ANAEROBIC DIGESTION OF HIGH-STRENGTH OR TOXIC ORGANIC EFFLUENTS IN AVAILABLE DIGESTER CAPACITY

J Sacks • CA Buckley

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Water Research Commission

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Report to the
WATER RESEARCH COMMISSION

by

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Executive Summary

1 Background

The KwaZulu-Natal region has the potential to attract a significant amount of new industry due to its coastal location and the availability of space. Since the province has an abundance of water, relative to the rest of the country, it is probable that some of the industries will be from the agro-industrial sector. One of the characteristics of this class of industries is high-strength organic effluent. Other classes of industries, which produce high-strength or toxic organic liquid effluents, could also develop.

The Department of Water Affairs and Forestry identified the need to advise industries with high-strength organic effluents on the most suitable treatment route to be followed. Anaerobic digestion has the potential to treat complex organic wastes such that they are either completely mineralised or that they could be further degraded aerobically.

Tracer tests on a number of existing anaerobic digesters in the KwaZulu-Natal Region indicated that the mixing volume could be as low as 50 % of the actual volume, i.e. as little as half of the total volume was actively being used for the degradation process. Two WRC research contracts undertaken by the Pollution Research Group aimed to increase the mixing efficiency of the anaerobic digestion process (WRC No. 648 - *The Application of Computational Fluid Mechanics to Improve the Design and Operation of Water and Wastewater Treatment Plants* and WRC No. 560 - *The Development of a Cross-Flow Microfilter to Improve the Performance of Anaerobic Digesters*). During these investigations it was found that there were a number of sewage works with under-utilised anaerobic digestion facilities.

Control of the wastewater treatment plants in the greater Durban area is currently (1997/8) being assumed by the Durban Metropolitan Council. This standardisation provides the potential for the utilisation of under-utilised capacity of some of the sewage treatment plants and alleviation of the *bottleneck* at plants operating at or over design capacity. This should result in a delay in the need for capital expenditure and an increase in the income from capital already expended.

The KwaZulu-Natal Region has a great need for the provision of sanitation. The increasing urban and peri-urban population will require the extension of sewage reticulation and an increase in sewage treatment capacity. The increased use and income from existing but under-utilised capacity will assist in financing the additional infrastructure in areas where it is needed.

2 Project Aims

The main aims of the project were as follows:

1. To provide information that will allow for the rational location, in KwaZulu-Natal, of new industries that produce high-strength or toxic organic effluents;

2. To assist in the optimal utilisation of effluent treatment facilities in the region;

3. To identify under-performing digesters with a view to recommending courses of remedial action;

4. Identify industries in the region that produce high-strength or toxic organic effluents in order to allow rational decisions to be taken for their safe disposal;

5. To safeguard the aquatic environment through providing suitable industrial effluent treatment options; and

6. To promote the regional development of new industries or agro-industries that produce high-strength or toxic organic effluents by providing effluent treatment options.

This project was therefore initiated to investigate the utilisation of available anaerobic digester capacity for the treatment of high-strength or toxic industrial effluents. These effluents would normally be diluted prior to discharge to the local sewage works, discharged to sea or co-disposed into municipal landfill sites. The focus of the project was on undertaking a survey of available anaerobic digester capacity and the evaluation of the performance efficiency of each of the anaerobic digesters. A protocol was established to assess the anaerobic degradability and the potential toxicity of an effluent, on a laboratory-scale.

3 Project Approach

The local authorities were approached for information regarding the anaerobic digesters in the region. The digesters were visited and physical and operating data for each were obtained and used to calculate the performance efficiencies. This allowed for the identification of under-performing digesters and digesters available for the treatment of high-strength or toxic industrial effluents.

The regional pollution control officials were interviewed to identify industries producing high-strength or toxic organic effluents. Selected industries were contacted to obtain data on their effluents and the local authorities provided information on the proposed development of new industries. Possibilities for pollution prevention, waste minimisation and stream segregation were discussed. From these data, a matrix was compiled which identified potential anaerobic digesters for treatment of effluents produced in the vicinity.

Anaerobic digestion has the potential to stabilise the degradable fraction of high-strength or toxic organic effluents, either entirely or such that they can be further degraded aerobically. To achieve the research objective, a strategy, which can be applied to different effluents, was developed. The overall strategy follows two concurrent pathways, the first investigates the effluent degradability and the second evaluates the digester capacity and efficiency. A protocol was developed for the laboratory assessment of the degradability and potential toxicity of an effluent. The digester capacity and performance efficiency was assessed simultaneously. From these initial assessments, the feasibility of full-scale could be predicted.

The strategy was applied to determine the feasibility of using anaerobic digestion to treat a textile size effluent.

4 Summary of Results

A survey of 24 wastewater treatment plants was undertaken which included a total of 56 anaerobic digesters. The survey identified the availability of hydraulic or organic capacity. It was proposed that this available capacity could be utilised for the treatment of high-strength or toxic organic effluents, produced by industries in the vicinity of the wastewater treatment works. Six of the investigated treatment plants had digesters that were not utilised at all with a total available volume of 21 223 m^3. The average residence time of all of the investigated digesters was 61 d which was 36 d longer than the nominal retention time of 25 d. This indicated that the digesters were under-loaded. Using the design criteria of 25 d hydraulic retention time and 3 kg VS/m^3.d organic load, on average the digesters were 32 % hydraulically under-loaded and 58 % organically under-loaded.

Industries producing high-strength or toxic organic effluents were identified and selected industries were visited. Disposal of these types of effluent is problematic if the General Standards for disposal into a sewer system are not met. The solution generally involves costly tariffs, dilution of the wastewaters with valuable potable water, marine discharge or co-disposal into municipal landfill sites. Anaerobic digestion has been shown to have the potential to treat effluents of this nature. Microorganisms have the ability to acclimate to xenobiotic or toxic substrates which provides the potential for the anaerobic degradation of most substrates. The survey concentrated on two regions, viz. Durban South and Pinetown, due to the availability of anaerobic digestion capacity at the Southern, and Umbilo and New Germany Works, respectively. Industries producing an effluent with a COD > 2 000 mg/ℓ were included in the survey. A matrix was compiled in which available digestion capacity was matched with potential effluents for treatment. From the investigation of the industries and the composition of effluents it was concluded that there was the potential for the utilisation of available resources to effectively stabilise effluents which otherwise could have an adverse effect on the environment.

The laboratory-scale screening test was based on the method of Owen et al. (1979) which was found to be a suitable method for the easy assessment of the anaerobic degradability and potential toxicity of a compound. These assays facilitated the determination of whether the loading of a substrate into an anaerobic digester would be detrimental to its operation and provided information on volumes and concentrations of an effluent that could be treated effectively. Material and energy balances provided an indication of the efficiency of the digestion process in the serum bottles.

Detailed evaluation of the anaerobic digesters at the Umbilo Sewage Purification Works (USPW) identified available capacity in terms of both hydraulic and organic load. This was determined by investigation of the flow to the digesters and the properties of the feed sludge. The hydraulic load to the USPW was 75 % of the design capacity (it was designed to treat a flow of 23.2 Mℓ/d but was only treating 17.38 Mℓ/d) hence the load the anaerobic digesters was below capacity. The anaerobic digesters were high-rate digesters in that they were heated and mixed. They could, therefore, receive an organic load of between 1.5 and 3 kg VS/m^3.d. The annual average feed to the digetsers was 1.12 kg VS/m^3.d which indicated that the digesters were organically underloaded.

The stability of the Umbilo digestion process was assessed by analysis of the characteristics of the digester sludge. Operation of the digesters was efficient. Similar analyses were performed at the other wastewater treatment works to determine the performance efficiency and highlight under-performance. This facilitated the recommendation for remedial action and the ultimate improvement of utilisation of digestion facilities.

Tracer tests are useful to assess the mixing and flow patterns within an anaerobic digester as well as the quantification of active volume. A residence time distribution test was performed on an anaerobic digester at the USPW. The tracer test indicated that the entire digester volume was utilised thus indicating the absence of dead volume. The mixing process was efficient with the reactor approximating a perfect completely stirred tank reactor (CSTR). A sludge bypass of 1.94 % of the flow was detected. This should be remedied to prevent the presence of undegraded substrate in the final effluent.

The laboratory-scale test protocol was applied to assess the anaerobic degradability of a textile size solution. The size solution was chosen due to its high organic strength (ca. 120 000 mg/ℓ) and because the textile mill producing the effluent was located in the vicinity of the USPW. The effluent was being tankered approximately 40 km for marine discharge. The serum bottle tests showed that the size solution was anaerobically degradable. Interactions between microbial populations together with co-metabolism resulted in the efficient degradation of the substrate even though components of the size solution were found to be inhibitory to the biomass. Acclimation experiments were undertaken with the inhibitory size components since it is known that microorganisms have the ability to acclimate to inhibitory substrates so that they can be degraded at concentrations which were previously inhibitory. These results indicated the potential to treat of the textile size effluent in the available anaerobic digester capacity at the Umbilo Sewage Purification Works.

Cleaner production is *the continuous application of an integrated preventative environmental strategy to be applied to processes, products and services to increase eco-efficiency and to reduce risks for humans and the environment*. Segregation and concentration of the high-strength or toxic effluent components would facilitate cleaner production and eco-efficiency since the strength of the final effluent would be much lower, the concentrated waste could be recycled in the process or it could be treated in available anaerobic digester capacity thus reducing co-disposal in landfill sites and marine discharge. In terms of the *Cradle to Grave* concept, a waste generator must assume full responsibility for its waste, including the safe disposal.

5 Realisation of Objectives

From the results obtained during the course of this project, it is evident that the objectives have been achieved. The survey of the anaerobic digesters and the evaluation of the performance efficiencies of the individual digesters provided an indication of the wastewater treatment plants with the potential to accept greater loads, in the form of industrial effluent. This information could facilitate the rational location, in KwaZulu-Natal, of new industries that produce high-strength or toxic organic effluents. The survey also identified under-performing digesters. Remedial action, which often involved simple solutions such as heating or mixing the digester contents to improve the degradation process, was suggested. Improvement of the degradation process would facilitate the optimal utilisation of the effluent treatment facilities.

Industries producing high-strength or toxic organic effluents were identified. Nearby wastewater treatment works were evaluated to assess the potential for treatment of the effluents in the available anaerobic digester capacity. The majority of the high-strength effluents were discharged to sea, thus the implementation of anaerobic treatment would safeguard the aquatic environment.

A laboratory-scale protocol was developed for the assessment of the anaerobic degradability of an effluent and its components. This research concentrated on the application of high-strength organic effluents, however, the protocol could also be applied to toxic organic effluents. Investigation of the high-strength textile size effluent allowed for the development of the protocol. The size solution contained toxic components thus acclimation techniques were investigated.

During the course of the project, two landfill sites in the greater Durban area were closed to co-disposal due to subsidence problems. Implementation of this research work would provide a safe treatment option for those industries producing high-strength or toxic organic effluents. This would provide a solution to the co-disposal problem, prevent dilution of the effluents with valuable potable water and would also protect the marine environment by preventing sea outfall.

6 Recommendations

1. The anaerobic digester performance evaluation should be extended throughout the country. The utilisation of these available resources would generate income which could be used for social improvement such as the provision of sanitation.

2. A thorough survey of industries with emphasis on the identification of point source emissions within the factories should be undertaken. This would facilitate the segregation and concentration of the high-strength or toxic effluent components on-site. These could then be tankered to a nearby wastewater treatment works for anaerobic treatment in available capacity.

3. Segregation of high-strength or toxic components on-site would promote cleaner production strategies such as recycling. Raw material substitution could also be implemented. This involves the replacement of recalcitrant components with biodegradable substitutes.

4. The information from the effluent survey could contribute to the proposed national database on effluent production and characteristics.

5. Assessment of the cost-effectiveness of the proposed treatment option and logistical considerations, such as road quality and maintenance with increased usage by tankers, should be undertaken.

6. There should be long-term monitoring of effluent degradation by the staff at the wastewater treatment works.

7. Research into the concentration, or thickening, of digester sludge for the efficient utilisation of digester volume should be carried out. Investigation of the computational fluid dynamics of an under-performing digester could also contribute to improved process efficiency.

8. The serum bottle test should be scaled up to a 20 ℓ laboratory-scale reactor to provide more accurate information for prediction of operation in a full-scale digester. The set-up and operating procedure for these tests are presented in **Appendix E**.

9. The described protocol should be employed in the laboratories at the respective wastewater treatment works for the assessment of effluents prior to their acceptance for anaerobic digestion.

10. The closure of the Bulbul Road landfill site to co-disposal has necessitated the co-disposal of toxic wastes onto the unlined Springfield Park landfill. This poses grave environmental problems in terms of contamination of the groundwater and rivers. There is the potential for these effluents to be treated in available anaerobic digester capacity thereby safeguarding the environment.

11. Dedicated or specialised digesters could be developed to treat the toxic effluents on-site. Acclimation of the biomass would facilitate efficient pre-treatment of the effluent, which could then be discharged to sewer. The digesters would be under the control of the local authority who would monitor the effluent quality. This would reduce transportation risks.

7 *Technology Transfer*

The research facilitated interaction with, and contribution to, the following projects:

1. The residence time distribution test carried out on the Umbilo digester was modelled using IMPULSE, which was developed during the course of WRC Project No. 363 entitled *The Development and Evaluation of Small-scale Potable Water Treatment Equipment*.

2. The project was motivated by conclusions reached during the course of WRC Project No. 456 entitled *The Regional Treatment of Textile and Industrial Effluents* which identified the under-utilisation of anaerobic digestion facilities in the KwaZulu-Natal Region.

3. An Honours project (Department of Microbiology and Plant Pathology at the University of Natal, Pietermaritzburg) to isolate bacterial populations targeting selected industrial wastewaters.

4. A student laboratory project (Department of Chemical Engineering, University of Natal, Durban) applied the biodegradability and toxicity assays to ascertain the anaerobic treatability of ice cream waste.

5. The biodegradability and toxicity protocol will be applied by a number of B-Tech students (Natal Technikon) in order to assess a number of identified effluents.

6. A student laboratory project (Department of Chemical Engineering, University of Natal, Durban) assessed the baffled (compartmentalised) anaerobic digester for the treatment of a high strength organic effluent.

7. An effluent survey conducted by a research team at Natal Technikon.

The establishment of the KwaZulu Natal Water Research Network and the frequent meeting of its members has facilitated the exchange of ideas and collaborative research as well as the ability to use equipment in other laboratories.

Two paper and 5 poster presentations were made at various conferences.

One MScEng thesis (publication pending examination).

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List of Abbreviations

ADWF	Average dry weather flow
ATA	Anaerobic toxicity assay
ATP	Adenosine triphosphate
BMP	Biochemical methane potential
BOD	Biochemical oxygen demand
CMC	Carboxymethyl cellulose
COD	Chemical oxygen demand
CSTR	Completely stirred tank reactor
DAF	Dissolved air flotation
IC	Inorganic carbon
MRR	Maximum rate ratio
NADH	Nicotinamide-adenine-dinucleotide (oxidised form)
OA	Oxygen absorbed
OFN	Oxygen-free nitrogen
OMS	Oxidised modified starch
PCB	Polychlorinated biphenyl
PVA	Polyvinyl alcohol
PST	Primary settling tank
SRB	Sulphate-reducing bacteria
SRT	Sludge residence time
STP	Standard temperature and pressure
TC	Total carbon

TCA	Tricarboxylic acid
TOC	Total organic carbon
TS	Total solids
US EPA	United States Environmental Protection Agency
USPW	Umbilo Sewage Purification Works
VFA	Volatile fatty acid
VS	Volatile solids
VSS	Volatile suspended solids
WWTW	Wastewater treatment works

Glossary

Acclimation
The adaptation of a microbial community to degrade a previously **recalcitrant** compound through prior exposure to that compound.

Adaptation
A change in the microbial community that increases the rate of transformation of a test compound as a result of prior exposure to that test compound.

Agro-industry
Industry based on the processing of agricultural products.

Anaerobe
A microorganism capable of growing or metabolising in the absence of free oxygen. These microorganisms may be facultative or obligate; the latter will perish in the presence of free oxygen.

Anaerobic digestion/ biodegradation
The microbial degradation of an organic compound in the absence of oxygen. It is effected by anaerobic bacteria which degrade the compound in a step-wise process yielding organic acids, carbon dioxide and hydrogen and, ultimately, methane and carbon dioxide.

Anoxic
An environment where oxygen is present in the form of chemical compounds such as nitrate or sulphate.

Archaebacteria
An evolutionary distinct group of prokaryotes, including the methanogenic, extremely halophilic and sulphur-dependent bacteria.

Batch culture
A closed culture environment in which conditions are continuously changing according to the metabolic state of the microbial culture.

Biodegradable
A property which allows the microbial decomposition of an organic compound to inorganic molecules.

