					
33	162		0.066	70,0	6 600	6 340	6,2						
34	55		0,044										
35	135		0,028										
36	110		0,029	59,0									
37	120		0,034	60,4	9 110	6 810	6,3						
38	332		0,052	71,4				2 500		990		60,4	
39	374		0,026	70,5									
40	100		0,052	87,8	6 160	6 950	7,1						
41	132		0,054										
42	125		0,139	79,0									
43	112		0,200	75,7	7 060	6 850	6,5						
44	0		0,265	79,3									
45	370		0,327	79,0	7 230	6 220	6,4	2 900		785		72,8	

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	GAS Rate 1/hr	$\%CH_4$	ACIDS Conc mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION OA	% REDUCTION COD
46	410		0,440	76,7			6,3						
47	440		0,478	77,5	5 490	5 950	6,7						
48	430		0,486	79,5									
49	480		0,436	81,6									
50	450		0,430	84,4	4 550	5 360	6,8						
51	460		0,455	81,1				2 900					
52	450		0,451	79,0	4 460	5 140	6,9						
53	450		0,415	81,6									
54	330		0,393	80,0									
55	410		0,239	83,1									
56	410		0,239										
57	312		0,149	84,9	3 580	4 150	7,2	1 630		710		56,4	
58	275		0,112	86,4									
59	0		0,016										
60	400		0,180										
61	490		0,313	80,8	3 810	4 300	6,8	2 390		735		69,2	
62	200		>0,16										
63	200		>0,16										
64	328		0,473	71,5									
65	305		0,464	73,9	4 110	4 360	6,5						
66	282		0,432	76,3									
67	250		>0,21	79,0									

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	GAS Rate l/hr	% CH_4	ACIDS Conc mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA / l	FEED STRENGTH mg COD / l	EFFLUENT STRENGTH mg OA / l	EFFLUENT STRENGTH mg COD / l	% REDUCTION O A	% REDUCTION C O D
68	250		>0,21										
69	250		>0,21										
70	285		0,251										
71	260		0,116	81,6	3 930	3 700	6,8						
72	175		0,060	86,1									
73	200		0,086		3 560	4 290	7,1	2 300					
74	0		0,076	87,0									
75	0		0,076										
76	0		0,076										
77	0		0,052										
78	16		0,036										
79	310		0,175		2 670	2 390	6,2						
80	290		0,258	85,3			7,0	2 300					
81	285		0,200	87,6									
82	300		0,170	87,6			6,9						
83	300		>0,17										
84	300		>0,17										
85	450		0,251	88,6	3 140	2 100	7,4						
86	225		0,274					2 200					
87	310		0,173	90,8									
88	275		0,295										
89	120		0,244	87,3			7,2						
90	180		>0,23										

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA/hr.	RATE kg COD/m³Day	GAS Rate l/hr	% CH_4	ACIDS Conc mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA/l	FEED STRENGTH mg COD/l	EFFLUENT STRENGTH mg OA/l	EFFLUENT STRENGTH mg COD/l	% REDUCTION O A	% REDUCTION C O D
91	180		>0,23										
92	200		0,255	89,5	2 750	6 260	7,4						
93	80		0,206										
94	110		0,170	90,4									
	FILTER DORMANT UNTIL DAY 161 WHEN STARTED WITH FRESH SEWAGE SLUDGE												
156	0	0	0,006										
157	0	0	-										
158	0	0	-										
159	0	0	-										
160	0	0	-										
161	800	5,49	0,606		450	2 980	7,3	7 980	22 400				
162	1 180	8,05	0,783	67,7			6,2						
163	0	0	0,521	60,4			6,0						
164	780	6,40	0,484	77,2			7,0			2 290	9 690	71,3	56,7
165	178	1,51	0,367		3 340	6 250	6,2						
166	60	0,50	0,250				7,2	2 000	5 600				
167	176	1,49	0,225				6,8						
168	152	1,30	0,180	71,5			6,6						
169	153	1,30	0,181										
170	160	1,36	0,171		480	3 040	6,7						
171	132	0,90	0,182	79,3				1 600	4 500				

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3Day	GAS Rate 1/hr	% CH_4	ACIDS Conc mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION OA	% REDUCTION COD
172	210	1,47	0,213										
173	190	1,40	0,212										
174	190	1,40	0,212										
175	180	1,39	0,203										
176	200	1,58	0,155	74,2				2 580	4 430	895	3 800	43,3	15,7
177	153	1,03	0,155		330	2 575	6,8						
178	130	0,90	0,150										
179	165	1,10	0,170	82,7									
180	175	1,17	0,199										
181	155	1,05	0,183										
182	150	1,00	0,207				7,0	1 590	4 470	780	3 310	50,8	25,4
183	178	1,20	0,160	75,7									
184	179	1,21	0,168										
185	165	0,90	0,175	80,8				1 280	3 590				
186	165	0,90	0,152										
187	155	0,86	0,063										
188	132	0,75	0,137	79,6									
189	100	0,68	0,120										
190	180	1,52	0,160		840	2 490	7,0	2 050	5 760	745	3 160	41,3	12,2
191	175	1,51	0,159										
192	174	1,51	0,162	77,2									
193	190	1,60	0,156					2 140	6 000				
194	179	1,53	0,156										

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA/hr.	RATE kg COD/m³Day	GAS Rate l/hr	%CH_4	ACIDS Conc mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA/l	FEED STRENGTH mg COD/l	EFFLUENT STRENGTH mg OA/l	EFFLUENT STRENGTH mg COD/l	% REDUCTION O A	% REDUCTION C O D
195	174	1,48	0,159										
196	185	1,70	0,163	74,5	305	2 710	7,1	2 200	6 160	760	3 220	64,5	46,3
197	180	1,68	0,170										
198	170	1,58	0,183				6,8						
199	214	1,81	0,193	74,6	410	2 590	6,7	2 180	6 120	835	3 540	60,5	42,5
200	217	1,88	0,163										
201	186	1,58	0,197										
202	186	1,58	0,197										
203	188	1,58	0,154		420	2 660	7,1	1 940	5 450	890	3 770	58,4	38,4
204	195	1,65	0,150	72,7									
205	183	1,54	0,168										
206	189	1,60	0,172										
207	112	1,07	0,145	74,6	280	2 590	6,7	1 890	5 300				
208	∞	∞	0,219		*		*						
209	0	0	0,131		370	2 540	6,9						
210	0	0	0,093		305	2 630	7,2						
211	220	1,87	0,150	75,5				2 470	6 940	955	4 050	54,9	23,7
212	199	1,63	0,146					1 930	5 420				
213	186	1,52	0,159	76,0									
214	175	1,40	0,170										
215	200	1,64	0,184										
216	183	1,50	0,159	70,2									

* See Fig. B.2.

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	GAS Rate 1/hr	% CH_4	ACIDS Conc mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
217	196	1,66	0,160					2 050	5 750				
218	137	1,16	0,148										
219	330	2,87	0,217	72,8	430	2 410	6,8						
220	417	3,53	0,313		555	2 410	6,8						
221	392	3,35	0,300	70,4				2 000	5 600	845	3 580	59,9	37,7
222	360	3,07	0,342										
223	137	1,17	0,181	72,8									
224	59	0,51	0,062										
225	310	2,30	0,330					1 700	4 480				
226	330	2,65	0,273	70,8	410	2 530	7,0	1 970	5 520	745	3 160	62,2	29,6
227	314	2.67	0,270										
228	356	3,00	0,285	71,4									
229	283	2,40	0,267										
230	302	2,69	0,272					1 950	5 480	810	3 440	58,5	37,7
231	318	2,83	0,259	70,2									
232	255	2,29	0,250		930	2 050	6,5						
233	334	2,80	0,251	72,6				1 990	5 590				
234	370	3,10	0,360										
235	342	2,89	0,323	69,5						710	3 010	64,4	45,0
236	366	3,10	0,320					1 990	5 590				
237	396	3,36	0,314	68,1									
238	347	2,96	0,314										
239	435	3,73	0,338	69,5	415	1 930	6,6	1 900	5 320				

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	GAS Rate 1/hr	% CH_4	ACIDS Conc mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
240	387	3,30	0,344	70,2						680	2 880	64,2	45,9
241	451	3,82	0,418										
242	290	2,45	0,300	69,5				1 990	5 590				
243	255	2,15	0,270										
244	247	2,09	0,234	69,8									
245	243	2,06	0,247		665	2 060	6,7			760	3 220	61,7	42,3
246	216	1,83	0,200	73,5				2 080	5 820				
247	238	2,02	0,225										
248	236	2,00	0,208	71,6						785	3 330	62,0	42,8
249	210	1,77	0,210										
250	213	1,80	0,231										
251	200	1,70	0,220	71,3				2 000	5 670				
252	194	1,59	0,203					1 900	5 340				
253	294	2,40	0,230				6,5						
254	226	1,84	0,220	69,3	1 090	2 020							
255	241	1,20	0,246										
256	199	1,60	0,200	72,2						690	2 930	63,7	45,2
257	270	2,17	0,172										
258	270	2,17	0,204										
259	309	2,73	0,272	72,4				2 040	5 710				
260	396	3,36	0,346		480	1 960	6,5						
261	450	3.88	0,400	68,8						700	2 970	65,6	48,1
262	697	5,94	0,500	71,3	445	1 930	6,5	2 520	7 060				

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3Day	GAS Rate 1/hr	% CH_4	ACIDS Conc mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
263	750	6,35	0,600	66,3						800	3 390	60,5	52,0
264	466	3,96	0,501	69,8									
265	439	3,46	0,477	69,1				2 340	6 560				
266	460	3,65	0,450										
267	499	4,23	0,485	68,1	625	2 390	6,6						
268	500	4,24	0,520	71,2						770	3 270	67,0	50,2
269	560	4,83	0,560	70,5				2 540	7 140				
270	590	5,00	0,562	69,8									
271	715	6,05	0,500	68,5									
272	700	5,95	0,607	69,0									
273	777	6,59	0,772	68,3				3 070	8 610	795	3 370	68,7	52,8
274	813	6,89	0,734	68,1									
275	785	6,65	0,714	68,7	675	2 650	6,5						
276	584	4,95	0,614	65,1				3 250	10 200				
277	437	3,71	0,545	62,3									
278	720	6,20	0,667	69,1									
279	735	6,67	>0,12										
280	725	6,90	0,68	64,6				3 480	9 760				
281	506	4,29	0,749	67,0	820	2 870	6,6			1 010	4 260	67,0	56,3
282	1 040	8,84	0.781	63,9									
283	880	7,45	0,810	64,8									
284	690	5,94	0,819	65,8				3 970	11 100				
285	793	6,72	0,869	64,2									

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	GAS Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
286	793	6,72	-										
287	1 190	10,10	0,397	67,9						1 230	5 220	68,9	53,2
288	1 040	8,84	0,915	72,8	1 080	3 210	6,8	4 490	12 600				
289	1 120	9,50	1,01	62,2									
290	1 140	9 63	1,02	63,4									
291	1 090	9,23	1,00	63,6									
292	1 350	11,5	1,18	63,6				6 460	18 100				
293	1 500	12,7	1,50										
294	1 400	11,9	1,45	61,4						1 780	7 550	72,4	58,4
295	1 280	10,5	1,39	63,0									
296	1 590	13,3	1,70	64,0				7 660	21 500				
297	957	8,12	0,927	59,0									
298	1 470	12,4	1,36	61,8	2 210	5 110	6,4						
299	1 880	16,0	1,52	60,8									
300	1 880	16,0	-										
301	890	7,20	0,870	56,0	2 300	5 440	6,7	7 670	21 500				
302	1 010	8,20	0,985	60,8									
303	1 080	9,17	0,965	61,5									
304	1 340	11,4	1,05	61,6						2 180	9 240	70,1	57,1
305	1 380	11,7	1,05	57,5									
306	824	6,98	-										
307	824	6,98	-										
308	1 500	12,7	1,00	59,0				8 250	23 200				

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg COD / m^3 Day	GAS Rate 1/hr	% CH_4	ACIDS Conc. mg/1	ALKALIN mg/1	p H	FEED STRENGTH mg OA / 1	FEED STRENGTH mg COD / 1	EFFLUENT STRENGTH mg OA / 1	EFFLUENT STRENGTH mg COD / 1	% REDUCTION O A	% REDUCTION C O D
309	1 440	12,2	1,07	56,9									
310	1 490	12,7	1,07	56,0									
311	895	7,56	0,790	50,0									
312	1 460	12,4	0,852	56,9									
313	1 460	12,5	0,960	53,0				7 970	22 500	2 750	12 200	66,1	49,8
314	1 480	12,6	>0,75										
315	1 450	12,3	0,910		5 270	5 600	6,8						
316	0	0	0,217	53,0						2 640	11 900	66,9	47,3
317	0	0	0,119	74,6									
318	166	1,42	0,237		830	6 800	7,5						
319	0	0	0,575	67,0									
320	0	0	>0,35										
321	0	0	0,051	61,6									
322	0	0	0,051										
323	89	0,755	0,122	82,7				8 510	24 000				
324	2 990	25,4	0,738	74,0									
325	0	0	0,421	39,7									
326	560	4,75	0,443	61,5									
327	954	8,08		51,5									
328	954	8,08											
329	0	0											
330	0	0											
331	0	0											

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA/hr.	RATE kg COD/m³Day	GAS Rate l/hr	% CH_4	ACIDS Conc. mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA/l	FEED STRENGTH mg COD/l	EFFLUENT STRENGTH mg OA/l	EFFLUENT STRENGTH mg COD/l	% REDUCTION O A	% REDUCTION C O D
332	570	4,67	0,370					6 840	18 600				
333	261	2,15	0,300	55,0	2 240	5 830	6,8						
334	0	0	0,071										
335	0	0	0,071										
336	0	0	0,164	64,2									
337	86	0,70	0,644		2 800	4 600	6,8						
338	57	0,47	0,290										
339	302	2,64	0,238	66,4				1 910	5 330	1 060	4 030	44,5	24,4
340	1 050	8,72	0,300		1 130	3 720	7,1						
341	1 080	9,01	0,306										
342	0	0											
343	590	5,09	0,413					3 930	11 400				
344	545	4,71	0,425	58,0	1 840	4 560	6,8						
345	700	6,00	0,430							1 380	5 980	65,0	47,5
346	737	6,37	0,460	53,6									
347	650	5,80	0,471	57,7	1 720	4 600	6,8						
348	701	6,05	0,471					4 110	11 900				
349	682	5,88											
350	844	7,28	0,520		1 770	3 230	6,6			1 570	6 730	61,9	43,5
351	1 160	10,2	0,608	56,0						1 700	7 280	58,6	38,9
352	388	3,32	0,306	53,0									
353	715	5,90	0,597					5 140	14 100				
354	900	7,50	0,520	59,5	1 750	4 240	6,9						

TABLE C.2. DAILY RESULTS OF FILTER II (Contd.)