Biorefractory
A property which renders a compound resistant to biological degradation.

Biogas	The gas produced, principally methane and carbon dioxide, by the action of anaerobic microorganisms on organic compounds.
Catabolism	The degradation of complex organic molecules into simpler compounds with the release of energy.
Chemical oxygen demand (COD)	A measure of the total amount of organic material in a waste stream.
Co-disposal	The calculated and monitored treatment of industrial and commercial liquid and solid wastes by interaction with biodegradable wastes in a controlled landfill.
Degrade	Break down into simpler substances by bacterial action.
Dewatering	The removal of water from a sludge.
Eco-efficiency	The delivery of competitively priced goods and services that satisfy human needs and quality of life, while progressively reducing ecological impacts and resources intensity throughout the life cycle to a level in line with the Earth's carrying capacity.
Effluent	A stream flowing from a sewage tank or industrial process.
Facultative anaerobe	An organism capable of either aerobic or anaerobic growth.
Feed schedule	Pre-determined schedule which sets out the digester feed programme.
Grit	Heavy mineral matter associated with wastewater e.g.. sand.
Hazardous waste	An inorganic or organic element or compound that, because of its toxicological, physical or chemical properties, may cause detrimental impacts on human health and the environment.

Headspace	The volume in a sealed vessel not occupied by the liquid phase.
Immobilisation	A mechanism of bacterial agglomeration and bacterial attachment to support material.
Inhibition	An impairment of bacterial function.
Kinetics	The explanation of the observed characteristics of chemical reactions.
Labile	Readily degradable.
Lithotroph	An organism that can obtain its energy from oxidation of inorganic compounds.
Loading rate	Measure of the organic content of the feed in relation to the digester volume.
Methanogens	Bacteria which utilise volatile organic acids as substrates and produce methane and carbon dioxide.
Mineralisation	Microbial decomposition of an organic compound to inorganic constituents such as carbon dioxide, methane and water.
Pollution	An adverse alteration of the environment.
Primary anaerobic digester	Digester, at a sewage works, in which the substrate is anaerobically digested by the microorganisms in the sludge; it is usually heated and mixed.
Recalcitrant	Resistant to microbial degradation.
Retention time	Average period of time that the incoming sludge is retained in the digester for completion of the biological reactions - calculated by dividing the digester volume by the incoming flow.

Screen	Device for the removal of large solids from the waste water.
Scum	Layers of fats and oils which float on a liquid surface.
Secondary anaerobic digester	Digester, at a sewage works, in which the separation of the sludge from the supernatant takes place; usually unheated and unmixed.
Seeding	The use of an actively digesting sludge to aid the start-up of a digester by supplying a quantity of the preferred types of organisms. This usually reduces the time taken for a digester to become active.
Size	A coating applied to **warp** yarn to improve its weaving efficiency.
Sludge	The general term applied to the accumulated solids separated from waste water. A large portion of the sludge material in a digester consists of bacteria which are responsible for its decomposition.
Suspended solids	Undissolved non-settleable solids present in wastewater.
Syntrophy	A nutritional situation in which two or more organisms combine their metabolic capabilities to catabolise a substance not capable of being catabolised by either one alone.
Total solids	The sum of dissolved and suspended constituents in wastewaters or sludges.
Toxicity	An adverse effect (not necessarily lethal) on bacterial metabolism.
Treatability	The ability of a given digestion system to stabilise an effluent.
Volatile fatty acids	Short-chain organic acids produced by the anaerobic digestion process.
Volatile solids	Organic solids which are lost on ignition at 600 °C.
Warp	The longitudinal threads in a length of fabric.

Waste water	General term to denote a combination or mixture of domestic sewage and industrial effluents.
Working volume	The portion of the total volume that is actively involved in the digestion process.
Xenobiotics	Synthetic organic chemicals or natural chemicals present in unnatural concentrations.

Chapter 1
Introduction

Water is essential to life, to social development and to economic progress

(Department of Water Affairs, 1986).

According to the new constitution of the Republic of South Africa (Constitutional Assembly, 1996), *everyone has the right to an environment that is not harmful to their health or well-being and to have the environment protected, for the benefit of present and future generations, through responsible legislative and other measures that prevent pollution and ecological degradation, promote conservation, and secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development. Everyone has the right to have access to water.*

1.1 Water Quality and Regulation in South Africa

In South Africa, the increasing demand for water arising from the growth of the population and the economy has to be met from limited resources (Department of Water Affairs, 1986). **Sustainable development** is development that meets the needs of the present generation without compromising the ability of future generations to satisfy their own needs. Water is a public commodity and the actions of users and polluters generally affect others. An expanding demand due to rapid population increase and demographic changes will result in water becoming increasingly scarce in many parts of South Africa. Greater pollution loads and reduced flows in the country's rivers, due to the expanding demand, will in future place additional pressure on the already limited water resources (Department of Water Affairs and Forestry, 1993).

Although industry only accounts for approximately 16 % of South Africa's direct water use, its impact is much higher because effluents often contain toxic pollutants (Stander, 1997). In coastal areas, the biggest problem with industrial water users is the amount of fresh water lost via effluent pipelines to sea; the water should be treated and returned to the rivers for reuse. The strict effluent discharge regulations promulgated in terms of the Water Act of 1956 resulted in the construction of wastewater purification plants which discharge highly treated effluent (Department of Water Affairs, 1986). Technically, it is possible to purify effluent to any desired quality. The reuse of effluent as a source of water will assume increasing importance in many areas of the country, particularly in areas of urban and industrial growth (Department of Water Affairs, 1986). For this additional source to be used to its best advantage requires the purposeful management of effluent.

Before the advent of the Water Act of 1956, there was no statutory provision for State control over the purification and disposal of effluent (Department of Water Affairs, 1986). The Water Act, in anticipation of water shortages, made provision for the compulsory purification of effluent by the user to specified standards and its subsequent disposal in a manner that would make it available for reuse. The Act provided for control over the use of water for industrial purposes as well as for control over and the prevention of water pollution.

An intensive review of the 1956 Water Law was conducted in 1997 by the Department of Water Affairs and Forestry. The review was motivated by the need for preparation for new legislation that would reflect democratic principles and equitable access to the resource by all; symbolised by the slogan *some for all, forever* (Department of Water Affairs and Forestry, 1997). While management's goal is to ensure all water users will benefit from access to the water resource, ecological integrity provides a good indication of sustainability in the use of the resource. The proposed policy (Department of Water Affairs and Forestry, 1997) integrated resource-directed measures for protection, such as resource quality objectives, with source-directed measures, such as effluent standards.

The source-directed measures included the use of discharge or impact standards. These standards should be stringent enough to protect the specific water resource affected. The development of new standards was proposed. Waste discharge or impacts which can meet these national standards would not require an impact assessment, thus minimising the human and financial resources needed for administration (Harris , van Vliet and MacKay, 1997). Specific criteria will be developed to provide guidelines for impact assessment studies to determine allowable exemptions. With the adoption of the White Paper a new process of consultation will begin in support of the development of a new National Water Bill and regulations for implementation of the policy. Participation will include communities, water users, academic institutions, scientific councils, and Government at national, provincial, and local levels. The Water Bill will provide the basis from which to ensure that all South Africans are able to satsify their basic needs for water supply and sanitation with dignity and equity. *Unless measures are taken to cherish and maintain the scarce water resources on which these services depend, these efforts will come to nothing* (Department of Water Affairs and Forestry, 1997).

1.2 Industrial Effluent Treatment

The KwaZulu-Natal region has the potential to attract a significant amount of industry in the near future. Due to the abundance of water relative to the rest of the country, it is probable that some of these industries will be from the agro-industrial sector. One of the characteristics of this class of industries is the high concentration of organic compounds in the effluents. A second class of industry that could be attracted is that which produces high-strength or toxic organic effluents. Industries of this type already exist in the region and, due to the nature of the effluents that they produce, encounter difficulties in the safe disposal of the effluents, with co-disposal into municipal landfill sites or marine discharge being the common solutions.

Cleaner production is the continuous application of an integrated preventative environmental strategy, applied to processes, products and services to increase eco-efficiency and to reduce risks for humans and the environment. Implementation of cleaner production and waste minimisation practices, at the effluent source, will lead to the production of more concentrated effluents. Anaerobic digestion has the potential to treat these concentrated wastewaters.

Investigations have identified the need for anaerobic digestion facilities that can accept high-strength organic effluents. Tracer tests on a number of anaerobic digesters in the KwaZulu-Natal region showed that the average mixing volume is can be as low as 50 % of the actual volume (Barnett, 1995; Barclay, 1996). These results confirmed studies undertaken previously, on digesters in the United States of America, by the United States Environmental Protection Agency. Other research projects, undertaken in the Department of Chemical Engineering of the University of Natal, Durban, have shown that there are a number of sewage works, in KwaZulu-Natal, with under-utilised anaerobic digestion facilities (Barnett, 1995; Barclay, 1996).

The KwaZulu-Natal region has a great need for the provision of sanitation. The increasing urban and peri-urban population will require the extension of sewage reticulation and an increase in sewage treatment capacity. The increased use and income from existing but under-utilised capacity will assist in financing the additional infrastructure in areas where it is needed. Control of the wastewater treatment plants in the greater Durban area is currently (1997/8) being assumed by the Durban Metropolitan Council. This standardisation provides the potential for the utilisation of the available capacity which would provide relief at plants operating at or over design capacity. This would delay the need for capital expenditure and increase the income from capital already expended.

1.3 Project Aims

This project is part of a larger overall plan in which the existing anaerobic digestion capacity in South Africa can be extended and used more intensively. The main objectives of this research were:

1. To provide information that will allow for the rational location, in KwaZulu-Natal, of new industries that produce high-strength or toxic organic liquid effluents;
2. To assist in the optimal utilisation of effluent treatment facilities in the region;
3. To identify under-performing digesters with a view to recommending courses of remedial action;
4. Identify industries in the region that produce high-strength or toxic liquid effluents in order to allow rational decisions to be taken for their safe disposal;
5. To safeguard the aquatic environment through providing suitable industrial effluent treatment options; and
6. To promote the regional development of new industries or agro-industries that produce high-strength or toxic organic aqueous effluents by providing effluent treatment options.

1.4 Project Approach

The principal objective of this investigation was to assess the potential to treat high-strength or toxic organic effluents in the under-utilised anaerobic digester capacity in the region. The following approach was adopted.

A review of the literature was undertaken to gain familiarity with the fundamentals of anaerobic digestion such that the required techniques for anaerobic test work could be understood and mastered. A literature review was also undertaken to investigate the kinetics and modelling of anaerobic systems.

The literature gave an indication of the parameters affecting the efficient functioning of an anaerobic digester. The local authorities were interviewed and the digesters were visited. Physical and operating data for each of the digesters were obtained and used to calculate the performance efficiencies. This allowed for the identification of under-performing digesters and digesters available for the treatment of high-strength or toxic industrial effluents.

Selected industries were contacted to obtain data on their effluents and the local authorities provided information on the proposed development of new industries. From these data, a matrix was compiled which identified potential anaerobic digesters for treatment of effluents produced in the vicinity.

Anaerobic digestion has the potential to stabilise the degradable fraction of high-strength or toxic organic effluents either entirely or such that they can be further degraded aerobically. To achieve the research objective, a strategy was followed (**Figure 1.1**). The strategy, which can be applied to different effluents, was developed during the course of this research project.

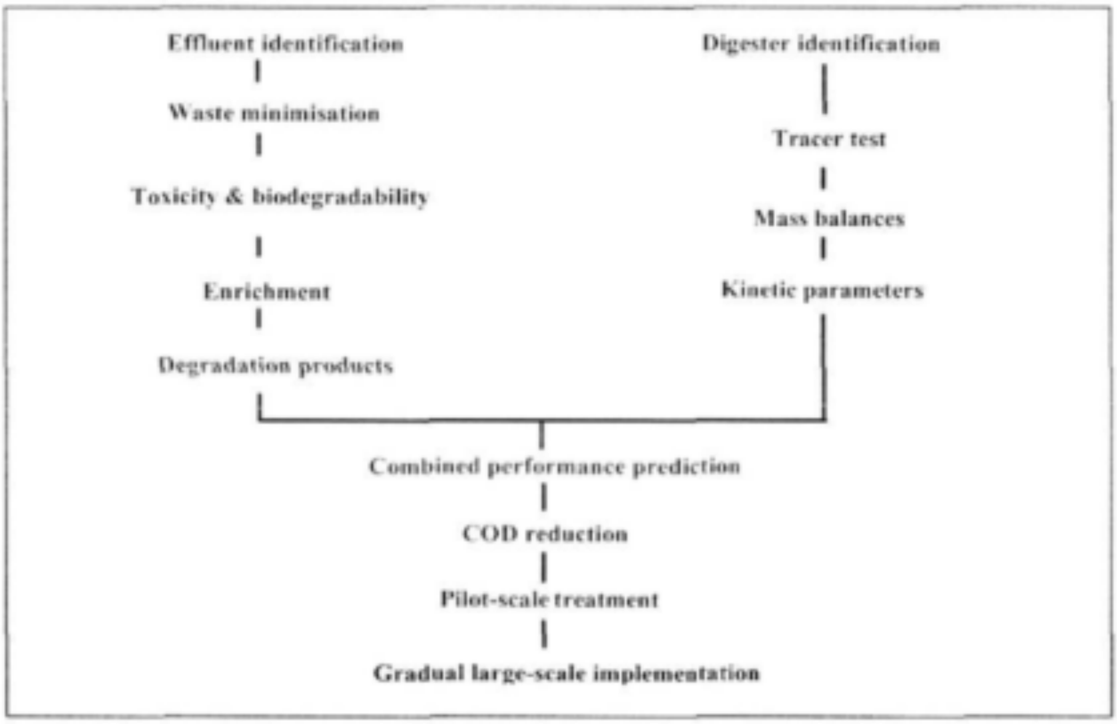

FIGURE 1.1: Strategy for the anaerobic treatment of organic effluents.

The overall strategy follows two concurrent pathways; one investigates the effluent and the other the digester.

Effluent: the first step is to identify an appropriate effluent. Effluents of interest are those with very high chemical oxygen demand (COD) values which would overload conventional treatment processes; those that are co-disposed on municipal landfill sites; and those that are discharged to sea. Options for waste minimisation are examined with the aim to concentrate the high-strength waste. The principal objective is for the industries to concentrate the high-strength waste on site rather than to dilute and discharge. The waste could then be tankered to the nearest wastewater treatment works for treatment in the available digester capacity. It is critical to determine the anaerobic degradability and potential toxicity of an effluent prior to its loading into a digester, to prevent digester failure. A laboratory-scale batch test protocol was developed to screen the effluents. Anaerobic biomass may have to undergo a period of enrichment to acclimatise it to a particular effluent if, during the laboratory-scale tests, it is found to be toxic or inhibitory. The biomass is exposed to small, but increasing, concentrations of the molecule over a period of time. The culture could then be used to seed digesters thus preventing digester failure and reducing the lag period. In the event of inhibition, degradation products should be identified since anaerobic digestion is a multi-phase process and intermediates formed during the degradation of a specific effluent may be inhibitory to the microorganisms performing the later stages of the digestion process. The batch tests allow for the determination of the degradation rate and the ultimate degradability of an effluent.

Digester: a locally available anaerobic digester is identified. A tracer test should be done on the digester to assess the mixing efficiency. Other important considerations include mass balances and kinetic parameters.

The two pathways then merge. Knowledge of the digester efficiency and the effluent degradation kinetics should facilitate the prediction of whether an effluent can be treated anaerobically, on a large scale. The reduction in COD is important as it gives an indication of the extent of organic degradation. The batch tests provide information of the volumes and concentrations of an effluent that can be treated effectively. This information can then be applied, initially at pilot-scale and ultimately for full-scale implementation, in an existing digester.

The described strategy was applied to determine the feasibility of the anaerobic digestion of a textile size effluent. The effluent was chosen due to its high organic strength (ca. 140 000 mg/l) and because the mill producing it was located within 10 km of the Umbilo Sewage Purification Works which had available anaerobic digestion capacity.

The report begins with a review of literature on the subject of anaerobic digestion of industrial effluents which is presented in **Chapter 2**. An inventory of the anaerobic digesters, in KwaZulu-Natal, and an assessment of their performance efficiencies is given in **Chapter 3**. The results of the industry survey are presented in **Chapter 4**. **Chapter 5** describes the laboratory-scale protocol which was developed to determine the anaerobic degradability of an effluent.

The case study, investigated in this project, aimed to assess the feasibility of treating a textile size effluent in available digester capacity at the Umbilo Sewage Purification Works. **Chapter 6** describes the investigation of these digesters and the evaluation of their potential to treat the high-strength textile effluent. Results of the investigation of the treatment of the textile size effluent are also presented in **Chapter 6** with a discussion of the application of these results for full-scale treatment.