Day No.	LOAD mg OA/hr.	RATE kg COD/m³Day	GAS Rate l/hr	% CH_4	ACIDS Conc. mg/l	ALKALIN mg/l	p H	FEED STRENGTH mg OA/l	FEED STRENGTH mg COD/l	EFFLUENT STRENGTH mg OA/l	EFFLUENT STRENGTH mg COD/l	% REDUCTION O A	% REDUCTION C O D
355	1 200	10,0	0,631										
356	1 350	10,9	0,655										
357	800	6,90	0,482	55,0									
358	740	6,08	0,503					5 210	14 400	1 960	8 150	62,4	43,2
359	850	6,97	0,490	56,0	1 390	4 850	6,6						
360	1 000	8,18	0,522										
361	1 110	9,06	0,570		1 340	4 880	6,6			2 260	8 470	56,6	41,2
362	800	6,90	>0,33	56,5									
363	800	6,90	>0,33										
364	432	3,55	0,400					5 780	16 000				
365	630	5,20	0,484	59,5	1 590	4 460	6,4						
366	690	5,68	0,489	57,5									
367	694	5,71	0,508	56,9	1 550	4 380	6,4			2 250	8 400	61,1	47,5
368	739	6,09	0,544	56,9									
369	750	6,19	0,545										
370	780	6,45	0,582										
371	675	5,43	0,610	58,0				7 740	20 800				
372	949	7,51	0,627	56,0			6,4			3 030	11 400	60,8	45,2
373	1 090	8,69	0,608	54,2									
374	973	7,80	0,862	53,1									
375	1 110	8,87	0,800	56,9	4 050	4 000	6,5						
376	1 110	8,92	0,753										
377	917	7,35	0,659										
378	826	9,47	0,639	53,5				9 050	34 700				

TABLE CC.2. DAILY RESULTS OF FILTER III (Contd.)

Day No.	LOAD mg OA / hr.	RATE kg. COD / m^3 Day	GAS Rate l/hr	%CH_4	ACIDS Conc. mg/l	ALKALIN mg/l	pH	FEED STRENGTH mg OA / l	FEED STRENGTH mg COD / l	EFFLUENT STRENGTH mg OA / l	EFFLUENT STRENGTH mg COD / l	% REDUCTION OA	% REDUCTION COD
379	716	8,18	0,495	50,5*						4 020	20 900		
380	1 170	13,3	0,655	51,5									
381	1 100	12,5	0,625		3 150	4 120	6,1			4 770	22 100	47,3	36,4
382	1 120	12,8	0,630	48,0									
383	1 200	13,7	0,659										
384	1 100	12,5	0,640										
385	1 230	14,0	0,634										
386	1 040	8,47	0,500	49,0				10 200	27 700				
387	900	7,30	0,485	49,5									
388	FLUSHED OUT FILTER												
389	1 030	8,33	0,386										
390	1 120	9,07	0,63	62,0									
391	1 060	8,55	0,870	51,0									
392	980	7,97	0,917	50,5	4 490	4 650	5,4			2 700	10 700	-	-
393	898	7,30	0,880	52,0									

* Acid in Orsat Apparatus

TABLE C.3 DAILY RESULTS OF FILTER III

Day No.	LOAD RATE mg OA/hr	kg COD/m³day	GAS Rate l/hr	%CH_4	ACIDS CONC. Acid mg/l	Circ. mg/l	ALKALIN Acid mg/l	Circ. mg/l	p H Acid	Circ.	FEED STRENGTH mg/OA l	mg COD l	EFF. STRENGTH mg OA l	mg COD l	% REDN. OA	COD
213	448	3,65	0,175								5 400	15 200				
214	600	5,10	0,200													
215	628	5,08	0,180													
216	594	4,81	0,180	82,7												
217	554	4,55									2 720	7 630				
218	600	5,08	0,160													
219	548	4,40	0,153	81,9	1 780		2 360		6,3		2 440	6 840				
220	506	4,57	0,150			1 380		2 170		7,0						
221	520	4,25	0,164	81,1							2 440	6 840	860	3 650	63,6	46,7
222	509	4,11	0,164													
223	170	1,37	0,163	74,6												
224	451	3,65	0,187													
225	440	3,62	0,186								2 380	6 670				
226	426	3 42	0,155	66,1	1 750		1 810		5,7				970	4 110	59,2	38,3
227	425	3,42	0,165													
228	450	3,70	0,177	68,3												
229	424	3,42	0,178													
230	495	4,01	0,187								2 510	7 050				
231	335	2,70	0,083*	60,4												
232	505	4,10	0,040						6,3	6,9						
233	393	3,19	0,260*								2 490	6 980				
234	484	3,90	0,190													
235	455	3,68	0,131	66,1									730	3 100	70,7	55,7

TABLE C.3. DAILY RESULTS OF FILTER III (Contd.)

Day No.	LOAD RATE		GAS		ACIDS CONC.		ALKALIN		p H		FEED STRENGTH		EFF. STRENGTH		% REDN.	
	mg OA / hr	kg COD / m^3 Day	Rate 1/hr	%CH_4	Acid mg/1	Circ. mg/1	Acid mg/1	Circ. mg/1	Acid	Circ.	mg OA / 1	mg COD / 1	mg OA / 1	mg COD / 1	OA	COD
236	510	4,20	0,103								2 500	7 010				
237	532	4,31	0,054	66,7												
238	328	2,65	0,440*													
239	712	5,76	0,390		1 440	715	2 150	3 250	6,6	7,3	2 470	6 930	775	3 290	68,6	53,1
240	669	5,41	0,415	70,4												
241	634	5,13	0,415													
242	404	3,34	0,392	66,7							2 340	6 710				
243	353	2,92	0,353													
244	350	2,90	0,326	72,4												
245	358	2,94	0,320		2 050	535	2 410	4 280	6,6	7,4			950	4 030	60,2	40,0
246	358	2,94	0,285	72,4							2 580	7 240				
247	382	3,10	0,323													
248	396	3,21	0,306	70,5									985	4 180	62,0	42,3
249	306	2,48	0,290													
250	352	2,86	0,307													
251	304	2,46	0,280	70,9							2 530	7 100				
252	∞	∞	0,292													
253	368	2,98	0,380	69,1	580	910	2 050	2 080	7,0	6,9	2 640	7 410				
254	363	2,94	0,300													
255	384	3,11	0,335													
256	317	2,56	0,290	70,5									855	3 630	67,6	51,1
257	317	2,56	0,267													
258	0	0														

* NEW SLUDGE

TABLE C.3. DAILY RESULTS OF FILTER III (Contd.)

Day No.	LOAD RATE mg OA/hr	LOAD RATE kg COD/m³Day	GAS Rate l/hr	%CH_4	ACIDS CONC. Acid mg/l	ACIDS CONC. Circ. mg/l	ALKALIN Acid mg/l	ALKALIN Circ. mg/l	pH Acid	pH Circ.	FEED STRENGTH mg OA/l	FEED STRENGTH mg COD/l	EFF. STRENGTH mg OA/l	EFF. STRENGTH mg COD/l	% REDN. OA	% REDN. COD
259	341	2,76	0,259								3 110	8 730				
260	446	3,62	0,370		1 580	405	2 530	2 590	6,5	7,0						
261	499	3,98	0,390	69,3									925	3 920	70,3	55,1
262	565	4,58	0,450	67,9	1 570	475	2 480	2 650	6,5	6,9						
263	640	5,20	0,491	67,7							3 170	8 890	1 030	4 350	67,1	50,2
264	505	40,8	0,466	68,1												
265	480	3,89	0,400	67,9												
266	490	3,90	0,440													
267	412	3,34	0,475	66,1	1 360	475	2 690	2 890	6,7	7,1	3 560	10 000				
268	839	6,79	0,593	65,7									1 020	4 330	69,4	56,8
269	750	6,07	0,650	65,7												
270	770	6,24	0,618	66,8						6,9						
271	796	6,45	0,648	69,0							3 790	10 600				
272	886	7,18	0,723	66,5												
273	975	7,91	0,760	65,7									865	3 670	77,2	65,5
274	168	1,36	0,338	67,0												
275	>1090	>9,1	0,743	72,0	1 210	635	3 270	3 320	6,6	7,0						
276	6800	55,1	0,353	65,1							3 640	10 200				
277	0	0	0,550								3 400	9 550				
278	510	4,13	0,570	71,2												
279	718	5,81	>0,7													
280	694	5,62	0,645	65,2												
281	686	5,56	0,630	68,1	2 000	495	2 680	3 250	6,4	7,1			1 100	4 640	67,8	51,4

TABLE C.3. DAILY RESULTS OF FILTER III (Contd.)

Day No.	LOAD RATE mg OA/hr	kg COD/m³Day	GAS Rate 1/hr	%CH_4	ACIDS CONC. Acid mg/l	Circ. mg/l	ALKALIN Acid mg/l	Circ. mg/l	p H Acid	Circ.	FEED STRENGTH mg OA/l	mg COD/l	EFF. STRENGTH mg OA/l	mg COD/l	% REDN. OA	COD
282	726	5,88	0,685	68,5							3 950	11 100				
283	794	6,43	0,750	66,8												
284	966	7,81	0,770	65,1												
285	965	7,81	0,777	66,5												
286	482	3,90														
287	902	7,41	0,790	71,6							4 730	13 300	1 250	5 280	68,4	52,4
288	1050	8,66	0,945	65,8	1 610	705	3 370	3 600	6,8	7,0						
289	995	8,17	0,855	65,0												
290	981	8,07	0,900	65,7												
291	1020	8,40	0,870	67,4							5 320	14 900				
292	964	7,79	0,899	63,6												
293	1000	8,12	>0,88													
294	1100	8,90	0,950	63,8							6 430	18 000	1 630	6 910	69,4	53,8
295	1130	9,11	1,07	63,0												
296	1180	9,54	1,14	63,8												
297	1130	9,11	1,10	63,0												
298	1150	9,31	1,02	65,0	2 750	1 110	4 300	4 720	6,7	7,2						
299	1600	13.0	1.13	62,5							6 510	18 300				
300	1580	12,8														
301	1450	11,8	0,950	56,0	3 000	1 490	4 360	4 830	6,7	7,1						
302	1000	8,00	0,960	60,5												
303	900	7,50	0,830	63,8							6 640	18 600				
304	1090	8,86	0,980	64,6									1 970	8 330	70,4	55,3

TABLE C.3. DAILY RESULTS OF FILTER III (Contd.)

Day No.	LOAD RATE mg OA/hr	LOAD RATE kg COD/m³Day	GAS Rate l/hr	%CH_4	ACIDS CONC. Acid mg/l	ACIDS CONC. Circ. mg/l	ALKALIN Acid mg/l	ALKALIN Circ. mg/l	p H Acid	p H Circ.	FEED STRENGTH mg OA/l	FEED STRENGTH mg COD/l	EFF. STRENGTH mg OA/l	EFF. STRENGTH mg COD/l	% REDN. OA	% REDN. COD
305	1280	10,4	0,970	60,4												
306	1140	9,20														
307	1140	9,20														
308	1400	11,7	>1,0	57,7							7 980	22 400				
309	1490	12,1	1,29	56,9												
310	1560	12,7	1,29	59,5												
311	1425	11,5	1,23	60,5												
312	1460	11,8	1,23	60,0												
313	1350	11,3	1,26	59,6							7 890	23 100	2 590	8 160	66,0	62,2
314	1320	11,1	>1,17													
315	1280	10,8	1,18		7 500	8 900	4 780	5 570	6,6	6,8						
316	0	0	0,383	56,9									2 780	9 810	64,8	57,6
317	0	0	0,125	71,0												
318	212	1,79	0,200		884	940	7 060	7 010	7,5	7,6						
319	895	7,55	0,360	71,8												
320	895	7,55	0,490													
321	0	0	0,228	51,0												
322	0	0	0,228													
323	472	3,80	0,285	70,3							8 060	22 400				
324	1320	10,6	0,580	61,6												
325	0	0	0,370	42,2												
326	580	4,65	0,443	63,4												
327	945	7,57	0,344	55,5												

TABLE C.3. DAILY RESULTS OF FILTER III (Contd.)

Day No.	LOAD RATE		GAS		ACIDS CONC.		ALKALIN		p H		FEED STRENGTH		EFF. STRENGTH		% REDN.	
	mg OA / hr	kg COD / m^3Day	Rate 1/hr	$\%CH_4$	Acid mg/1	Circ. mg/1	Acid mg/1	Circ. mg/1	Acid	Circ.	mg OA / 1	mg COD / 1	mg OA / 1	mg COD / 1	OA	COD
328	945	7,57	0,344													
329	930	7,40	0,344													
330	930	7,40														
331	930	7,40														
332	850	6,73	0,251								6 950	19 000				
333	288	2,27	0,330	58,0	3 780	2 900	5 100	5 300	6,5	6,9						
334	0	0	0,290													
335	0	0	0,147													
336	116	0,91	0,147	68,8												
337	404	3,18	0,138		2 650	1 790	5 350	6 710	6,9	7,3						
338	104	0,80	0,163													
339	482	4,08	0,235	69,8							1 930	5 490				
340	1010	9,00	0,360		1 300	1 180	3 680	4 280	7,1	7,2			1 080	4 050	44,3	26,2
341	0	0	0,370													
342	0	0														
343	605	5,05	0,386								3 990	11 200				
344	688	5,74	0,480	61,0	2 380	1 800	3 820	4 700	6,7	7,1						
345	850	7,00	0,525										1 290	5 800	67,6	48,3
346	731	6,11	0,540	56,9												
347	750	6,20	0,537	58,0	2 580	1 990	4 010	4 660	6,8	7,1						
348	974	8,47	0,611								4 150	12 100				
349	875	7,62														
350	895	7,80	0,620		1 710	1 860	3 670	4 430	6,6	7,0			1 470	6 310	64,5	48,2

TABLE C.3. DAILY RESULTS OF FILTER III (Contd.)