The report is concluded with **Chapter 7**. A summary of the experimental work is presented and recommendations for future research are made. **Chapter 8** is a summary of technology transfer that was achieved during the duration of the project.

Chapter 2

Anaerobic Digestion - An Overview

Anaerobic digestion has gained popularity, in recent years, as an efficient, cost-effective treatment method. This literature review describes the mechanism and the microbiology of anaerobic digestion and gives a brief overview of the kinetics and modelling of anaerobic systems. Details of the numerous digester configurations that have been developed to treat wastewaters of various compositions are given and the anaerobic degradation process is described in detail.

2.1 Anaerobic Digestion

Anaerobic digestion is a process by which a wide variety of organic molecules can be converted into a gas rich in methane. In view of the current problems, both in the protection of the environment and the search for sources of renewable energy, anaerobic digestion appears to be a favourable biotechnological process to treat an organic waste through bioconversion into energy.

The increasing presence of organic compounds in the country's water resources is cause for major concern. There are a range of techniques eg. advanced oxidation, activated carbon and membranes, for the removal of organic molecules from potable water. These processes are, however, expensive and treat the symptoms and not the cause. Anaerobic digestion has the potential to break down complex biorefractory organic compounds so that they may be further degraded aerobically or to mineralise biorefractory compounds.

Anaerobic microorganisms are ubiquitous and occur in many natural ecosystems as well as in process simulations used for waste management (Pohland, 1992). Anaerobic treatment of complex organic materials is a multi-phase process (**Figure 2.1**).

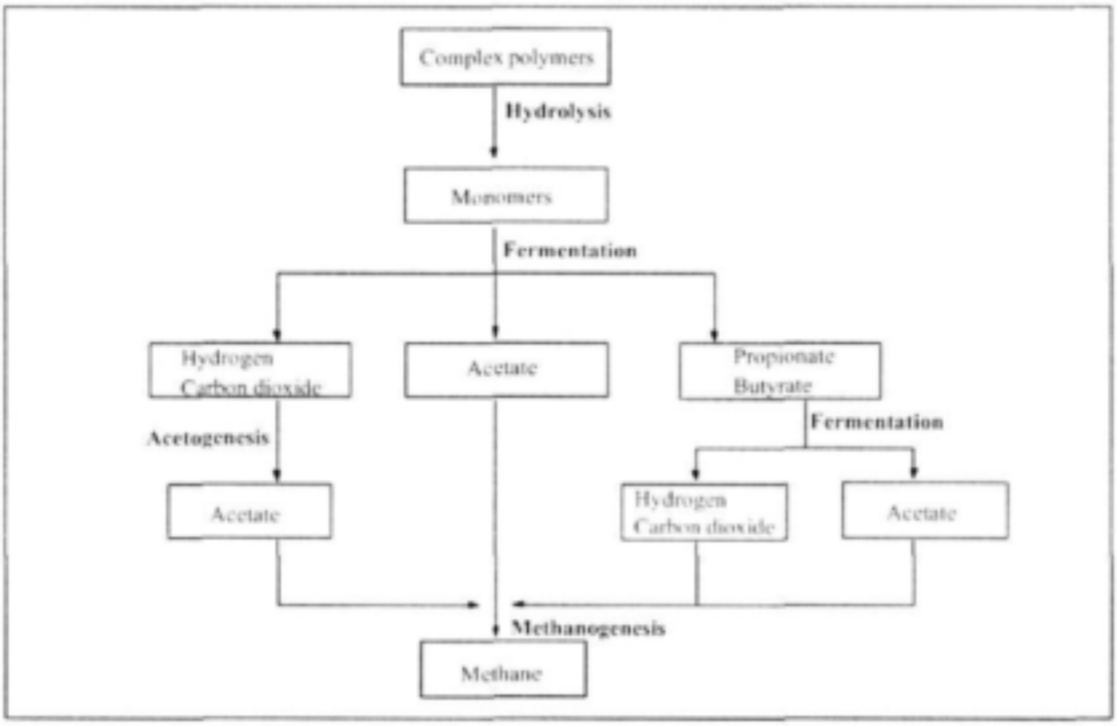

FIGURE 2.1 : Overall process of anaerobic decomposition (After: Brock and Madigan, 1991) .

Currently, most soluble effluents, which are treated at wastewater treatment works, are treated by the activated sludge process and not by anaerobic digestion. The anaerobic degradation process has several advantages over aerobic processes for treatment of high-strength organic effluents. Although the microbiology and biochemistry of the process are complex, it normally operates effectively with minimal control (McCarty, 1964).

In aerobic treatment, the microorganisms use the organic waste as substrate and use the oxygen in the air to metabolise a portion of this to carbon dioxide and water. Since these organisms obtain energy from this oxidation, their growth is rapid and a large portion of the organic waste is converted to new cells (Speece, 1996). The portion converted to biomass is not actually stabilised but is simply biotransformed. Although these cells can be removed from the waste stream, the biological sludge they produce still presents a significant disposal problem. Unlike aerobic oxidation, the anaerobic conversion to methane gas provides relatively little energy to the microorganisms. Thus, their rate of growth is slow and only a small portion of the waste is converted to new biomass with the major portion converted to methane gas. Conversion to methane represents waste stabilisation since methane is poorly soluble and escapes from the waste stream where it can be collected. As much as 80 to 90 % of the degradable organic portion of a waste can be stabilised in anaerobic treatment, even in highly loaded systems. This is in contrast to aerobic systems where only about 50 % of the waste is actually stabilised, even with conventional loadings (McCarty, 1964).

Another advantage of anaerobic digestion is, since only a small portion of the waste is converted to cells, the problem of disposal of excess sludge is greatly minimised. The absolute quantity as mass of organic matter is low and the dewatering capacity is high (Jewell, 1987; Lettinga, de Man, van der Last, Wiegant, van Knippenberg, Frijns and van Buuren, 1993; Etheridge and Leroff, 1994).

Since anaerobic treatment does not require oxygen, the treatment rates are not limited by oxygen transfer and the non-requirement for oxygen also reduces the power requirements. In contrast, the methane gas produced is a good source of fuel energy (McCarty, 1964). A disadvantage of anaerobic digestion, however, is the global warming potential of the methane gas, which is approximately 11 times greater than that of carbon dioxide. Some 250×10^6 tonnes/year of methane are released world-wide into the atmosphere from uncontrolled methanogenic fermentation of organic wastes and residues.

2.2 *Anaerobic Microbiology*

During **hydrolysis** (**Figure 2.1**) complex long-chain macromolecules (carbohydrates, lipids and proteins) are hydrolysed extracellularly, via the Embden-Meyerhof pathway (EMP), to short-chain compounds (sugars, fatty acids and glycerol, and amino acids, respectively). Hydrolysis can be a slow process and can be the rate-limiting step in fermentation particularly if the influent contains particulate or large complex molecules in significant quantities. The resulting monomers are **fermented** to various intermediates, primarily acetate, propionate and butyrate, with the production of carbon dioxide and hydrogen. The biochemical pathways and end products for this phase depend upon the substrate and the hydrogen partial pressure (**Figure 2.2**). At a low hydrogen partial pressure, glucose is catabolised to acetate, carbon dioxide and hydrogen. At both low and high hydrogen partial pressures, glucose can be degraded to butyrate, carbon dioxide and hydrogen (McCarty and Smith, 1986; Sam-Soon, Wentzel, Dold, Loewenthal and Marais, 1991). When the hydrogen partial pressure is high, acetate, propionate, carbon dioxide and hydrogen will be formed from glucose. The propionate and butyrate produced in this phase cannot be used directly for methanogenesis and they are converted to acetic acid, carbon dioxide and hydrogen in a second fermentation phase. This conversion can only occur under conditions of low hydrogen partial pressures. Additional acetate is produced by a second group of microorganisms termed acetogenic bacteria (Pfeffer, 1979; Sam-Soon et al., 1991). The acetic acid becomes the substrate for a group of strictly anaerobic methanogenic bacteria. These bacteria ferment acetic acid to methane and carbon dioxide. This methane, together with the methane formed by bacteria which reduce carbon dioxide utilising hydrogen gas or formate produced by other species, accounts for the methane produced in this process (Pfeffer, 1979). The methane formed in this last stage, being poorly soluble in water, is lost to the gas phase. It can be collected and used for its energy value. The carbon dioxide that is evolved partially escapes to the gas phase (Pfeffer, 1979; Fang and Lau, 1996). Thus, two main substrate sources are used for methanogenesis, namely, hydrogen and acetate. The methanogens are classified into three groups according to their energy source: hydrogenotrophs, which use hydrogen as the only energy source, acetoclastic methanogens, which use acetate as their sole energy source, and hydrogen/acetate utilisers, which can utilise both hydrogen and acetate.

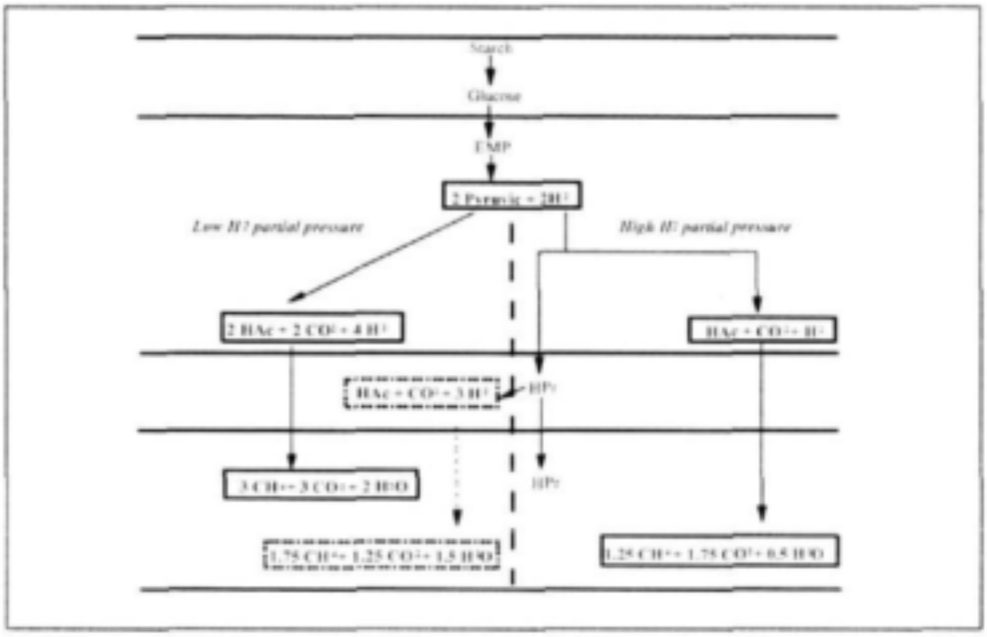

FIGURE 2.2 : Methane fermentation under high and low hydrogen partial pressure conditions (After : Sam-Soon, Loewenthal, Wentzel and Marais, 1989).

The methanogens (e.g. *Methanosaeta*, *Methanosarcina* and *Methanospirillum*) belong to a special group of bacteria (the Archaebacteria). They differ from other bacteria in their type of metabolism and in the composition of cell constituents (Zehnder, 1988; Schlegel, 1992). Methanogens are obligate anaerobes with strict requirements for low redox potentials and the absence of dissolved oxygen. They normally grow in close association with other non-methanogenic bacteria to form a symbiotic community of microorganisms with a self-regulating fermentation which automatically controls its own pH value, redox potential and oxygen tension.

Many anaerobic bacteria can perform electron-transport phosphorylation (regeneration of ATP) under anaerobic conditions, by transferring electrons derived from a substrate via a short electron-transport chain to an external electron acceptor supplied in the nutrient medium or an internal electron acceptor derived from substrate degradation (Senior, 1991; Schlegel, 1992). In most cases, the energy sources used by organisms carrying out anaerobic respiration are organic compounds but several lithotrophic organisms are also able to carry out this process (Brock and Madigan, 1991). Nitrate, sulphate, carbonate and fumarate ions, as well as sulphur and carbon dioxide can function as electron acceptors (Schlegel, 1992). The presence of alternative electron acceptors may inhibit methanogenesis (Pohland, 1992).

2.3 Anaerobic Kinetics and Modelling

Anaerobic treatment is a multi-disciplinary field. Whilst numerous studies have significantly increased the understanding of the microbiology and biochemistry of anaerobic treatment, knowledge of process kinetics is needed to establish a rational basis for system design and analysis. The efficiency of a wastewater treatment process is influenced by the microbiology and the associated biochemistry and, when located in a reactor, biochemical reactions are also affected by flow dynamics and associated mass transfer considerations (Harper and Suidan, 1991). Much of the kinetic data available in the literature were derived in laboratories where the methods used may not clearly represent microbial behaviour in pilot- or full-scale wastewater treatment reactors. However, these data are useful in describing critical associations. This review concentrates on the concepts behind the equations for the determination of kinetic parameters associated with the complex microbial conversion of wastewater substrates, and the ways in which the equations can be linked together to build a mathematical model.

2.3.1. Anaerobic kinetics

Anaerobic treatment is a complex process involving the parallel and consecutive reactions of many interrelated populations whose biochemical behaviour can be dynamic or transient. In such a complex multi-step process, the kinetics of the slowest step will govern the overall kinetics of waste utilisation (Lawrence and McCarty, 1969). The rate-limiting step is believed to be methane fermentation since the bacteria that ferment acetate to biogas grow slowly (McCarty and Mosey, 1991).

In a completely-mixed reactor, the biodegradable portion of the waste that flows into the reactor is catabolised by the microorganisms. The concentrations of waste and microorganisms in the effluent are equal to the concentrations in the reactor itself since it is fully mixed. The effluent concentration of organic material consists of the remaining refractory and biodegradable portions of the original waste and the organic portion of the microorganisms. These relationships can be explained by the determination of mass balances around the reactor (Jeyaseelan, 1997). The following expression describes the condition :

$$\mu = \frac{\mu_m \ S}{K_s + S} - b \qquad [2.1]$$

where: μ = specific cell growth rate (1/time).

μ_m = maximum specific growth rate which the population can achieve in the absence of any nutrient limitations (1/time).

K_s = saturation constant (mg/l).

S = substrate concentration (mg/l).

b = death constant (1/time)

The net specific growth rate, μ, is equal to the net growth per unit weight of microorganisms per unit time. This equation (Monod kinetic rate equation) is applicable to both the CSTR reactor and the anaerobic contact process (Lawrence and McCarty, 1969). The maximum specific growth rate is a function of temperature since it increases with increasing temperature. The significance of this is that more stable and faster fermentation occurs at higher temperatures (Terzis, 1994).

To evaluate the coefficients of the kinetic model (Eq. 2.1), it is necessary to calculate the specific utilisation, U which is defined as the weight of substrate converted per unit weight of microorganisms per unit time (Lawrence and McCarty, 1969). Calculation of substrate-specific fractions of the microbial mass are based on thermodynamic considerations which show that microbial growth is related to the free energy made available as a result of biochemical transformations of the substrate. Methane production can be used to determine relative growth of substrate-specific microbial populations. Since 2 moles of oxygen are required to oxidise one mole of methane gas, the COD equivalent of methane is 64 g/mole. From this relationship, the grams of substrate COD converted to methane gas can be determined. The reduction of 1 g of COD (at 0 °C and 1 atm) is equivalent to the production of 0.35 l of methane (Speece, 1996).

Identification of the kinetic coefficients of the Monod kinetic rate equation for each component of the solids in a wastewater allows for the improved prediction of the anaerobic digestion process (Jeyaseelan, 1997; McCarty, 1974). Separate kinetic coefficients for acid formation and methane formation should be identified. **Table 2.1** presents several kinetic constants as reported in the literature.

TABLE 2.1 : Kinetic and stoichiometric constants reported in the literature.

	μ_{max} (1/time)	Ks (mg COD/l)	b (1/time)	Y (mg cells/mg COD)
Acidogens				
Denac et al., 1988	1.2	140	0.04	0.03
Zoetemeyer et al., 1982	7.2	22	-	0.1
Acetogens				
Lawrence and McCarty, 1969	0.31	48	0.01	0.042
Gujer and Zehnder, 1983	0.15	246	-	0.036
Acetoclastic methanogens				
Denac et al., 1988	0.34	237	0.015	0.03
Lawrence and McCarty, 1969	0.24	356	0.037	0.038
Smith and Mah, 1966	0.6	320	-	0.04
Gujer and Zehnder, 1983	0.34	165	0.015	0.04
Kuba et al., 1990	0.26	20	-	-
Jeyaseelan, 1997	-	400	0.037	0.03
H_2 utilising methanogens				
Denac et al., 1988	1.4	0.6	0.09	0.029
Gujer and Zehnder, 1983	1.4	0.6	-	0.04

b = death rate
K_s = half saturation constant
Y = yield
μ_{max} = maximum specific growth rate

The variation in parameters arises from the fact that no two mixed cultures will have the same population of bacteria, even when grown on the same substrate, since the populations of the inocula will vary (Grobicki, 1989).

A continuous flow system can eventually reach a steady state in which the mass of microorganisms in the total system will remain constant, i.e. the rate at which microorganisms are wasted from the system equals the net microbial growth rate. When time is expressed in days, the daily net specific growth rate is the reciprocal of the biological solids retention time (SRT). In a completely mixed system, the microorganism concentration is the same in the digester and in the effluent. The quantity of solids wasted daily is equal to Q/V times the total mass of microorganisms in the system, where Q and V are the daily flow rate and volume of the digester, respectively. Since Q/V is the reciprocal of the hydraulic retention time (HRT), the equation reduces to SRT = HRT for the CSTR process. Process failure due to kinetic stress will occur when the SRT is reduced to a value at which the microorganisms are washed out from the system at a rate greater than their maximum net specific growth rate. Under these conditions waste treatment efficiency decreases and the effluent waste concentration, S, approaches the influent waste concentration, S_o. When the influent substrate concentration is large enough to be non growth-limiting, the value of SRT at which process failure occurs is a characteristic parameter of the waste assimilating microbial population (Terzis, 1994).

2.3.2. Modelling of the anaerobic degradation process

A model can be defined simply as a representation or description of a system (Cloete and Muyima, 1997). Several mathematical models have been developed to characterise the anaerobic digestion process (Jeyaseelan, 1997). Different types of models are useful for different purposes (Hobson, 1983). The best models are those which make assumptions carefully and fully explain or justify the assumptions made. Models should be flexible enough to accommodate new findings in biochemical mechanisms, pathways and microbial ecology. Engineers use models of biological processes to aid design, as a tool for process optimisation and as a method of reducing extensive and complex experimental data to simple, manageable formulae (McCarty and Mosey, 1991). Models of biological processes tend to be empirical models based upon observed correlations between the performance of the plant and its main design and operating variables.

Many models have been developed to describe different aspects of the anaerobic degradation process: formate transfer (Harper and Suidan, 1991); biofilm formation (Harper and Suidan, 1991); pelletised sludge bed (Sam-Soon et al., 1991); modelling over a wide pH range (McCarty and Mosey, 1991); the anaerobic digestion of farm wastes (Hobson, 1983); abattoir effluent (Batstone, Keller, Newell and Newland, 1997); olive mill wastewater (Borja, Martin, Alonso, Garcia and Banks, 1995); glucose (Graef and Andrews, 1973); and molasses wastewater (Denac, Miguel and Dunn, 1988). The Monod model has been the most commonly used empirical model to investigate the applicability of the anaerobic digestion of an organic effluent (Jeyaseelan, 1997). An estimation of the kinetic parameters of the Monod model provides a quantitative description of the anaerobic degradation of the organic molecules and also offers useful design information (Terzis, 1994). First order rate equations are commonly used for the initial hydrolysis of complex organic molecules and Monod kinetics are used to describe methanogenesis from acetate (McCarty and Mosey, 1991).

2.4 Anaerobic Digesters

When a digester is commissioned for industrial purposes the emphasis must be placed on the efficiency of bioconversion, on both thermodynamic and kinetic grounds (Nyns and Naveau, 1979). The design of an anaerobic digester and the engineering associated with it depends upon the type and volume of the waste it is required to process (Horton, 1979).

Anaerobic digestion tanks vary in shape but are usually either cylindrical or egg-shaped (Pohland, 1992). The bottoms of the tanks usually slope towards the centre, to form a cone in which the digested solids can collect. A number of design configurations have been used (**Figure 2.3**).

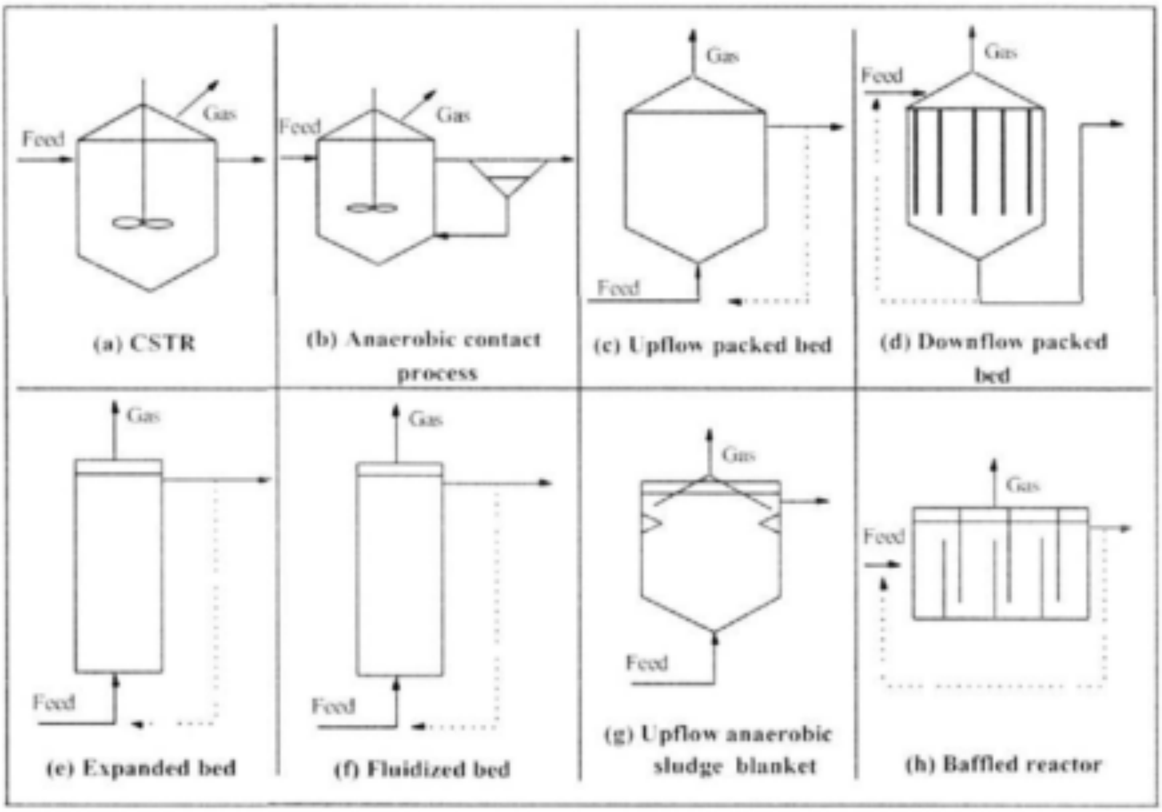

FIGURE 2.3 : Schematic diagrams of various anaerobic digester configurations (After: McCarty and Mosey, 1991; Speece, 1996) .

The conventional **completely stirred tank reactor** (CSTR) (**Figure 2.3 (a)**) contains a mechanical agitation system consisting of a vertical shaft with a number of impellers and a number of baffles around the vessel perimeter. The impeller and baffle system provide an effective agitation system for the dispersion of the effluent. Mixing in anaerobic digesters is advantageous as it eliminates scum and thermal stratification. It also provides good contact between the active biomass and the sludge (Pohland, 1992). The major disadvantage of complete mixing in digesters, in addition to the cost of mixing, is the need for a facility that will enhance the separation of the digested solids from the liquid phase.

In the **anaerobic contact process (Figure 2.3 (b))** the wastewater is treated in a continuously stirred tank reactor with an active population of flocculating bacteria degrading the organic material. The effluent passes through a sludge settler where the bacteria settle before being returned to the reaction tank. The biomass separation system retains both active microorganisms and undigested influent suspended solids thus promoting more extensive biodegradation of wastewater particulates (Pohland, 1992). This process requires effective mixing, settleable biomass and efficient clarification and degassing. The process has a limited tolerance to hydraulic loading and biomass retention.

Stationary biofilm reactors use a fixed film for the development of the high biomass concentrations required for the efficient anaerobic treatment of wastewater (Pohland, 1992; van Haandel and Lettinga, 1994). An inert medium or biomass carrier is added to the treatment vessel and the process is operated to favour the growth of the microorganism biofilm on the medium surface. This prevents biomass wash out, allowing the reactors to operate with liquid flow velocities which would wash out non-attached biomass. The fixed film anaerobic reactor designs include upflow fixed bed reactors, downflow fixed bed reactors and expanded and fluidised bed reactors. In general, fixed bed processes provide a stable and easily operable form of anaerobic treatment technology.

Upflow fixed / packed bed reactors (Figure 2.3 (c)). The wastewater is passed upwards through the medium particles resulting in a large proportion of the retained biomass not being attached to the packing medium. This non-attached material is retained in the interstices between the medium particles partly by settling and partly through the influence of physical contact with the medium (Pohland, 1992). Since the non-attached biomass contributes significantly to the treatment activity in an upflow fixed bed system, relatively low upflow velocities are usually maintained to prevent washout of the material. New synthetic packings are large open structures with high void volumes. The large voidage maximises the available reaction volume and provides space for the accumulation of non-attached biomass (Pohland, 1992). A disadvantage of this system is blockage due to excess biomass accumulation which ultimately leads to decreased retention capacity of the bed.

For wastewaters with high concentrations of suspended solids, **downflow fixed bed reactors (Figure 2.3 (d))** may be preferable to operation in the upflow mode. They utilise ordered, modular packing which provides a surface for the development of the biofilm (Pohland, 1992). By operating the reactor in a downflow mode, suspended solids and sloughed biofilm solids will be carried down with the liquid flow and out of the reactor. This efficient removal of the suspended solids results in a process which retains only the attached microorganisms. These systems are able to withstand severe hydraulic overloading conditions with only a slight reduction in treatment efficiency. Mixing in the downflow system is provided by a combination of both effluent recycle and the action of rising gas bubbles (Pohland, 1992).

With the expanded and fluidised bed processes, attempts have been made to improve anaerobic reactor mass transfer characteristics by the utilisation of small or medium particles with very high surface-to-volume ratios. By applying high liquid upflow velocities, the medium can be expanded to produce a substantial increase in bed porosity (Pohland, 1992; van Haandel and Lettinga, 1994). The differences between expanded and fluidised beds are the upflow velocity used and the degree of medium expansion maintained. In **expanded bed** systems **(Figure 2.3 (e))**, sufficient flow is applied to increase the settled bed volume by 15 to 30 %. At this point, individual particles are supported partly by the fluid flow and partly by contact with adjacent particles. **Fluidised beds (Figure 2.3 (f))** utilise higher upflow velocities to produce 25 to 300 % bed expansion. In the fluidised state, the medium particles are supported entirely by the flowing liquid and are, therefore, able to move freely in the bed (Pohland, 1992). In both processes an anaerobic biofilm is developed on the surface of the medium particles by the process of immobilisation (Lettinga, 1995). The large upflow velocities applied in these systems provide turbulence at the biofilm liquid interface, thus producing good mass transfer into and out of the biofilm. The high upflow velocities allow the reactors to be designed with relatively large height to diameter ratios and, thus, smaller land area requirements (Pohland, 1992). The major disadvantages of these systems include the energy cost required for effluent recycle and the combination of thin biofilms and high turbulence prevents the capture and retention of influent suspended solids within the reactor. Sloughed biofilm solids are also rapidly washed out of the reactor.

Upflow anaerobic sludge blanket (UASB) (Figure 2.3 (g)) digesters are designed to treat low- and medium-strength wastewaters at high volumetric loading rates and, therefore, at short hydraulic retention times. The most characteristic device of the UASB reactor is the phase separator. It is situated at the top of the reactor and divides it into the lower digestion zone and the upper settling zone (van Haandel and Lettinga, 1994). No support medium is added to the reactor since the process is based on the immobilisation of the biomass in the form of sludge granules. Thus, the success of the reactor depends on the formation of these highly flocculated granules. The granules allow the active biomass to be retained in the reactor, independent of the flow rate, thus maintaining a good conversion efficiency. The wastewater enters at the bottom of the digester and flows up through the bed of anaerobic granular sludge. The biomass of the sludge blanket converts the organic compounds to biogas. At the top of the reactor, the mixture of wastewater, sludge and biogas is separated into its components by the phase separator. The anaerobic granular sludge is retained in the reactor and an effluent, essentially free of suspended solids, is discharged (van Haandel and Lettinga, 1994). Baffles, placed beneath the apertures of the gas collector units, operate as gas deflectors and prevent biogas bubbles from entering the settling zone where they would create turbulence and, consequently, hinder the settling of sludge particles (van Haandel and Lettinga, 1994). Periodically, excess granular sludge can be removed and stored for use in other anaerobic treatment plants. The UASB system relies on the agitation brought about by biogas production since there is no mechanical mixing (Lettinga, 1995). The UASB is a simple process to operate.

The **anaerobic baffled reactor (Figure 2.3 (h))** is a simple rectangular tank which is divided into a number of equal volume compartments by means of partitions from the roof and bottom of the tank (Gunnerson and Stuckey, 1986). The liquid flow is alternately upward and downward between the partitions and on its upward passage the waste flows through an anaerobic sludge blanket (Gunnerson and Stuckey, 1986). Hence, the waste is in contact with the active biomass but, because of the design, most of the biomass is retained in the reactor. Due to its physical configuration, this type of reactor should be able to treat wastes with high solids contents (Gunnerson and Stuckey, 1986). In principle, all phases of the anaerobic degradation process can proceed simultaneously (Lettinga, 1995). The sludge in each compartment will differ depending on the specific environmental conditions prevailing there and the remaining compounds or intermediates to be degraded. A staged reactor can provide a higher treatment efficiency because more biorefractory intermediates, such as propionate, will be in an optimal environment for degradation (Lettinga, 1995). The process stability is a distinct advantage.

2.5 Anaerobic Degradation Process

The applicability of anaerobic processes for treatment of industrial wastewaters and domestic sludges has been recognised for many years. However, there has been some scepticism due to the lack of quantitative information on the capability of such processes to handle potentially toxic or high-strength wastes (Haghighi-Podeh and Bhattacharya, 1996).

The main aims of anaerobic treatment are the purification of the wastewater so that it can be discharged into watercourses (Baader, 1981) and the transformation of sludges to innocuous and easily dewatered substances (Pohland, 1992). Thus, there is a marked reduction in the amount of organic material, measured as COD. The final product is a stable, innocuous sludge which can be used as a soil conditioner or which can be co-disposed (Pohland, 1992). The anaerobic digestion system applied should offer the highest possible organic matter removal efficiency and the shortest possible hydraulic retention time, i.e. the volume of the system should be as small as possible (van Haandel and Lettinga, 1994) .

2.5.1. Conventional anaerobic sewage treatment

Ross et al. (1992) provided a comprehensive overview of the anaerobic digestion process in the form of an operating guide. A brief description of the process is given below. Initially the larger, heavier solids in the effluents are removed by screens. Screening is essential since the raw wastewater contains solids which, if not removed, will accumulate in the digester thus reducing its volume (Ross, Novella, Pitt, Lund, Thomson, King and Fawcett, 1992). Grit is also removed to prevent reduction of the digester volume. The wastewater then passes into primary sedimentation tanks where the settleable suspended material settles out. This sludge is withdrawn and used in the secondary treatment. The volume of primary sludge removed represents about 2 % of the influent wastewater volume being treated but around 40 % of the organic load received, expressed as the COD, or around 60 % of the influent loading expressed as suspended solids. Primary sedimentation is the process by which the velocity of the wastewater is reduced below the point at which it can transport the settleable and a major part of the suspended solids (Ross et al., 1992). It is essential that the primary sedimentation tanks are operated correctly as this is the first stage of water and solids separation in a treatment works. If this separation is not carried out correctly then the processes downstream will be adversely affected. The solids content of the sludge being withdrawn from the tanks should be maintained between 2 % to 5 % total solids. The longer the desludging period, the less concentrated the sludge will become resulting in a very thin sludge being passed to the digester. As the cost of sludge handling and treatment may exceed 50 % of the operating costs of the works, the efficient operation of the sludge processing stream offers the potential for significant savings in treatment costs.

The primary sludge comprises ca. 70 % organic and 30 % inorganic solids. The organic solids are problematic and have to be reduced or stabilised. It is this fraction which is mostly used as the substrate for the anaerobic bacteria (Ross et al., 1992). The inorganic fraction is not generally considered a problem since the larger inorganic materials are removed by the screens.

The sludge may be thickened in a process which increases the concentration of suspended solids by the separation and removal of some of the liquid phase. This increase in solids concentration is important to promote effective digestion (prevent dilution of the bacterial substrate) and to maximise the use of the available digester capacity, i.e., excess water uses up digester capacity and reduces retention time. Thickening also reduces the amount of heat required in a heated digester and prevents the washout of solids and organisms from a hydraulically overloaded digester (Ross et al., 1992).