Day No.	LOAD RATE		GAS		ACIDS CONC.		ALKALIN		pH		FEED STRENGTH		EFF. STRENGTH		% REDN.	
	mg OA / hr	kg COD / m^3 Day	Rate 1/hr	$\%CH_4$	Acid mg/l	Circ. mg/l	Acid mg/l	Circ. mg/l	Acid	Circ.	mg OA / 1	mg COD / 1	mg OA / 1	mg COD / 1	OA	COD
351	383	3,33	0,479	56,0												
352	0	0	0,318	60,5												
353	110	0,85	0,228								5 310	14 700				
354	280	2,20	0,217	68,5	1 390	705	4 810	4 950	7,2	7,4						
355	250	2,10	0,250													
356	466	3,57	0,479													
357	650	4,95	0,510	61,5												
358	716	5,45	0,520										1 630	6 310	66,6	56,5
359	700	5,33	0,495	60,0	2 420	1 710	4 380	4 840	6,8	7,1						
360	709	5,39	0,515													
361	690	5,30	0,545		2 150	1 880	4 830	5 000	7,0	7,1			1 850	6 770	58,0	50,8
362	875	7,10	>0,33	60,9							7 490	20 400				
363	875	7,10	>0,33													
364	865	7,01	0,750													
365	930	7,50	0,742	56,0	2 880	2 720	4 600	4 850	6,9	7,0						
366	∞	∞	0,696	56,9												
367	710	5,40	0,740	61,8	1 030	825	5 270	2 890	7,3	7,4	9 180	23 300	2 280	6 560	75,2	71,9
368	1020	7,71	0,900	53,6												
369	1130	8,56	>0,68													
370	1170	8,88	0,861													
371	1240	9,41	0,851	53,1												
372	1170	8,86	0,910	53,1					6,5	6,6			3 220	14 000	64,9	40,2
373	1290	9,74	0,905	53,1												

TABLE C.3. DAILY RESULTS OF FILTER III (Contd.)

Day No.	LOAD RATE mg OA/hr	kg COD/m³Day	GAS Rate l/hr	%CH_4	ACIDS CONC. Acid mg/l	Circ. mg/l	ALKALIN Acid mg/l	Circ. mg/l	pH Acid	Circ.	FEED STRENGTH mg OA/l	mg COD/l	EFF. STRENGTH mg OA/l	mg COD/l	% REDN. OA	COD
374	1250	9,55	0,940	53,1												
375	1600	16,8	0,750	56,0	3 110	3 440	4 810	4 330	6,9	6,8	10 600	37 600				
376	2000	21,0	>0,84													
377	2280	24,2	>0,73													
378	1820	19,3	1,14	55,2												
379	1830	19,4	1,13	46,0*									3 860	22 900	63,5	39,1
380	1770	18,0	1,14	46,0							10 600	37 300				
381	1790	18,2	1.10		4 890	5 160	5 230	5 230	6,7	6,7			4 500	22 900	57,4	39,2
382	1810	18,4	1,05	47,0												
383	1830	18,7	1,03													
384	1840	18,7	0,970													
385	1850	18,8	0,970													
386	1630	12,8	1,00	44,0							10 000	27 300				
387	1600	12,6	0,960	45,0												
388	1260	9,93	0,870													
389	FLUSHED OUT		FILTER													
390	934	7,35	0,324	60,2												
391	915	7,20	0,580	46,0												
392	985	7,75	0,660	45,0	4 860	3 530	4 450	4 630	6,3	6,6			2 790	13 100	72,1	51,9
393	1100	8,62	0,680	44,0												
394			0,75	45,0												

* ACID IN ORSAT APPARATUS

A P P E N D I X D

FLOCCULATION STUDIES

D.1. INTRODUCTION

As stated in Chapter 1, there was good reason to believe that flocculation of the yeast wastes would be feasible, especially in view of the work done by Federov and Golod (14), Clayton (8) and Ross and Conradie (48) who demonstrated the colloidal nature of molasses and yeast wastes. Hence a series of tests were carried out in order to determine the optimum dosages of coagulant, pH and flocculation times required for flocculation of the yeast waste.

D.2. FLOCCULATION THEORY

The basic theory of coagulation and flocculation is well known, and has been covered by many authors, including Sawyer and McCarty (57), and so it will not be repeated. The choice of coagulant was governed by some aspects of the theory, however, and these relevant portions will be discussed briefly.

Most colloids of organic origin are hydrophilic in nature, and the particles carry negative charges, although these are often weak (57). Consequently these colloids are best coagulated by ions carrying many positive charges each, e.g. Fe^{+++} and Al^{+++}. When these ions are used for coagulation, only a small fraction of the ions applied actually cause coagulation of the colloid, the remainder form a positively charged metallic hydroxide colloid. Consequently it is customary to use the sulphates of Fe^{+++} or Al^{+++} since the negatively charged SO_4^{--} ion causes coagulation of the hydroxide colloid (57). In choosing between

ferric sulphate and aluminium sulphate as coagulant, the solubilities of the resulting hydroxides was the deciding factor. Since $Fe(OH)_3$ is effectively insoluble at any pH greater than 4, while $Al(OH)_3$ is only insoluble between pH 4,5 and 7,0 it was decided to use ferric sulphate as coagulant for most of the tests to be performed.

D.3. EXPERIMENTAL METHOD

The flocculation tests were carried out by the well- known jar-test method (57). The procedure was the same for all the tests: A 300 - 400 ml sample of the yeast waste was placed in a 600 ml glass beaker. The volume of concentrated coagulant solution required to give the desired final concentration was then added from a burette with rapid mixing from a high speed propeller stirrer. The pH was then adjusted to the desired value using either sulphuric acid or sodium hydroxide solutions, whilst rapid mixing continued for not longer than 2 minutes. The samples were the then placed on a slow speed (60 - 80 r.p.m.) paddle stirrer and stirred gently for 20 minutes, after which time the floc that had formed was allowed to settle, usually overnight. Samples for analysis were drawn off from approximately 1 cm below the surface with a pipette, taking care not to disturb the settled floc.

In addition to the runs using ferric sulphate as described above, two runs at low pH were carried out using the same procedure but with aluminium sulphate as coagulant. Also a run was carried out using 0,8 g/l of Fe^{+++} as $Fe_2(SO_4)_3$ over a pH range from 3,0 to 9,0 at intervals of 0,2 pH units, and a further run using the supernatant from two flocculations with aluminium sulphate as samples for flocculation with ferric sulphate.

D.4. RESULTS

Detailed results of all the runs carried out are given in Table D.1 These results are discussed in Section D.5 below.

D.5. DISCUSSION OF RESULTS

The results given in Table D.1 show that it is possible to reduce the OA of the waste by up to 60%, but the coagulant dosage required for this - 5 g/l of Fe^{+++} and a pH of 3,5 - is far too high for economic practical use. The results also show wide variations from run to run with similar dosages, e.g. in Run 4, 3 000 mg/l of Fe^{+++} at pH 9,0 gave a reduction in OA of 25,5%, but the same dose at the same pH in Run 7 gave a reduction of 30,3%. This indicates that the character of the waste changes from batch to batch and that this affects the dosage of coagulant needed for optimum flocculation. This means that with a large scale process, each batch of waste would have to be tested to determine the optimum coagulant dose required, and this would be extremely costly as well as posing a control problem in dosing.

The results of Run 22 show that more than one colloid is present in yeast waste, and that successive flocculations can effect reductions greater than the 60% achieved in Run 13. The coagulant dosage required is still extremely high, however. In view of the high dosages required to effect these reductions it seems likely that the mechanism of the process taking place is not true coagulation and flocculation at all, but adsorption of the materials in the waste onto the hydroxide floc particles This is also indicated by the almost universal rise in percentage removal with increasing coagulant dosage exhibited by the results at any one value of the pH, indicating that the more floc particles there are, the more material is adsorbed from solution. Had the process been purely destabilization of a colloid, the results would have shown a peak at a certain dosage, with reduced removal at higher dosages caused by charge reversal and restabilization of the colloid.

Because of the high chemical dosage needed to effect a significant reduction in strength and because of the variable nature of the waste, flocculation cannot be recommended as a method of treating the waste.

TABLE D.1. FLOCCULATION RESULTS

RUN NO.	COAGULANT	CONCENTRATION OF CATION mg/1	p H	OA mg/1	% REDUCTION
1	$Fe_2(SO_4)_3$	-	9,0	19 600	-
		280	9,0	17 800	9,2
		559	9,0	17 300	11,7
		838	9,0	15 600	20,4
		1 120	9,0	14 300	27,0
		1 400	9,0	13 300	32,1
2	$Fe\ SO_4$	-	7,8	19 200	-
		1 400	7,8	17 800	7,3
		2 000	7,8	17 700	7,8
		3 000	7,8	17 300	9,9
		4 000	7,8	17 100	12,5
		5 000	7,8	16 000	16,7
3	$Fe\ SO_4$	-	8,7	20 600	-
		100	8,7	18 800	8,7
		500	8,7	18 700	9,2
		1 000	8,7	18 600	9,7
		3 000	8,7	17 200	16,5
		5 000	8,7	16 300	20,9
4 *	$Fe_2(SO_4)_{33}$	-	9,0	16 500	-
		750	9,0	14 000	15,2
		1 500	9,0	13 700	17,0
		2 000	9,0	13 400	18,8
		2 500	9,0	12 900	21,8
		3 000	9,0	12 300	25,5
5	$Fe_2(SO_4)_3$	-	8,0	19 600	-
		250	8,0	18 700	4,6
		873	8,0	18 100	7,7
		1 750	8,0	17 800	9,2
		2 500	8,0	16 800	14,3
		5 000	8,0	14 200	27,6

* Old Yeast Waste

TABLE D.1. FLOCCULATION RESULTS (Contd.)

RUN NO.	COAGULANT	CONCENTRATION OF CATION mg/l	p H	OA mg/l	% REDUCTION
6	$Fe_2(SO_4)_3$	-	8,0	18 900	-
		500	8,0	15 700	16,9
		1 000	8,0	16 300	13,8
		1 500	8,0	15 500	18,0
		2 500	8,0	14 000	25,9
		3 500	8,0	12 500	33,9
7	$Fe_2(SO_4)_3$	-	9,0	19 500	-
		500	9,0	17 800	8,7
		1 000	9,0	17 900	8,2
		2 000	9,0	16 300	16,4
		3 000	9,0	13 600	30,3
		3 500	9,0	13 300	31,8
8	$Fe_2(SO_4)_3$	-	4,8	19 500	-
		500	9,0	17 200	11,8
		1 000	9,0	16 400	15,9
		2 000	9,0	14 700	24,6
		3 000	9,0	13 200	32,3
		500	10,0	17 200	11,8
		1 000	10,0	16 100	17,4
		2 000	10,0	14 500	25,6
		3 000	10,0	13 200	32,3
9	$Fe_2(SO_4)_3$	-	5,4	26 800	-
		-	5,5	27 600	- 3,0
		25	5,5	26 500	1,1
		50	5,5	25 000	6,7
		100	5,5	23 300	13,1
		150	5,5	25 000	6,7
		300	5,5	24 600	8,2
		450	5,5	22 900	14,6

TABLE D.1. FLOCCULATION RESULTS (Contd.)

RUN NO.	COAGULANT	CONCENTRATION OF CATION mg/l	p H	OA mg/l	% REDUCTION
10	$Fe_2(SO_4)_3$	-	5,4	28 400	-
		-	4,0	27 600	2,8
		25	4,0	24 600	13,4
		50	4,0	26 800	5,6
		75	4,0	25 000	12,0
		100	4,0	25 500	10,2
		125	4,0	26 400	7,0
		150	4,0	26 900	5,3
11	$Fe_2(SO_4)_3$	-	5,3	22 200	-
		-	3,5	22 200	0
		10	3,5	22 000	0,9
		25	3,5	22 000	0,9
		50	3,5	21 500	3,2
		75	3,5	21 900	1,4
		100	3,5	21 900	1,3
		150	3,5	21 200	4,5
12	$Fe_2(SO_4)_3$	-	5,2	22 300	-
		200	3,5	22 100	0,9
		500	3,5	21 900	1,8
		1 000	3,5	21 600	3,1
		1 500	3,5	21 300	4,5
		2 000	3,5	17 800	20,2
		2 500	3,5	15 900	28,7
		2 940	3,5	14 800	33,6
13	$Fe_2(SO_4)_3$	-	5,9	19 300	-
		-	3,5	19 300	0
		2 500	3,5	12 500	35,2
		3 000	3,5	11 700	39,4
		3 500	3,5	10 600	45,1

TABLE D.1. FLOCCULATION RESULTS (Contd.)

RUN NO.	COAGULANT	CONCENTRATION OF CATION mg/l	p H	OA mg/l	% REDUCTION
		4 000	3,5	9 400	51,3
		4 500	3,5	8 500	56,0
		5 000	3,5	7 700	60,1
14	$Fe_2(SO_4)_3$	-	5,7	18 200	-
		25	7,0	18 000	1,1
		75	7,0	18 100	0,6
		200	7,0	17 600	3,3
		1 000	7,0	16 300	10,4
		2 000	7,0	14 900	18,1
		3 000	7,0	13 600	25,3
		4 000	7,0	12 200	33,0
		5 000	7,0	11 300	37,9
15	$Fe_2(SO_4)_3$	-	5,7	18 200	-
		10	4,7	18 000	1,1
		50	4,7	18 100	0,6
		100	4,7	18 100	0,6
		500	4,7	17 500	3,9
		1 500	4,7	16 100	11,5
		2 500	4,7	13 300	26,9
		3 500	4,7	11 400	37,4
		4 500	4,7	9 000	50,6
16	$Fe_2(SO_4)_3$	-	5,6	18 200	-
		10	6,5	17 900	1,6
		50	6,5	18 000	1,1
		100	6,5	17 800	2,2
		500	6,5	17 200	5,5
		1 500	6,5	15 800	13,2
		2 500	6,5	14 800	18,7
		3 500	6,5	12 900	29,1
		4 500	6,5	11 900	34,6

TABLE D.1. FLOCCULATION RESULTS (Contd.)

RUN NO.	COAGULANT	CONCENTRATION OF CATION mg/l	p H	OA mg/l	% REDUCTION
17	$Fe_2(SO_4)_3$	-	5,7	17 600	-
		1 000	5,5	16 300	7,4
		2 000	5,5	15 100	14,2
		3 000	5,5	13 500	23,3
		4 000	5,5	11 500	34,7
		5 000	5,5	8 500	51,7
18	$Al_2(SO_4)_3$	-	5,1	18 500	-
		10	4,0	18 500	0
		50	4,0	18 400	0,5
		100	4,0	18 300	1,1
		500	4,0	17 800	3,8
		1 500	4,0	16 200	12,4
		2 500	4,0	14 400	22,2
		3 500	4,0	12 500	32,4
		4 500	4,0	11 600	37,3
19	$Al_2(SO_4)_3$	-	5,2	18 100	-
		25	5,0	19 900	-10,0
		75	5,0	18 100	0
		200	5,0	18 100	0
		1 000	5,0	17 100	5,5
		2 000	5,0	15 600	13,8
		3 000	5,0	12 100	33,2
		4 000	5,0	10 000	44,8
		5 000	5,0	8 950	50,5
20	$Fe_2(SO_4)_3$	-	5,7	19 500	-
		800	3,0	18 600	4,7
		800	3,2	18 700	4,1
		800	3,4	18 700	4,3
		800	3,6	18 500	5,2

TABLE D.1. FLOCCULATION RESULTS (Contd.)