Environmental factors, such as pH, temperature, ionic strength or salinity, nutrients and toxic or inhibitory substances, affect the rates of methanogenesis in anaerobic microbial conversion processes (Pohland, 1992). Most anaerobic conversion processes operate best at a near neutral pH and methanogenesis only proceeds at a high rate when the pH is maintained in the neutral range (Ross et al., 1992). At pH values lower than 6.8 or higher than 7.8 the rate of methanogenesis decreases (van Haandel and Lettinga, 1994). Two factors closely associated with pH are the concentration of volatile fatty acids and the alkalinity of the system. The alkalinity of an anaerobic digester is a measure of the buffering capacity of the contents of the digester. Alkalinity is important to counteract sudden increases in the fatty acid content (Kotze et al., 1969). Digesters usually have a good buffering capacity due to the presence of nitrogen in urine which forms ammonium bicarbonate (NH_4HCO_3).

Temperature is a key variable in biological processes (Zinder, Anguish and Cardwell, 1984). There are two temperature ranges generally used for anaerobic digestion: mesophilic (30 to 40 °C) and thermophilic (50 to 60 °C) (Zinder et al., 1984). Most digesters are heated and operated in the mesophilic temperature range of 32 to 38 °C. The optimum digestion temperature is approximately 35 to 37 °C and effects efficient digestion in ca. 20 d. Anaerobic digesters are heated for two principal reasons: to increase the activity of the methane-producing bacteria thus reducing the digestion time; and to liquefy fats and greases to hasten their decomposition (Ross et al., 1992). The methanogens are sensitive to temperature changes and their activity can be severely affected by sudden changes. Controlling the temperature is largely determined by the degree of mixing in the digester. An important advantage of thermophilic digestion is a greater destruction of pathogenic organisms although these processes are not always cost effective (Pfeffer, 1979; Pohland, 1992). Thermophilic processes are less stable than mesophilic processes.

High salinities (> 0.2 M NaCl) have an inhibitory effect on mixed methanogenic populations (Dolfing and Bloemen, 1985). The total ionic strength also affects chemical activity and, therefore, the possible effects of other chemical species in terms of inhibition (Pohland, 1992).

In addition to the fundamental requirements for macronutrients such as carbon and nitrogen, the inability of many anaerobes to synthesise some essential vitamin or amino acid often necessitates supplementation (Pohland, 1992; Lettinga, 1995). Four elements, iron, cobalt, nickel and sulphur, have been found to be obligatory nutrient requirements for methanogens to convert acetate to methane (Speece, 1983).

Toxicity or inhibition of methanogenic processes can be caused by a variety of conditions such as the generation of inhibitory intermediates. The effects of these compounds can depend on the particular culture and the system configuration and operation. Heavy metals, present in concentrations greater than those required for enzyme viability, can be potentially toxic and inhibitory (Pohland, 1992; van Haandel and Lettinga, 1994). Compounds in low concentrations may provide stimulation while in high concentrations they may be toxic (**Table 2.2**). Acclimation to inhibitory substances is possible.

TABLE 2.2 : Total concentration of individual ions required to inhibit anaerobic digestion (After: Water Pollution Control Federation, 1987).

Molecule	Maximum concentration (g/*l*)
Sodium	2.2
Ammonia	1.1
Potassium	1.71
Calcium	1.4
Magnesium	0.6
Sulphide	0.2
Copper	0.0005
Zinc	0.001
Nickel	0.002

There are various other factors which affect the rate and efficiency of the anaerobic digestion process. The composition of the sludge is one such factor and is determined by properties such as the nutrient content, solids content and toxicity. The method of sludge addition to the digester is also important. The concepts of feeding and loading a digester are interrelated but do differ. Feeding involves the physical transfer of sludge to the digester , while loading considers the feeding in relation to the contents and volume of the digester (Ross et al., 1992). The *specific hydraulic load* is defined as the ratio of the influent flow rate to the working volume of the reactor. Therefore, the specific hydraulic load is numerically equal to the inverse of the hydraulic retention time (van Haandel and Lettinga, 1994). The *organic load* of a system is defined as the mass of influent organic material per unit time and the *specific organic load* is the mass of influent organic material per unit time and per unit of reactor volume (van Haandel and Lettinga, 1994). The best influent feed schedule is a continuous feed at a low rate as it eliminates any abrupt flow rate or organic loading changes that could result in shock loading. Shock loading can result in fluctuations in gas production, pH, alkalinity, organism growth rate, volatile acids concentration, etc. (Ross et al., 1992).

Digestion cannot occur without contact of the bacteria with the substrate which is facilitated by mixing (Osborn, 1992). Mixing has numerous other benefits which include: an even distribution of contents throughout the digester; reduction of grit settlement and scum formation so that there is less reduction in effective digester volume; reduction of the effects of toxic substances by promoting rapid dispersion and dilution; provision an even temperature profile throughout the digester; and enabling chemicals added for pH control to be evenly distributed throughout the digester (Kotze et al., 1969; Pohland, 1992; Ross et al., 1992; Lettinga, 1995). Mixing may be effected by gas recirculation, sludge recirculation or mechanically turned impeller blades (Kotze et al., 1969).

If the solids retention time in the digester is too short, the slow-growing methanogens will be washed out. For high rate digestion, retention times of 25 to 30 d may be used. For cold digestion, retention times in excess of 50 d are required (Ross et al., 1992).

The main constituents of the gas produced in a digester are carbon dioxide (25 to 40 %) and methane (65 to 75 %). Small volumes (1 to 5 %) of nitrogen, hydrogen sulphide and hydrogen are also produced (Ross et al., 1992; Etheridge and Leroff, 1994). The composition of the digester gas depends mainly on the mean oxidation state of the carbon in the organic matter (**Figure 2.4**). For a typical sewage sludge with an oxidation state of -2 this would correspond to approximately 70 % methane and 30 % carbon dioxide. For monitoring anaerobic digestion, the $CH_4 : CO_2$ ratio represents a rapid and sensitive parameter (Kotze et al., 1969). Any sudden marked change in this ratio is indicative of unbalanced conditions. The volume of biogas produced per unit mass of volatile solids destroyed is an important and sensitive process control indicator to assess the activity of the microorganisms and the progress of digestion (Ross et al., 1992). The earliest definition of the stoichiometry of anaerobic digestion was that of Tarvin and Buswell (1934). This provides a good approximation of the biogas composition from a waste of known chemical composition (Tarvin and Buswell, 1934):

$$C_n H_a O_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 \qquad [2.2]$$

This equation reflects algebraically what is shown in **Figure 2.4**, i.e., that the higher the oxidation state of the carbon in the organic substrate, the lower will be the proportion of methane in the biogas.

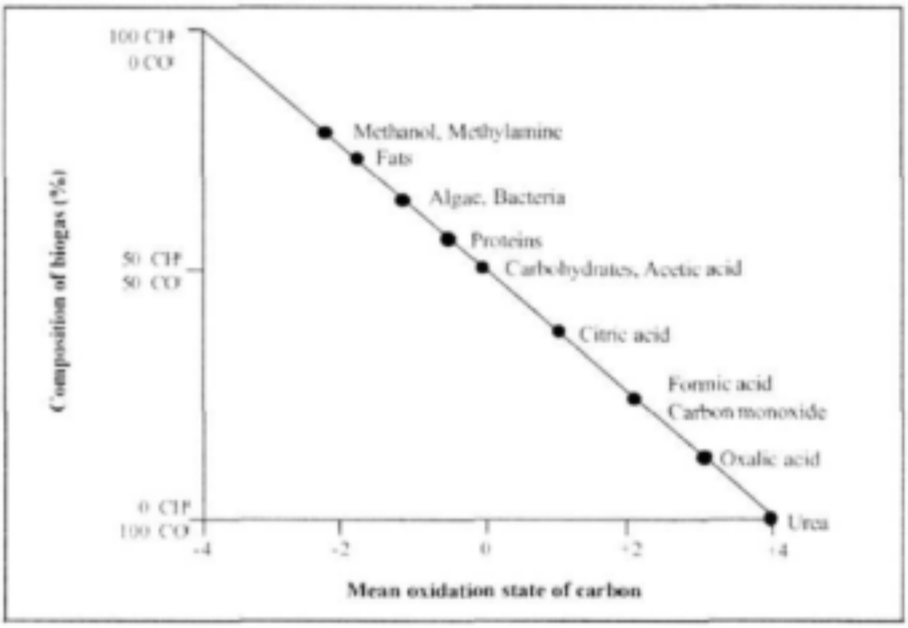

FIGURE 2.4 : Composition of the biogas depending on the mean oxidation state of the carbon in the substrate (After: Gujer and Zehnder, 1983).

The methane produced in the process is normally partly used or flared. The energy in the digester gas can be used to heat the sludge and to maintain the digester contents at the desired temperature. The digester is covered to contain odours, maintain temperature, omit air and to collect the gas. There is a space between the cover and the liquid surface of the digester contents for gas collection. Many anaerobic digestion plants have a means of storing excess gas, such as a separate gas holder. If a constant flow and load are applied and organic matter does not accumulate in the treatment system (steady-state conditions), the daily mass of influent COD should be equal to the sum of the daily mass of COD leaving the system as methane and in the excess sludge produced, in the effluent (van Haandel and Lettinga, 1994).

Anaerobic sludge digestion can be divided into two phases, primary and secondary. The main role of the primary phase is to stabilise the sludge while the secondary phase is to allow for solid liquid separation (Ross et al., 1992; van Haandel and Lettinga, 1994). There is no mixing in the secondary phase and the sludge can, therefore, settle to the bottom of the digester. This creates a layered structure of the contents inside the secondary digester. A scum layer is often formed on the surface while the middle zone of supernatant is relatively solids free. It is important that the supernatant and sludge are drawn off correctly from the digester as incorrect procedures can upset the sludge stabilisation process. The supernatant, or final effluent, produced by anaerobic treatment contains solubilised organic matter which is amenable to quick aerobic treatment or can be recycled as the primary sedimentation tank influent (Gray, 1989). Efficiency of anaerobic digestion may be measured from a knowledge of the COD or carbon content of the substrate supplied and the COD or carbon content of the final effluent, i.e., by doing a mass balance on the substrate (Kotze et al., 1969):

in - out - cell growth - product formation - maintenance = accumulation

The withdrawn sludges are discharged to a dewatering process such as sludge drying beds or mechanical dewatering systems (Ross et al., 1992). Drying beds are the most common method of dewatering at wastewater treatment plants. The primary objective in the drying bed operation is to reduce the moisture content of the sludge cake to a level consistent with the mode of sludge removal and final dry cake utilisation (Ross et al., 1992).

There are various other dewatering methods available including centrifugation, belt filter press, vacuum filter, filter press and tubular filter press.

A very large percentage of the solids loading received at the wastewater treatment works is present as, or is converted into, sludge. Although the anaerobic digestion process reduces the mass of sludge produced, the remaining sludge mass requires disposal. It is necessary to ensure that secondary pollution does not occur as a result of unsuitable disposal practices. In addition to macro-nutrients, such as nitrogen and phosphorus, the sludge also contains minor nutrients such as calcium, magnesium, iron and sulphur. Depending on the source of the wastewater, the sludge may also contain heavy metals (Ross et al., 1992). The organic content, nutrients and trace metals present in the sludge may be advantageously utilised if the sludge is incorporated into agricultural land as a soil conditioner. However, due to the presence of certain contaminants, such as heavy metals, viable pathogens and complex organic compounds, consideration must be given to its potentially dangerous and hazardous properties when disposing of sludge.

The Department of National Health and Population Development produced a set of guidelines indicating permissible utilisation and disposal routes for wastewater sludge (Department of National Health and Population Development, 1991). Sludge is classified into three types, A, B and C, in decreasing order of potential to cause odour nuisances, fly breeding and to transmit pathogenic organisms to man and his environment (Department of National Health and Population Development, 1991; Ross et al., 1992; Department of Water Affairs and Forestry, 1994). When the sludge cannot be disposed of as a soil conditioner, it must be co-disposed in admixture with refuse in a sanitary landfill.

Control of anaerobic digestion is complicated since the different parameters that characterise the environment within the digester tank are all interrelated and one variable may directly or indirectly affect the others (Pohland, 1992).

2.5.2. Anaerobic degradation of industrial wastewaters

Anaerobic processes have been used for the treatment of concentrated municipal and industrial wastewaters for over a century (McCarty and Smith, 1986). Concentrated organic industrial wastes such as distillery effluents and wastes from the manufacture of various foodstuffs generally create serious treatment or disposal problems for the industry or the local authority concerned because of their high organic load. These wastes have high chemical oxygen demand (COD) concentrations compared with domestic sewage (Ross, 1989). A COD measurement gives an indication of the amount of organic material in the wastewater, which could be oxidised by microorganisms. The efficiency of a treatment process can, therefore, be expressed in terms of the decrease of the initial COD (Boyd, 1988). Effluents with a low fraction of readily degradable COD are reluctantly accepted into communal sewers by the controlling authority and the manufacturer is faced with heavy trade-effluent charges. Research has shown that aerobic methods are seldom efficient in treating these effluent types (Ross, 1989).

The surge of interest in the anaerobic digestion process, supported by advances in process engineering, has been translated into numerous treatability studies of various industrial wastewaters (Speece, 1983). The fruition of this activity has been manifested in the commissioning of a number of full-scale industrial treatment installations. Initially, the anaerobic digestion process was applied primarily to municipal wastewater sludges, which contained a wide range of nutrients and alkalinity sources (Speece, 1983). Other candidate feedstocks considered for anaerobic treatment were food processing wastewaters such as the effluent from meat-packing plants (Steffen and Bedker, 1961) and sugar beet operations (Speece, 1983). It was found that these wastewaters contained readily degradable organic molecules and that the solutions had normal complements of inorganic ions such as those commonly found in surface or ground waters. Other feedstocks which have been investigated include those from pulp and paper mills, coal conversion processes and deionised industrial process wastewaters. Anaerobic digestion of inorganic wastewaters has also been investigated with acclimation of bacteria to inhibitory concentrations of heavy metals. The basic question is no longer whether an industrial effluent can be anaerobically biodegraded to methane, since most organic molecules are amenable to anaerobic treatment, but rather at what rate is it degradable and to what degree is it degradable (Speece, 1983).

2.6 *Current Fate of Industrial Effluent*

High-strength or toxic organic effluents are difficult to dispose of. Current disposal options, in the KwaZulu-Natal region, include marine outfall or co-disposal into municipal landfills.

2.6.1. Marine outfall

Marine disposal of wastewater, via submarine pipeline, relies on the powerful dispersing capability of the sea, its ability to biodegrade many organic wastes and the binding ability of sea sediments. Marine disposal has proved to be an inexpensive disposal option and has been widely used in South Africa (Department of Water Affairs and Forestry, 1994).

In 1983, a need for seawater quality guidelines in South Africa became apparent to make decisions regarding pipeline discharges of effluents to sea (Department of Water Affairs and Forestry, 1992). The South African National Scientific Programme Report No. 94 was published and now forms the basis for the planning of sea outfalls and also for environmental assessments of areas subjected to pollution loads (Department of Water Affairs and Forestry, 1992). Maximum allowable concentrations were stipulated for the discharge of effluents to the sea. An important consideration was to involve a broad spectrum of the community concerned with the management of the marine water quality in South Africa (Department of Water Affairs and Forestry, 1992). The main purpose of these guidelines was to maintain South Africa's marine water resources in a state fit for use. Fitness for use is related to the specific characteristics of the coastal zone and its physical ability to assimilate external inputs such as discharges from land (Department of Water Affairs and Forestry, 1992).

A number of industries are situated in the KwaZulu-Natal region, especially along the south coast of Natal and in the Durban are and at Richards Bay. The KwaZulu-Natal coastline is one of the most popular tourist and recreation areas in South Africa (Department of Water Affairs and Forestry, 1992; Scott, 1997). Marine pollution is defined as *the introduction by man, directly or indirectly, of substances or energy into the marine environment resulting in such deleterious effects as harm to living resources, hazards to human health, impairment of quality for use of seawater and reduction of amenities* (Department of Water Affairs and Forestry, 1992). Aquatic systems have a limited capacity to assimilate or disperse some substances or energy without unacceptable effects. Situated along the KwaZulu-Natal south coast are three large companies which discharge industrial effluent into the sea via pipelines subject to the conditions of a permit granted by the Department of Water Affairs and Forestry. The water quality guidelines define the level of acceptability and thereby the water quality management objectives or goals to be achieved by controlling or limiting waste discharges or other man-induced impacts on the marine environment (Department of Water Affairs and Forestry, 1992). Standards are set by the Department of Water Affairs and Forestry for the discharge of water into the marine environment. Stricter standards are set for discharge into rivers due to potential contamination to humans. Discharge into rivers is the preferred option as it results in the recycling of water whereas discharge to sea results in the loss of freshwater.