RUN NO.	COAGULANT	CONCENTRATION OF CATION mg/l	p H	OA mg/l	% REDUCTION
		800	3,8	18 600	4,7
		800	4,0	18 700	4,3
		800	4,2	18 900	3,2
		800	4,4	18 900	3,2
		800	4,6	18 500	5,2
		800	4,8	18 900	3,2
		800	5,0	18 800	3,7
		800	5,2	18 800	3,7
		800	5,4	18 700	4,3
		800	5,6	18 900	3,2
		800	5,8	18 500	5,2
21	$Fe_2(SO_4)_3$	-	5,7	19 900	-
		800	6,0	18 600	6,7
		800	6,2	16 700	6,4
		800	6,4	18 500	7,3
		800	6,6	18 600	6,7
		800	6,8	18 600	6,7
		800	7,0	18 600	6,7
		800	7,2	18 500	7,3
		800	7,4	18 400	7,6
		800	7,6	18 100	9,4
		800	7,8	18 500	7,3
		800	8,0	18 400	7,6
		800	8,2	18 400	7,6
		800	8,4	18 500	7,3
		800	8,6	18 600	6,7
		800	8,8	18 100	9,4
		800	9,0	18 500	7,3

TABLE D.1. FLOCCULATION RESULTS (Contd.)

RUN NO.	COAGULANT	CONCENTRATION OF CATION mg/l	p H	OA mg/l	% REDUCTION
22	3 000 mg/l	0	-	12 400	31,7
	Al^{+++}	500	3,5	12 100	32,8
	then	2 000	3,5	10 100	44,0
	$Fe_2(SO_4)_3$	4 000	3,5	6 770	62,6
	400 mg/l	0	-	10 500	42,2
	Al^{+++}	500	3,5	8 790	51,4
	then	2 000	3,5	9 240	49,0
	$Fe_2(SO_4)_3$	4 000	3,5	6 000	66,9

APPENDIX E

REGRESSION PROGRAMME

E.1. INTRODUCTION

The computer programme listed below and used in the statistical treatment of results detailed in Chapter 4, Section 4.3., was based on the standard Multiple Linear Regression Program, "REGR", given in the IBM Scientific Subroutine Package (20). The original programme read in data from tape, but since only 17 sets of data were to be treated, these were read in from cards, the programme being modified accordingly. The programme makes use of 5 subroutines, viz., "CORRE" (which in turn calls for a special subroutine named "DATA"), "ORDER", "MINV" and "MULTR". The four main subroutines are available from the Scientific Subroutine Package (20), but the subroutine "DATA" must be supplied by the user. Because of the simplicity of the data used in this case, the main programme was modified and a dummy subroutine was used. This consisted of:

```
      SUBROUTINE DATA
      RETURN
      END
```