2.6.2. Co-disposal in municipal landfill sites

The objectives of co-disposal are to absorb, dilute and neutralise any liquids or sludges, and to provide a source of biodegradable materials in order to encourage microbial activity that will assist in the degradation of hazardous compounds (Department of Water Affairs and Forestry, 1994). The major problem with the co-disposal of wastewater is the generation of excess leachate (Ross et al., 1992).

Effluents which do not comply to the standards for discharge to sewer, or marine outfall, are co-disposed into municipal landfills. In KwaZulu-Natal, there are limited landfills properly designed to accept liquid wastes. An example is the Bisasar landfill site, in Springfield Park, which receives approximately 200 m³ of liquid waste per day. This poses grave environmental problems in terms of contamination of the groundwater and rivers. There is the potential for these effluents to be treated in available anaerobic digester capacity thereby safeguarding the environment.

In a sustainable world, little or no industrial and hazardous waste would be generated by society and those which were produced would be treated and re-used in other processes. However, in the real world, considerable quantities of industrial wastes are generated and must be treated and disposed of in an environmentally acceptable manner (Forster, 1994). Efficient wastewater treatments are, therefore, critical and anaerobic digestion has potential as icient, cost-effective treatment process.

Chapter 3

Digester Survey

This chapter presents the investigation of the anaerobic digesters in KwaZulu-Natal in terms of physical and operating data and ultimate performance efficiencies. The purpose of this investigation was to identify under-utilised digesters, for the proposed treatment of high-strength or toxic organic industrial effluents, and to identify under-performing digesters with an aim of effecting remedial action to assist in the optimal utilisation of effluent treatment facilities in the region.

3.1 Introduction

Several of the wastewater treatment plants, in the KwaZulu-Natal region, have anaerobic digestion facilities which are under utilised. The Durban Metropolitan Council is currently (1997/8) taking control of approximately 30 treatment plants in the greater Durban area. This standardisation should provide the potential for the utilisation of available capacity of some of the plants and to relieve the *bottleneck* at the plants operating at or over design capacity. Other wastewater treatment works in the region are either controlled by regional municipalities or independent organisations such as Umgeni Water.

Despite the widespread use of anaerobic treatment, optimum process performance is seldom achieved due to the high degree of empiricism which prevails in the design and operation (Lawrence and McCarty, 1969). The aim of this chapter is to present the operating data for each anaerobic digester and to assess the performance efficiency.

The concept of *available digester capacity* needs to be clearly defined. A digester with available **hydraulic capacity** is one which is receiving a smaller volumetric load than its design specifications. The hydraulic load is measured in the units of m^3/d. **Loading capacity** is the ability of a digester to accept a greater organic load (kg $VS/m^3.d$) without experiencing an overload or shock loading.

3.2 Design of a Biological Wastewater Treatment Works

The design of a new wastewater treatment works is based on the volumetric assessment of the flowrate, which would determine all hydraulic aspects of the works, and sewage strength, which would determine the biological and chemical processes in the works (Cloete and Muyima, 1997). Rainfall records, conditions of sewer systems and enforcement of by-laws should be considered. It is necessary to inspect the functioning of an existing works to establish possible shortcomings in its design and to assess the maximum capacities of the various units. The quality of the final effluent should be aligned with the standard requirements

3.2.1. Assessment of flow

Infiltration of groundwater and ingress of surface stormwater into the sewage system would affect the rate of flow significantly. Hence, flow recording during both wet and dry weather is necessary (Cloete and Muyima, 1997). The domestic sewage component is normally the major contributor to the total flow. In providing for the full design life of a sewage works the upward trend in per capita sewage contribution should be taken into consideration and an annual increase of 1.5 to 2.5 % could be expected (Cloete and Muyima, 1997). The average dry weather flow (ADWF) is the flow used for the design of treatment units and is measured in m^3/d. This flow should, however, include provision for peak dry weather flow, infiltration of groundwater and stormwater and peak wet weather flow.

3.2.2. Assessment of sewage strength

The strength of the sewage fed to a wastewater treatment works varies de*p+1X on the domestic living standards of the contributing population. Sewage characteristics can be divided into three main categories: the concentration of oxidisable organic material (substrate), the concentration of nutrients present and the solids concentration (Cloete and Muyima, 1997). Assessment of the organic concentration could be achieved by the COD, BOD or oxygen absorbance (OA) methods.

The design parameters attained from the preceding estimates should be moderated by reference to appropriate expertise and consultation.

3.2.3. Design parameters for anaerobic digesters

The normal design rules for anaerobic digesters are based on an extensive removal of labile matter (Henze, Harremoës, la Cour Jansen and Arvin, 1997). The purpose of the design is to ensure the survival of the methanogens.

The basis for the design of these plants is the organic load or the sludge age. The organic load (kg VS/m^3.d) varies with the type of plant as well as the flow and organic strength characteristics. The purpose of design by means of sludge age is to ensure that the methanogens can survive in the plant. Sludge separation is designed on the basis of the hydraulic surface load and the sludge surface load (Henze et al., 1997).

Operational problems can be experienced in anaerobic plants. The slow growth rate of the methanogens can result in an extended start-up period for a new anaerobic digester. Seeding with anaerobic bacteria, for example from another plant, could reduce the start-up period. There should be a step-wise increase in the substrate load, starting with approximately 10 % of the maximum load (Henze et al., 1997). When the volatile fatty acid content of the digester effluent is sufficiently low then the load can be increased. The washout of biomass may occur if the sludge age is reduced. Inhibition of the biomass may occur by means of internally produced inhibition (fatty acids, ammonia, pH) or by means of substances supplied from the external environment (sulphate, ammonia, metals, specific organic materials). External inhibition normally occurs faster than internal inhibition. The type of substance and exposure time determine the inhibitory effects of external substances on the anaerobic wastewater treatment processes.

Several anaerobic digester designs, or configurations, were described in **Chapter 2** In the conventional anaerobic digester, the entire reactor content is mixed by internal stirring or cyclic external pumping (Zehnder, 1988). Fresh and digested materials are thus kept in close contact but separation of biomass and treated water is difficult. Recycling of biomass overcomes the general drawbacks of anaerobic versus aerobic treatment, namely, the low growth rates and yields of anaerobes. The main drawbacks of anaerobic bacteria (low growth rates and yields) have been overcome by the construction of various types of anaerobic reactors which either retain or recycle the active biomass to maintain substrate conversion rates which are competitive with aerobic processes (Zehnder, 1988).

3.3 *Anaerobic Digester Survey*

The regional authorities were approached for information regarding digesters in their areas. The individual digesters were visited and physical details and operating data were obtained (**Appendix A**). An inventory of the anaerobic digesters in the KwaZulu-Natal region is given in **Table 3.1**.

TABLE 3.1 : Inventory of the primary anaerobic digesters in KwaZulu-Natal.

WWTW	No.	Design vol. per digester (m^3)	Idle volume (m^3)	HRT (d)	Actual hydrulic load (m^3/d)	Possible hydraulic load, at 30 d HRT (m^3/d)
Amanzimtoti	6	2 012 (x3) 2 068 (x1) 3 640 (x2)	6 036 0 0	0 26 46	0 80 80	67 69 121
Cato Ridge Abattoir	2	2 866	N/D	5	1 230.4	96
Darvill	2	4 500	0	20	227	150
Estcourt	N/D	N/D	N/D	N/D	N/D	N/D
Kwa Makutha	1	1 650	0	18	90	55
Kwa Mashu	2	1 750	0	27	130	58
Kwa Ndengezi	1	1 550	0	53	29	52
Mpophomeni	2	683 (x1) 683 (x1)	0 683	15 0	45	23
Mpumalanga	4	1 052	0	94	45	35
Newcastle	3	850 (x1) 850 (x2)	0 1 700	N/D 0	N/D	28
New Germany	2	1 000	0	200	5	33
Noodsburg	1	11 700	0	15	800	390
Northern	3	2 350 (x2) 2 350 (x1)	0 0	36 24	65 100	78 78
Phoenix	2	2 600 (x1) 2 600 (x1)	0 2 600	31 0	85	87
Scottburgh	1	1 130	0	108	10.5	38
South African Breweries	1	1 700	0	0.5	3 303	57
Southern	2	4 620 (x1) 4 620 (x1)	4 620 4 620	0 0	0	154
Sundumbili	4	1 387	0	14	100	46
Tongaat southern	2	2 000	0	100	40	67
Umbilo	4	1 340	0	22	54.3	45

Treatment works	Primary digesters				Secondary digesters	
	No.	Design vol. per digester (m^3)	Idle volume (m^3)	HRT (d)	Actual hydrulic load (m^3/d)	Possible hydraulic load, at 30 d HRT (m^3/d)
Umbogintwini	1	103	0	26	4	3
Umlazi / Isipingo	6	964 (x5) 964 (x1)	0 964	16 0	300	32
Umzinto	1	705	0	200	N/D	24
Verulam	3	4 120 (x1) 8 200 (x2)	0 0	120 240	103 103	137 273
TOTAL		**124 980**	**21 223**			

N/D : Not determined

TABLE 3.2 : Inventory of the secondary anaerobic digesters in KwaZulu-Natal.			
	No.	Design vol. per digester (m^3)	Idle volume (m^3)
Amanzimtoti	3	587	0
Cato Ridge Abattoir	0	-	-
Darvill	2	1 000	0
Estcourt	N/D	N/D	N/D
Kwa Makutha	1	540	0
Kwa Mashu	1	2 310	462
Kwa Ndengezi	0	-	-
Mpophomeni	1	330	0
Mpumalanga	2	300	0
Newcastle	0	-	-
New Germany	1	450	0
Noodsburg	0	-	-
Northern	1	4 420	0
Phoenix	1	1 794	0
Scottburgh	1	565	0
South African Breweries	2	N/D	N/D

Treatment works	Secondary digesters		
	No.	Design vol. per digester (m³)	Idle volume (m³)
Southern	1	3 830	3 830
Sundumbili	4	1 387	0
Tongaat southern	0	-	-
Umbilo	4	1 340	0
Umbogintwini	0	-	-
Umzinto	0	-	-
Verulam	1	3 600	0
TOTAL	10	**37 332**	**4 292**

The data obtained in the survey facilitated the calculation of the perforfficiency of each digester. They also identified *idle* digesters (those not being used at all) and digesters with low hydraulic loads.From the above tables, it can be seen that 17 % of the design primary digester capacity is not being utilised, and 11.5 % of the design secondary digester volume. Idle capacity refers to those anaerobic digesters which are not in operation. An extenbded retention time (greater than 15 to 30 d) indicates that the digester was being under-loaded and could facilitate efficient digestion, at a lower HRT, with an increased load. A nominal HRT of 30 d was used; an HRT below this suggested available capacity.

The theoretical hydraulic retention times (d) were calculated based on the volume of the digester and the flow to the digester. Most of the digesters which were investigated were completely mixed, thus the hydraulic retention time (HRT) was equal to the solids retention time (SRT). The nominal HRT is in the range of 20 to 30 d (Ross et al., 1992). The throughput of the digester may be increased by increasing the feed flowrate and thereby reducing the HRT. This would, however, result in a reduction in the quality of the final sludge. Acclimation of the anaerobic biomass can result in increased digester capacity since, if the biomass is acclimated to the substrate, degradation rates increase with a subsequent decrease in the HRT.

The survey revealed that, although the utilised digester volume was maintained at a maximum to prevent explosion by the accumulation of biogas, the retention time was often much greater than the nominal 20 to 30 d. The reason for this is that the hydraulic load to the digesters was below the design capacity. These digesters could, therefore, receive a greater hydraulic load. The stability of an anaerobic digester, however, is dependent on the organic load and digesters are designed to treat a specific loading. An exceedence of this load may result in shock loading and ultimate digester failure. Options for waste minimisation at the effluent source should, therefore, be examined to reduce the volumes of high-strength effluent being produced. These lower volumes of industrial effluent could then be loaded into the available digesters without a marked increase in the hydraulic load. With lower volumes, the retention time would still be greater which would provide the necessary time for the degradation of the high concentration of organic molecules in the effluents.

The volumes of screenings and grit removed, at the head of the works, were important as the presence of screenings and grit in a digester can significantly reduce the working volume. Ideally, digesters should only be fed with sludge from the primary sedimentation tanks (PST) (Ross et al., 1992) and not with waste activated sludge, dissolved air flotation (DAF) sludge or grit as these occupy digester volume and are not as effectively degraded. Hydraulic overloading occurs when a digester residence time is reduced to the point where organisms are washed out or diluted faster than they are formed (Graef and Andrews, 1973). Increased digester flow rates and decreases in effective digester volume caused by grit and scum accumulations can both lead to hydraulic overloading (Graef and Andrews, 1973). Organic overloading is caused by an increase in the rate of organic mass loading to the reactor. The organic substrate concentration in the reactor increases and inhibits the microbial conversion of volatile acids to methane and carbon dioxide. Thus, organic substrate accumulates in the digester causing it to fail or *sour*.

As stated, the survey facilitated the identification of *idle* and under-performing digesters. The Amanzimtoti Wastewater Treatment Works had a total of 6 anaerobic digesters although only three of these were operational (**Table 3.1**). The three off-line digesters could, therefore, be utilised for the treatment of industrial effluents produced in the vicinity. The Amanzimtoti Works is located near to the Prospecton industrial area thus this potential digester capacity could be well utilised.

The two primary anaerobic digesters and the one secondary digester, at the Southern Wastewater Treatment Works, in Durban, are no longer operational. They have been off-line since 1985. The influent to the works is screened and degritted prior to marine discharge via a 5 km pipeline. This works serves the industries in the Durban Mobeni, Jacobs and Prospecton areas. The digesters could, therefore, be used to treat either effluents which do not meet the General Standards for marine discharge or the low volumes of high-strength effluents which are currently diluted to meet discharge standards with excessive wastage of potable water.

One of the anaerobic digesters at the Mpophomeni Works was idle, as was a primary anaerobic digester at the Umlazi Works. This digester could be used to treat effluent from the surrounding Jacobs, Prospecton and Island View +IXI areas. Two of the 3 anaerobic digesters at the Newcastle Works are no longer used for active digestion. The one digester is used for the pre-treatment of blood waste from the local abattoir to prevent organic overloading of the works.

Only one of the 2 primary anaerobic digesters at the Phoenix Wastewater Treatment Works was operational due to the works operating at only 44 % (v/v) of its design load. The Phoenix area is zoned for industrial development within the next 5 to 10 years. The idle digester should, therefore, be seen as available capacity for the treatment of industrial effluents and should be considered during the decision-making for the rational location of new industries that produce high-strength or toxic organic effluents.

The digesters at the Cato Ridge abattoir operate entirely for the treatment of the abattoir waste. According to the works operators, the digesters are not run at their full volumetric capacity although the actual working volume was undetermined. The UASB reactor at the South African Breweries plant, in Prospecton, treats the brewery effluent. The organic load to this reactor was high and, consequently, the hydraulic retention time (HRT) was low.

Table 3.1 is an inventory of the anaerobic digesters in the province. The table summarises the design volume of each digester and the digester volume which is not utilised. The un-utilised digester volume was totalled at 21 223 m^3 (17 % v/v).

Several of the digesters were operated at extended hydraulic retention times (HRT) because they were running below design capacity. These included the digesters at Amanzimtoti (46 d retention time), Kwa Ndengezi (53 d), Mpumalanga (94 d), New Germany (200 d), Scottburgh (108 d), Tongaat southern (100 d) and Verulam (120 and 240 d). These digesters could receive a higher hydraulic load and operate at lower retention times.

The function of the secondary digesters is merely phase separation. They could, therefore, be seen as available digestion capacity since the closed settling tanks could be operated as primary digesters. This would, however, require an increase in the HRT of each digester to provide a period, without mixing, for the settlement of the sludge.

3.4 Digester Performance Calculations

Collation of data from the digester survey facilitated the determination of whether the operation of a digester was *healthy*, i.e., an evaluation of the efficiency of the anaerobic digestion process. Identification of unhealthy digesters provided information for the suggestion of remedial action. Available capacity should only be utilised in healthy digesters to prevent failure of the digester. The *health* of a digester can be assessed by the investigation of the following parameters:

1. Organic load (kg VS/m^3.d);
2. Gas production per kg volatile solids destroyed (m^3/kg) ;
3. pH, alkalinity and volatile fatty acid concentrations in the sludge;
4. Reduction of volatile solids;
5. Sludge temperature;
6. Biogas composition;
7. Digester mixing; and
8. Hydraulic retention time.

The organic load to a digester has a significant effect on the process efficiency since if the organic content of the substrate is too high it may result in a shock load to the digester, with a concomitant reduction in degradation efficiency or even complete digester failure. The ideal organic load, for a high-rate reactor, is in the region of 1.5 to 3.0 kg VS/m^3.d (Ross et al., 1992). Continuous feed to a digester is optimal as it prevents shock loading and promotes biomass stability. It is more favourable to feed small volumes frequently than to feed large volumes infrequently.