This Appendix also gives a sample print-out of the results of the regression, with the effluent concentration, E mg COD/l as the dependent variable and the square of the feed concentration F^2, as the independent variable.

```
C       SAMPLE MAIN PROGRAM FOR MULTIPLE REGRESSION - REGRE            REGR  10
C       THE FOLLOWING DIMENSIONS MUST BE GREATER THAN OR EQUAL TO THE  REGR  20
C       NUMBER OF VARIABLES. *                                         REGR  30
      DIMENSION XBAR(10),STD(10),DET(10),RY(10),ISAVE(10),B(10),SB(10),T(1REGR  40
     1O)                                                             REGR  50
C       THE FOLLOWING DIMENSION MUST BE GREATER THAN OR EQUAL TO THE   REGR  60
C       PRODUCT OF *-*                                                 REGR  70
      DIMENSION RX(100)                                              REGR  80
C       THE FOLLOWING DIMENSION MUST BE GREATER THAN OR EQUAL TO THE   REGR  90
C       PRODUCT OF *-*                                                 REGR 100
      DIMENSION X(6,0)                                               REGR 110
C       THE FOLLOWING DIMENSION MUST BE GREATER THAN OR EQUAL TO       REGR 120
C       (*-1)**/2.                                                     REGR 130
      DIMENSION R(6C)                                                REGR 140
C       THE FOLLOWING DIMENSION MUST BE GREATER THAN OR EQUAL TO 10.   REGR 150
      DIMENSION ANS(10)                                              REGR 160
    1 FORMAT(4A4,A2,I5,2I2)                                          REGR 170
    2 FORMAT(25H1MULTIPLE REGRESSION.....A4,A2///5X,14HSELECTION.....12//REGR 180
     1)                                                              REGR 190
    3 FORMAT(9HOVARIABLE,5X,8HMEAN,6X,8HSTANDARD,6X,11HCORRELATION,4X,1CREGR 200
     1HREGRESSION,4X,10HSTD. ERROR,5X,8HCOMPUTED/6H   NO.,18X,9HDEVIATIOREGR 210
     2N,7X,6HX VS Y,7X,11HCOEFFICIENT,3X,12HOF REG.COEF.,3X,7HT VALUE)  REGR 220
    4 FORMAT(1H ,I6,6F14.5)                                          REGR 230
    5 FORMAT(10H DEPENDENT)                                          REGR 240
    6 FORMAT(1H1//10H INTERCEPT,10X,F16.5//23H MULTIPLE CORRELATION  ,F13REGR 250
     1.5,5X,22HMULTIPLE DETERMINATION,F13.5//23H STD. ERROR OF ESTIMATE,REGR 260
     2F17.5//)                                                       REGR 270
    7 FORMAT(1H0,21X,39HANALYSIS OF VARIANCE FOR THE REGRESSION//5X,19HSREGR 280
     1OURCE OF VARIATION,7X,7HDEGREES,7X,6HSUM OF,1CX,8HMEAN,12X,7HF VALREGR 290
     2UE//30X,10HOF FREEDOM,4X,7HSQUARES,9X,7HSQUARES)               REGR 300
    8 FORMAT(30H ATTRIBUTABLE TO REGRESSION    ,I6,3F16.5/30H DEVIATION FREGR 310
     1ROM REGRESSION    ,I6,2F16.5)                                  REGR 320
    9 FORMAT(1H ,5X,5HTOTAL,19X,I6,F16.5)                            REGR 330
   10 FORMAT(3612)                                                   REGR 340
   11 FORMAT(1H ,15X,18HTABLE OF RESIDUALS//5H CASE NO.,5X,7HE VALUE,5X,REGR 350
     1HME ESTIMATE,6X,8HRESIDUAL)                                    REGR 360
   12 FORMAT(1H ,I6,F15.5,2F14.5)                                    REGR 370
   13 FORMAT(53H1NUMBER OF SELECTIONS NOT SPECIFIED.  JOB TERMINATED.) REGR 380
   14 FORMAT(52HOTHE MATRIX IS SINGULAR.  THIS SELECTION IS SKIPPED.) REGR 390
   15 FORMAT(2F10.2,F10.6,F10.2)                                     REGR 400
C       READ PROBLEM PARAMETER CARD                                    REGR 410
  100 READ(8,1) PP,PR1,N,M,NS                                        REGR 420
C       PP.........PROBLEM NUMBER (MAY BE ALPHAMERIC)                  REGR 430
C       PR1........PROBLEM NUMBER (CONTINUED)                          REGR 440
C       N..........NUMBER OF OBSERVATIONS                              REGR 450
C       M..........NUMBER OF VARIABLES                                 REGR 460
C       NS.........NUMBER OF SELECTIONS                                REGR 470
C       READ DATA: EFFLUENT STRENGTH, X1 FEED STRENGTH, X2 FLOW RATE,  REGR 480
C       X3 ALKALINITY, ETC AND COMPUTE SQUARES AND CROSS PRODUCTS      REGR 490
      DO 111 I=1,N                                                   REGR 500
      READ(8,15) X(I),X(I+N),X(I+2*N),X(I+3*N)                       REGR 510
      X(I+4*N)=(X(I+N)**2)/1000000.                                  REGR 520
      X(I+5*N)=(X(I+2*N)**2)*100.                                    REGR 530
      X(I+6*N)=(X(I+3*N)**2)/10000CO.                                REGR 540
      TTT=X(I)*X(I+N)*X(I+2*N)                                       REGR 550
      X(I+7*N)=X(I+N)*X(I+3*N)/1000000.                              REGR 560
      X(I+8*N)=X(I+2*N)*X(I+3*N)                                     REGR 570
  111 CONTINUE                                                       REGR 580
      I0=1                                                           REGR 590
      CALL CORRE (N,M,I0,X,XBAR,STD,RX,R,D,B,T)                      REGR 600
C       TEST NUMBER OF SELECTIONS                                      REGR 610
      IF(NS) 170,108,109                                             REGR 620
  108 WRITE(5,13)                                                    REGR 630
      GO TO 300                                                      REGR 640
  109 DO 200 I=1,NS                                                  REGR 650
      WRITE(5,2) PP,PR1,I                                            REGR 660
C       READ SUBSET SELECTION CARD                                     REGR 670
      READ(8,10) NPRESI,NDEP,K,(ISAVE(J),J=1,K)                      REGR 680
C       NPRESI.....OPTION CODE FOR TABLE OF RESIDUALS                  REGR 690
C                  0 IF IT IS NOT DESIRED                              REGR 700
C                  1 IF IT IS DESIRED                                  REGR 710
C       NDEP......DEPENDENT VARIABLE                                   REGR 720
C       K.........NUMBER OF INDEPENDENT VARIABLES INCLUDED             REGR 730
C       ISAVE.....A VECTOR CONTAINING THE INDEPENDENT VARIABLES        REGR 740
C                 INCLUDED                                             REGR 750
      CALL ORDER (M,R,NDEP,K,ISAVE,RX,RY)                            REGR 760
      CALL MINV (RX,K,DET,B,T)                                       REGR 770
C       TEST SINGULARITY OF THE MATRIX INVERTED                        REGR 780
      IF(DET) 112,110,112                                            REGR 790
  110 WRITE(5,14)                                                    REGR 800
      GO TO 200                                                      REGR 810
  112 CALL MULTR (N,K,XBAR,STD,D,RX,RY,ISAVE,B,SB,T,ANS)             REGR 820
C       PRINT MEANS, STANDARD DEVIATIONS, INTERCORRELATIONS BETWEEN    REGR 830
C       X AND Y, REGRESSION COEFFICIENTS, STANDARD DEVIATIONS OF       REGR 840
C       REGRESSION COEFFICIENTS, AND COMPUTED T VALUES                 REGR 850
      DETER=ANS(2)**2                                                REGR 860
      M=K+1                                                          REGR 870
      WRITE(5,3)                                                     REGR 880
      DO 113 J=1,K                                                   REGR 890
      L=ISAVE(J)                                                     REGR 900
  113 WRITE(5,4) L,XBAR(L),STD(L),RY(J),B(J),SB(J),T(J)              REGR 910
C       PRINT INTERCEPT, MULTIPLE CORRELATION COEFFICIENT, AND         REGR 920
C       STANDARD ERROR OF ESTIMATE                                     REGR 930
      WRITE(5,5)                                                     REGR 940
      L=ISAVE(M)                                                     REGR 950
      WRITE(5,4) L,XBAR(L),STD(L)                                    REGR 960
      WRITE(5,6) ANS(1),ANS(2),DET,ANS(3)                            REGR 970
C       PRINT ANALYSIS OF VARIANCE FOR THE REGRESSION                  REGR 980
      WRITE(5,7)                                                     REGR 990
      L=ANS(4)                                                       REGR1000
      WRITE(5,8) L,ANS(6),ANS(8),ANS(10),L,ANS(7),ANS(9)             REGR1010
      L=N-1                                                          REGR1020
      SUM=ANS(6)+ANS(7)                                              REGR1030
      WRITE(5,9) L,SUM                                               REGR1040
      IF(NPRESI) 200,200,114                                         REGR1050
C       PRINT TABLE OF RESIDUALS                                       REGR1060
  114 WRITE(5,12) PP,PR1,I                                           REGR1070
      WRITE(5,11)                                                    REGR1080
      DO 180 II=1,N                                                  REGR1090
      SUM=ANS(1)                                                     REGR1100
      DO 170 J=1,K                                                   REGR1110
      L=ISAVE(J)-1                                                   REGR1120
  170 SUM=SUM+X(II+N*L)*B(J)                                         REGR1130
      RESI=X(II)-SUM                                                 REGR1140
  180 WRITE(5,12) II,X(II),SUM,RESI                                  REGR1150
  200 CONTINUE                                                       REGR1160
  300 CONTINUE                                                       REGR1170
      END                                                            REGR1180
```

MULTI-LINEAR REGRESSION

MULTIPLE REGRESSION.....FINAL

SELECTION..... 4

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS E	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
5	95.56971	121.58293	.97291	17.92597	1.09982	16.29895
DEPENDENT 1	4592.35291	2240.17862				

INTERCEPT 2879.17313

MULTIPLE CORRELATION .97291 MULTIPLE DETERMINATION .94655

STD. ERROR OF ESTIMATE 534.87899

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	1	76002971.00000	76002971.00000	265.65591
DEVIATION FROM REGRESSION	15	4291433.00000	286095.53125	
TOTAL	16	80294404.00000		

TABLE OF RESIDUALS

CASE NO.	E VALUE	E ESTIMATE	RESIDUAL
1	3580.00000	3518.07080	61.92920
2	3900.00000	3570.47198	329.52802
3	3540.00000	3550.57956	-10.57956
4	4130.00000	3570.47198	559.52802
5	3770.00000	3550.57956	219.42044
6	3285.00000	3434.32648	-149.32648
7	3000.00000	3438.32397	-438.32397
8	3330.00000	3486.36871	-156.36871
9	3475.00000	3847.57883	-372.57883
10	3265.00000	3650.59213	-385.59213
11	3855.00000	4239.11066	-384.11066
12	3645.00000	4373.42639	-728.42639
13	4260.00000	4749.68042	-489.68042
14	6315.00000	5615.50116	699.49884
15	12165.00000	12490.25427	-325.25427
16	5830.00000	5566.99353	263.00647
17	6725.00000	5417.66974	1307.33026