The efficiency of the degradation process can be assessed in terms of biogas production with an ideal system producing 1 m^3 biogas per kg of volatile solids destroyed. The gas composition is also an important indicator of the state of the process. The ratio of carbon dioxide to methane should be in the region of 35 % to 65 %. A change in this ratio is indicative of stress in the system.

The volatile solids represent the organic portion of the feed, thus the reduction in volatile solids gives an indication of the degradability of the organic molecules in the substrate. The volatile solids in the influent are normally in the region of 70 % (m/v) of the total solids. A volatile solids concentration lower than this suggests the presence of grit in the feed sludge. A reduction of 50 to 70 % of the volatile solids is expected in a properly functioning system. The volume of total solids in the feed sludge should be in the region of 5 to 6 % (m/v). The thinner the feed slhe greater the digester volume occupied by water and the greater the amount of energy required to heat the sludge. A rise in temperature results in a concurrent increase in metabolic activity to a certain point, therefore, heating of a digester can result in a shorter hydraulic retention time and potentially increase the active or working volume. A decrease in temperature of the sludge can result in an organic overload as the drop in temperature would result in a decrease in the metabolic activity.

Control of the pH value and the VFA and alkalinity concentrations of the sludge is important. If these are not properly controlled, the biomass will not metabolise effectively and degradation rates will decrease with a concomitant increase in the necessary HRT. The VFA : alkalinity ratio (Ripley ratio) is important and, ideally, should be in the range of 0.1 to 0.35. An increase in this value suggests digester failure i.e., the lower the Ripley ratio, the healthier the digester (Ross et al., 1992).

The mixing efficiency of a digester can be assessed by the temperature and total solids profiles throughout the digester. Efficient mixing is represented by a uniform distribution of temperature and solids. The efficiency of the mixing can be assessed in terms of power requirements and the number of volume displacements per unit time. This provides an indication of the turnover rate of the digester since digester contents should be displaced at least once in 24 h.

The anaerobic digestion process may be regarded as being umbalanced or *upset* when the process control indicators show deviations from normal (Ross et al., 1992). The main changes indicating an upset digester are:

1. Increased percentage carbon dioxide in the gas produced;
2. Decreased gas production;
3. Increased volatile acid : alkalinity ratio of the sludge;
4. Production of malodorous sludge;
5. Decreased pH;
6. Increased solids in the supernatant;
7. Decreased volatile solids reduction; and
8. Increased foaming.

From the data collected in the digester survey, performance and operating efficiencies, for the individual digesters, were calculated (**Annexure 1**) and the results for each are described below. A summary of these results is given in **Table 3.3**.

Available digester capacity was identified at the **Amanzimtoti** Works, both in the form of the 3 idle digesters and the potential capacity in the operating digesters by improvement of the operating conditions. The feed sludge was thin with a total solids content of ca. 3.8 % (m/v). A batch feeding schedule was followed and the organic load was low (0.25 kg VS/m^3.d) which suggested available organic capacity. The biogas was wasted to the atmosphere as the on-site gas holder was not operational. Biogas production was, therefore, not monitored. The digester sludge pH, VFA and alkalinity concentrations suggested healthy operation, with measured averages of 7.4, 566 mg/ℓ and 3 343 mg/ℓ, respectively. These gave a Ripley ratio of 0.17. Volatile solids reduction was efficient at 60 %. The digesters were unheated and operated at ambient temperature. It is believed, however, that the temperature within the digesters increases due to the heat released during metabolism and the air-tight environment. It is, therefore, assumed that the unheated digesters operate at ca. 30 °C. The works was operating at 77 % (v/v) of its design capacity and the low hydraulic load to the anaerobic digesters resulted in the extended HRT (46 d). The process efficiency could be improved by heating the digesters (decreased HRT), increasing the organic load and, according to the works operator, more efficient mixing. Approximately 50 % of the volumetric load to the works is composed of industrial effluent.

The effluent treatment plant at the **Cato Ridge** abattoir was operating at only 14.3 % (v/v) of its design capacity and, therefore, had the potential to treat a greater hydraulic load. It was estimated, by the operator, that the digesters only operated at 17 % of their total design volume. The organic load to the digesters was high (4.1 kg VS/m^3.d) due to process and washwater effluent from the abattoir. Feeding to the digesters was continuous. This high organic load could result in a shock load and digester failure but, due to the acclimation of the biomass to the effluent, the process was effective. The retention time was low at ca. 5 d. The sludge alkalinity was low and resulted in a high VFA/alkalinity ratio (0.24), which indicated the need for buffering capacity in the digester. Volatile solids reduction was efficient at 72 %. There was no mechanical mixing of the digesters. The biogas was vented directly to the atmosphere, thus gas production was not measured. Digester performance could be improved by mixing, thickening of the feed sludge from 3 % to 5 % (m/v), heating and providing buffering capacity. These digesters showed that high-strength organic effluents can be successfully treated by anaerobic digestion.

The **Darvill** Wastewater Treatment Works, in Pietermaritzburg, was operating at 91.7 % (v/v) of its design capacity. The anaerobic digesters were run at a retention time of 20 d with an optimal organic load (2.03 kg VS/m^3.d). The two egg-shaped digesters were fed in alternating sequence, i.e., 3.5 d to the first then 3.5 d to the second. Thus, the digesters could accept a greater load as both digesters could be loaded simultaneously. The digesters were heated to 35 °C which is optimal for mesophilic digestion. Gas production was measured at ca. 10 000 m^3/d with a 60 % (v/v) methane content, thus 6 000 m^3 CH_4 were produced per day. With a volatile solids reduction of 64.6 %, this was reduced to a volume of 1.01 m^3 CH_4 /kg VS destroyed. The reported parameters indicated the efficient performance of these digesters. There was significant reduction in COD (95 %) over the entire works. The sludge parameters were ideal (**Appendix A**) and the mixing was efficient. Only 10 % (v/v) of the influent to the works was industrial effluent.

The data for the **Escourt** digesters were not made available by the local authority.

Kwa Makutha is located just west of Amanzimtoti, on the Natal south coast. It is a small works (3.0 Mℓ/d), treating purely domestic sewage. The works was operating at 117 % of its design capacity. This overloading resulted in a relatively high organic load to the digesters (2.1 kgVS/m^3.d) and a short HRT of 18 d. The volatile solids reduction averaged ca. 56 %. Biogas production was not measured. The sludge characteristics indicated that the process was healthy with an average pH of 7.0 and the ratio of VFA to alkalinity at 0.02. The digesters were not heated thus process efficiency could be improved by heating as degradation rates would increase. Mixing was achieved by a draft tube.

The **Kwa Mashu** Wastewater Treatment Plant is a large plant treating ca. 65 Mℓ/d. It is situated between Kwa Mashu and Phoenix, in Durban. The works treated mainly domestic sewage from these two areas with only ca. 10 to 15 % of the inflow volume being industrial wastewaters. The operation of the anaerobic digesters was stable and measured parameters indicated healthy conditions. The organic load to the digesters was 1.09 kg VS/m^3.d. The volatile solids reduction was ca. 59 % and the process efficiency was calculated at 0.76 m^3 CH_4 /kg VS destroyed. Operation could, therefore, be slightly improved but, overall, the digesters were healthy. The pH of the digedge averaged at ca. 7.2 and the ratio of VFA to alkalinity was 0.033. The digesters were heated to 37 °C and mixing was achieved by recirculation of the digester sludge. The average HRT was calculated at 27 d. The works was operating at 86 % of its design volume. Acceptance of a higher hydraulic load would reduce the HRT in the digesters which may not be optimal if the additional load was high-strength organic effluent. A reduced HRT may thus negate mineralisation of the high concentrations of organic molecules.

Kwa Ndengezi is a small works (2.9 Mℓ/d), recently taken under control by the Durban Metropolitan Council. The works treats purely domestic sewage from the surrounding area and is operated over (121 % (v/v)) its design volumetric capacity. The volumetric load to the anaerobic digester was, however, low; ca. 29 m^3/d with a low organic load (0.5 kg VS/m^3.d) resulting in an extended HRT of 53 d. Operation was not healthy with a volatile solids reduction of only 26 %. The digester sludge had an average pH of 7.1 and the ratio of VFA to alkalinity was 0.038. Biogas was not collected but vented to the atmosphere. Mixing was achieved by recirculation of the digester sludge. The efficiency of the degradation process could be improved by increasing the organic load and heating the digester. If the digester was operated at a retention time of 30 d, it would be able to accept a volumetric load of 52 m^3/d, compared to the current 29 m^3/d, thus verifying the availability of hydraulic capacity. The digester also had available loading capacity since the organic load to the digester was low.

Mpophomeni is a small works operated by Umgeni Water and serving the nearby rural areas. The works, which treats only domestic sewage, was overloaded relative to its design specifications (130 %). One of the digesters was idle which put an increased load on the operating digester (3.2 kg VS/m^3.d). Due to the overloading, the digester was operated at a low retention time (15 d) resulting in insufficient volatile solids reduction, ca. 33 %. The feed sludge was very thick (7.0 % total solids) and the percentage of total solids was not reduced during the treatment process. The pH of the sludge was stable at 7.0 and the VFA to alkalinity ratio was 0.04. Biogas production was not measured but vented to the atmosphere. Efficiency could be improved by operating both digesters and heating the digester contents. If both digesters were operated, the additional volume could be used to treat high-strength or toxic organic effluents produced in the region.

The **Mpumalanga** Wastewater Treatment Works has also recently been taken over by the Durban Metropolitan Council. It was previously controlled by Umgeni Water. The works, which treats only domestic sewage, is operating at 49 % (v/v) of its design capacity. The hydraulic load could be increased in the form of high-strength or toxic organic effluents. The Mpumalanga Works is located 4 km from Hammarsdale, which is an industrial area with mostly textile industries (producing high-strength organic size and scour effluents), and a chicken abattoir, producing a very high-strength organic effluent.

The organic load to the Mpumalanga digesters was relatively low (0.34 kg VS/m^3.d) and the anaerobic digesters were operated at an extended retention time of 94 d. The digester sludge was healthy, with average values calculated as follows: pH 7.1 and VFA/ alkalinity ratio of 0.03. The reduction in volatile solids was low (34.5 %). The reason for this was unclear as the extended retention time should have facilitated mineralisation of the organic molecules. The hydraulic load to the digesters was 45 m^3/d. This could be increased to 140 m^3/d if the digesters were operated at a HRT of 30 d. A draft tube facilitated agitation of the digester contents. Biogas production was not measured and the gas was vented to the atmosphere. The anaerobic degradation process efficiency could be improved by heating the digesters and thickening the feed sludge since, according to the operator, the sludge thickener did not operate efficiently. These digesters were sensitive due to the dosing of alum ($Al_2(SO_4)_3$), for pH control. A buffering method, more conducive to digester stability, should be employed. This works should be targeted for the treatment of industrial effluents.

There are 3 anaerobic digesters at the **Newcastle** Wastewater Treatment Works which are not used for active digestion. New pond reactors have been built with an anaerobic pit followed by aerobic treatment in the pond. One anaerobic digester is used to store and pre-treat blood waste from the local abattoir. The operators do not monitor any parameters on the digesters thus the performance calculations could not be assessed. The COD reduction over the entire works was ca. 90 %. The idle digesters could be used to treat industrial effluents produced in the region.

New Germany is located near to Pinetown, thus this wastewater treatment works could receive industrial effluent from the Pinetown, Westmead and New Germany industrial areas. The works currently treats only ca. 30 % (v/v) industrial effluent, with the majority of the inflow being domestic sewage from the nearby Claremont township. The anaerobic digesters at this works were greatly neglected and the operators knew very little of the operating parameters. The majority of the influent to the works was treated in the activated sludge plant while only an estimated 10 m^3/d was fed to the digesters. With such a low feed, the resulting HRT was 200 d. The organic load to the digesters was very low (0.08 kg VS/m^3.d). The volume of methane produced per kg VS destroyed could not be determined since biogas production was not measured. The digester sludge was unhealthy with an average pH of 6.6 and the VFA to alkalinity ratio at 0.1 due to the high concentrations of volatile fatty acids. The volatile solids reduction was low at 24 % indicating unhealthy operation. The digesters were heated to 37 °C. Mixing was facilitated by recirculation of the digester sludge. The efficiency of the digestion process could be improved by buffering the digester to reduceconcentration of volatile acids. Once the digester sludge was stable, the volumetric and organic loads should be increased. Under the conditions the digester contents were almost stagnant. The plant was operating at only half of its design capacity and, therefore, could receive a greater hydraulic load, in the form of industrial effluents. The hydraulic load to the digesters could be increased from 10 m^3/d to 67 m^3/d to give a HRT of 30 d. These digesters should be targeted as available capacity due to the abundance of industry in the vicinity.

The effluent treatment plant at Illovo Sugar, in **Noodsberg,** has an anaerobic lagoon committed entirely to the treatment of the mill effluent. The lagoon is large and very few operating parameters were monitored since the final effluent meets the required discharge standards (Department of Water Affairs and Forestry, 1994).

The **Northern** Wastewater Treatment Works, located in Springfield Park, is a large works, treating 43 Mℓ/d. It was, however, only operating at 61 % of its design hydraulic capacity. There were 3 anaerobic digesters on site, one was fed an extra 35 m^3/d, resulting in a lower HRT (24 d) than the other 2 digesters (36 d). These extended HRTs indicated the availability of hydraulic capacity which could be utilised for the treatment of effluents from the many industries in the Springfield Industrial Park. The performance efficiency of these digesters was good, with an average organic load of 1.6 kg VS/m^3.d, volatile solids reduction of 62 % and methane production of 0.3 m^3 CH_4 /kg VS destroyed. Biogas production was measured at ca. 3 550 m^3/d, with a CH_4 content of 64.7 % (v/v). A portion of the methane was used to heat the digesters to 37 °C. Mixing was achieved by recirculation of the digester sludge. The digester sludge was healthy with a pH of 7.4 and a Ripley ratio of 0.05. There was available organic capacity, at this WWTW since the digesters are high-rate (heated and mixed), they could, theoretically, accept an organic load of 3 kg VS/m^3.d, however, the average organic load was only 1.6 kg VS/m^3.d.

Phoenix is currently a residential area although the region has been targeted for industrial development in the next 5 to 10 years. There are 2 anaerobic digesters at the Phoenix Wastewater Treatment Works of which only one was operational. These digesters were designed for thermophilic operation but are successfully operated under mesophilic conditions. The evaluation of the performance efficiency of the operating digester indicated a healthy digestion process. The organic load of 1.06 kg VS/m^3.d could be increased by feeding thicker sludge (5 to 6 % (m/v) TS instead of 3.9 % (m/v) TS). The reduction of volatile solids was efficient (66 %) with a residence time of 31 d. This works was operating at 44 % (v/v) of its design capacity, therefore operation of the idle digester would facilitate the treatment of industrial effluents. Biogas production averaged ca. 1 500 m^3/d with a 65 % (v/v) CH_4 content. This resulted in CH_4 production of 0.55 m^3/kg VS destroyed. This could be improved by increasing the organic load to the digester. The digester sludge was healthy and the Ripley ratio averaged ca. 0.04. The pH was relatively low at 6.8 but was still within the range for efficient degradation. The digester sludge was recirculated to facilitate mixing.

Scottburgh, on the Natal south coast, has a small wastewater treatment works treating only domestic sewage. The flow to the works is seasonal due to the tourism associated with the area. Out of season, the works operated at only 49 % (v/v) of its design capacity. During holiday season, however, it operates near to the design specifications. The operating data for this wastewater treatment works, as presented in **Appendix A**, were collected during an off-season period thus reflecting the high retention time (108 d) and the low loading rate (0.14 kg VS/m^3.d). Biogas was not collected but was vented to the atmosphere. Volatile solids reduction was relatively low at 50.3 %. This could be improved by heating the digester and increasing the organic load. The VFA concentration in the digester sludge was high resulting in a high VFA to alkalinity ratio (0.6) which indicated the need for buffering capacity. It is not suggested that this works should accept industrial effluent as the seasonal variations in its load could result in overloading.

The volumetric load the UASB reactor at the **South African Breweries** effluent treatment plant was great (3 303 m^3/d) and the organic load was high (3.3 kg VS/m^3.d). The phase separator, in the digester, separated the sludge from the effluent, resulting in a low HRT (0.51 d). This was necessary due to the large volumes of effluent produced by the brewery. The efficient functioning of this digester is proof that high-strength organic effluents can be efficiently treated by anaerobic digestion. A volatile solids reduction of ca. 66 % was achieved and biogas was produced at a rate of 4 900 m^3/d. The CH_4 content of the biogas was ca. 73 % (v/v) resulting in the production of 1.3 m^3 CH_4/kg VS destroyed. The pH of the pelletised sludge was relatively low (6.5) resulting in a high VFA to alkalinity ratio (1.1). The temperature of the reactor was maintained at 37 °C and mixing was achieved with gas spargers. These parameters indicated that the digester was operating effectively and remedial action need not be taken except, perhaps, the suggestion to reduce the digester loading and implement better control of the pH.

The anaerobic digesters at the **Southern** Wastewater Treatment Works, in Jacobs, have been off-line since 1985. The operating data presented in **Appendix A** and the performance calculations were from recorded data from the time when the digesters were operational. The omission of data was due to the unavailability of old records. During their operation, these digesters were efficient and are, therefore, a ready source for the treatment of industrial effluents produced in the vicinity.

Sundumbili is located on the Natal north coast, just north of the Tugela River. This works is managed by the Water and Sanitation Services of South Africa (Pty) Ltd. There are 4 small anaerobic digesters on the plant which was operating close to its design capacity (99 % (v/v)). The feeding schedule to the anaerobic digesters was such that all 4 digesters are used alternately as primary and secondary digesters. A digester was fed for 3 d, with continuous mixing, whereafter the digester was taken off-line for 4 d to settle the sludge. The performance efficiency of these digesters was relatively good although the high volumetric loading resulted in a short HRT

(14 d) which could be the cause of the low reduction in volatile solids (36 %). The loading to the digesters was in the region of 1.01 kg VS/m³.d. Performance efficiency could be improved by thickening the feed sludge, at present it is only ca. 2 % (m/v), and heating the digesters. Biogas production was not monitored. Mixing was achieved by recirculation of the digester sludge. Approximately 50 % (v/v) of the inflow to the works was industrial effluent, mostly from the Esithebe region. The industrial effluents contained heavy metals, oils and vegetable oils.

Tongaat Wastewater Treatment Works is managed by Aquafund (Pty) Ltd. The works was operating at its design capacity (3 Mℓ/d) and treating only domestic sewage. The load to the digesters was relatively low (0.28 kg VS/m³.d) resulting in an extended HRT (ca. 100 d). The reduction in volatile solids averaged around 45 %. This could be improved by heating the digester and thickening the feed sludge. Biogas was vented to the atmosphere without measurement. A pH of 7.1 and a VFA/alkalinity ratio of 0.05 suggested relatively healthy digestion. The digester throughput could be increased resulting in a shorter HRT. Reduction of the HRT to 30 d would facilitate an increase in the digester feed from 40 m³/d to 133 m /d.

The **Umbilo** Sewage Purification Works is located in Pinetown, on the banks of the Umbilo river. The works treats ca. 75 % of its design volumetric load, at 17 Mℓ/d. There are 8 anaerobic digesters on site, 4 of which have been converted to secondary digesters. The design volume of each digester was 1 340 m³. The digesters were built into the ground. Each of the 4 primary digesters was fed ca. 60 m³/d with an organic load of 1.12 kg VS/m³.d. The operation of the digesters was efficient with a 72 % reduction in volatile solids and methane production of ca. 0.63 m³/kg VS, at a retention time of 22.3 d. The pH of the digester sludge was high at 7.5. These values are annual averages calculated from the monthly data reports. The VFA to alkalinity ratio of the digester sludge was 0.008. These performance calculations indicated that more of the digester capacity was being utilised than that estimated by the operators. The retention time was not protracted. Degradation was efficient and additional loading could be accepted in terms of both hydraulic and organic loads. However, investigations should be done to prevent an organic overload. Biogas production was estimated at ca. 1 200 m³/d, with a CH_4 content of 65 % (v/v). A portion of the CH_4 was used to heat the digesters to 36 °C. Mixing was achieved by a draft tube. The operation of these digesters was efficient. Detailed performance calculations are presented in **Chapter 6**.

The control of the **Umbogintwini** sewage disposal plant falls under AECI Operations Services (Pty) Ltd. Operational parameters were not monitored as the effluent met the General Standard for Wastewater (Department of Water Affairs and Forestry, 1994). This works treated only domestic sewage. The flow to the works was low and the digester was only fed ca. 4 m³/d. Parameters such as total solids and volatile solids were not monitored, therefore, the performance efficiency calculations could not be determined. The HRT of the digester was 27 d. This digester could receive a greater load but it is not recommended until the operational parameters of the digester are thoroughly assessed.

The **Umlazi** Wastewater Treatment Works has recently been renamed the Isipingo Wastewater Treatment Works, due to the take over by the Durban Metropolitan Council. This works treated purely domestic sewage, except for ca. 100 m³ /d of landfill site leachate. There were 6 small anaerobic digesters on this plant, 1 of which was idle. The works was operating at 64 % (v/v) of its design capacity. The organic load to the digesters was 1.7 kg VS/m³.d with a resultant 62.5 % reduction in volatile solids. The HRT was relatively low at 16.1 d, although an efficient reduction of volatile solids was achieved. The digester sludge was healthy with a pH of 7.3 and VFA/alkalinity ratio of 0.04. The digesters were unheated; heating could improve performance efficiency. Biogas production was not measured.

Umzinto is located on the Natal south coast. The works is monitored by the Umzinto Local Council and operated at ca 40 % (v/v) of its design capacity, with ca. 20 % (v/v) of the inflow being industrial effluent. There are several textile industries in the region. The operating parameters of the anaerobic digester were not monitored thus it was impossible to evaluate the performance efficiency of the digester. The digester was, however, operated at an extended retention time (ca. 200 d). There is the potential for the anaerobic digestion of high-strength or toxic organic effluents produced in the region. To ensure efficient degradation, the sludge would have to be stabilised, the digester should be heated and mixed to optimise degradation efficiency and digestion parameters should be monitored to evaluate the performance efficiency.

Verulam Wastewater Treatment Works is managed by Aquafund (Pty) Ltd. Almost 79 to 80 % (v/v) of the inflow to the works was industrial effluent, however, the works was only operating at approximately half of its design capacity. A result of this was a low organic load to the anaerobic digesters (0.14 kg VS/m^3.d) and an extended HRT of ca. 120 d. for the smaller digester and 240 d for the 2 larger digesters. Volatile solids reduction was efficient (57 %) due to the extended HRT. Process efficiency could be improved by increasing the temperature of the digester sludge and reducing the HRT. The digester sludge had an average pH of 7.2 and a VFA/alkalinity ratio of 0.04. These digesters have available capacity both on a hydraulic and organic scale.

Physical and operating data of the anaerobic digesters at the Dundee, Ladysmith and Vryheid Wastewater Treatment Works were not made available by the local authorities by the time that this report was written. The details will be submitted as a separate annexure once they are obtained.

A summary of these results is given below.

TABLE 3.3 : Digester performance details.

Treatment works	Fraction of total design digester vol. (%)	Organic loading rate (kg/m^3.d)	VS redn. in digester (%)	Vol. CH_4 / mass VS destroyed (m^3/kg)	COD red. in works (%)	Retention time (d)	Fraction ind. efflnt to works (% v/v)
Amanzimtoti	61	0.25	45	N/D	90	46	50
Cato Ridge Abattoir	17	4.1	72	N/D	95	5	100
Darvill	100	2.03	65	1.01	95	20	10
Estcourt	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Kwa Makutha	100	2.1	56	N/D	86	18	0
Kwa Mashu	100	1.09	59	0.76	70	27	10
Kwa Ndengezi	100	0.5	26	N/D	93	53	0

Treatment works	Fraction of total design digester vol. (%)	Organic loading rate (kg/m³.d)	VS redn. in digester (%)	Vol. CH_4 / mass VS destroyed (m³/kg)	COD red. in works (%)	Retention time (d)	Fraction ind. efflnt to works (% v/v)
Mpophomeni	50	3.2	33	N/D	94	15	0
Mpumalanga	100	0.34	35	N/D	94	94	0
Newcastle	33	N/D	N/D	N/D	90	N/D	10
New Germany	100	0.08	24	N/D	95	200	30
Noodsburg	100	0.05	N/D	N/D	25	15	100
Northern	100	1.6	62	0.3	72	36	4
Phoenix	50	1.06	66	0.55	76	31	0
Scottburgh	100	0.14	50	N/D	92	108	0
S.A. Breweries	100	3.3	66	1.3	96	0.5	100
Southern	0	58	55	1.2	N/D	0	40
Sundumbili	100	1.01	36	N/D	94	14	50
Tongaat southern	100	0.28	45	N/D	93	100	0
Umbilo	100	1.12	72	0.63	71	22	20
Umbogintwini	100	N/D	N/D	N/D	75	26	0
Umlazi	83	0.14	63	N/D	90	16	2
Umzinto	100		N/D	N/D	87	200	20
Verulam	100		57	N/D	80	240	80

N/D : Not determined

No correlation could be drawn between the reduction in volatile solids and the industrial effluent content of the feed sludge. The degree of reduction of the substrate is dependent on the degree of acclimation of the biomass to the particular substrate.

3.5 *Improving Digester Performance*

A wastewater treatment works can provide all of the necessary nutrients and biomass required for the treatment of an industrial effluent. The nutrients are present in the raw sewage feed which eliminates the costly need for supplementation. Another advantage of treatment of an industrial effluent at a wastewater treatment works is that the digesters are usually stable and should facilitate quick treatment of the effluent. However, optimum process performance is seldom achieved due to poor operating conditions.

One way to improve the performance of a treatment works is to improve the flow through the processes. If the flow is poor, for example, it does not use the entire volume of the process, or it bypasses part of the process, the performance will then be impaired. The flow patterns determine the length of time spent in the reactor by each element of the fluid and are also important to determine the heat and mass transfer (Rabbitts, 1982). The flow must, therefore, be understood and assessed. For this, it is necessary to model the process flow (Barnett, 1995). A model of flow patterns, or a flow model, facilitates possible improvements for more efficient operation and process intensification to be postulated. The effect of improvements may also be predicted. A flow model can, in addition, be used as a diagnostic tool in process failure as condition changes will be indicated by flow pattern changes.

The performance of large-scale reactors is affectedy by the retention time of the substrate in the reactor and the degree of contact between the incoming substrate and the viable bacterial population. These parameters are, primarily, a function of the hydraulic regime in the reactor (Smith, Elliot and James, 1996).

Other operating problems which may be encountered include pH control and a reduction in concentration (thickness) of the feed which could cause alkalinity wash-out and necessitate better temperature control. If the digester is found to be unhealthy, the organic load should be reduced.

3.6 Treatment of High-strength or Toxic Organic Effluents in Available Anaerobic Digester Capacity

The anaerobic digester survey identified the availability of either hydraulic or organic capacity, or both, in several of the municipal anaerobic digesters in KwaZulu-Natal (**Table 3.1**). It was proposed that this available capacity be utilised for the treatment of high-strength or toxic organic effluents, produced by industries in the vicinity, which are currently either disposed of into municipal landfill sites or via marine discharge. The feasibility of this proposal must be questioned in terms of the ability of wastewater treatment works to accept effluent tankers.

In terms of the *Cradle to Grave* concept, a waste generator must assume full responsibility for its waste, including the safe disposal. The generator must be able to define the composition of the waste, with particular reference to the presence of toxic, biorefractory or inhibitory components. A gross sample analysis, or screening test, can be performed to assess the feasibility of treating a particular effluent in an anaerobic digester, i.e., to assess the biodegradability and the potential toxicity of the effluent and its individual components (**Chapter 5**).

The principal objective is to concentrate the high-strength or toxic organic components at the source. Implementation of waste minimisation practices, such as recycling, should reduce the volumes of high-strength waste being produced. The concentrated waste could be collected on-site and then tankered to a nearby wastewater treatment works for treatment in the available anaerobic digester capacity. The waste generator would bear the costs of tankering and the tariffs imposed by the sewage works. Tariffs are calculated based on COD and suspended solids contents of an effluent. These tariffs may need to be increased, with increased usage of tankers, for road maintenance. In terms of estimation of cost, a quote was obtained for a municipal tanker (10 m^3), of R35/km (1997). There are several inportant issues that must be taken into consideration, regarding the tankering of effluents. These include: road maintenance; accessibility of waste water treatment works to large tankers; volume of effluents to be transported; ability of a WWTW to receive numerous tankers; etc.

On-site pre-treatment is an alternative although the waste generator would have to assess the overall capital and maintenance costs of an on-site treatment plant in comparison to the tankering and tariff costs.

Chapter 4

Effluent Survey

4.1 Introduction

Industrial water usage results in large volumes of liquid wastes rich in organic pollutants (Terzis, 1994). In the future, industry will use less water due to the implementation of cleaner production and waste minimisation practices. Increased water charges will lead to more precise control and integrated processes will reduce wastage.

This research investigated the feasibility of treating concentrated high-strength or toxic organic effluents in available anaerobic digester capacity. Effluents of interest were those with very high chemical oxygen demand values which would overload conventional treatment processes, those that were co-disposed in municipal landfill sites and those that were discharged to sea.

4.2 Effluent Compositions

Wastewaters contain a mixture of organic and inorganic solids which are suspended and/or dissolved in water (Ross et al., 1992). Some of these substances could be toxic and, in high concentrations, these compounds may kill the microorganisms and, in sub-lethal concentrations, significantly reduce the microbial activity (Gray, 1989; Lettinga, 1995). Substantial volumes of organic effluents are discharged to rivers and the sea where they can have adverse effects on the aquatic environment (Department of Water Affairs and Forestry, 1992). The presence of organic materials depletes the dissolved oxygen content of the water courses (Walters, 1981).

Organic matter comprises carbon, hydrogen and oxygen with nitrogen frequently present (Gray, 1989). The majority of the organic carbon can be attributed to the major organic groups, namely, the carbohydrates, fats, proteins, amino acids and volatile fatty acids. Synthetic organic materials which may be present in industrial effluents include pesticides, polychlorinated biphenyls and ethane derivatives (Boyd, 1988). Many of the synthetic organic molecules are recalcitrant whereas others are only decomposed at very slow rates (Gray, 1989). Below are descriptions of organic molecules commonly found in industrial effluents.

Hydrocarbons : hydrocarbons contain only carbon and hydrogen and the majority are poorly soluble in water (Brock and Madigan, 1991). Low molecular weight hydrocarbons are gases, whereas those of higher molecular weight are liquids or solids at room temperature. Relatively few microorganisms can utilise hydrocarbons for growth (Brock and Madigan, 1991). In aliphatic hydrocarbons, the carbon atoms are joined in open chains (Brock and Madigan, 1991). Utilisation of saturated aliphatic hydrocarbons is strictly an aerobic process although unsaturated aliphatic hydrocarbons containing a terminal double bond can be oxidised by certain sulphate-reducing and other anaerobic bacteria (Brock and Madigan, 1991). Aromatic hydrocarbons can be degraded anaerobically (Brock and Madigan, 1991).

Fats and phospholipids : fats are the major organic constituents in the suspended solids fractions of wastewaters since they are only sparingly soluble in water (Gray, 1989). Fats is a general term to describe the whole range of fats, oils and waxes that are discharged. Fats are esters of glycerol and fatty acids and are among the more stable organic compounds. They are not readily degraded (Gray, 1989). Microorganisms utilise fats only after hydrolysis of the ester bond, and extracellular enzymes (lipases) are responsible for the reaction (Brock and Madigan, 1991). The end result is the formation of glycerol and free fatty acids. Fatty acids are oxidised by the process of ß-oxidation, in which two carbons of the fatty acid are cleaved off at a time, with the subsequent release of acetyl-CoA molecules (Brock and Madigan, 1991). Acetyl-CoA is then oxidised by the tricarboxylic acid cycle (TCA) cycle or is converted into hexose and other cell constituents via the glyoxylate cycle (Brock and Madigan, 1991).

Proteins : proteins are a comparatively important source of carbon in wastewater although they are less important than soluble carbohydrates or fats (Gray, 1989). Protein is the principal constituent of all animal and, to a lesser extent, plant tissue thus waste from food preparation and excreta is rich in protein. Apart from containing carbon, hydrogen and oxygen, proteins also contain high proportions of nitrogen (Gray, 1989). Proteins are made up of long chains of amino acids connected by peptide bonds and are readily broken down by bacterial action to form free amino acids, fatty acids, nitrogenous compounds+1Xphates and sulphides (Gray, 1989). Ammonia toxicity is often a problem in feedstocks with a high protein content since ammonia is rapidly formed in a digester by deamination of protein constituents (Gunnerson and Stuckey, 1986).

Nitrosamines and nitrophenols : are used as intermediates in the synthesis of rocket fuel, as solvents in fibre and plastics industries, antioxidants in fuels and additions to fertilisers, insect repellents, insecticides, fungicides, bactericides and lubricating oils (Department of Water Affairs and Forestry, 1992; Haghighi-Podeh and Bhattacharya, 1996). These compounds are relatively persistent in the natural environment as they are not readily degraded.

Polychlorinated biphenyls (PCB's) : are a class of aromatic compounds which have found widespread applications because of their general stability and excellent dielectric properties (Oellerman and Pearce, 1995). The persistence of PCB's in the environment has invoked concern because of their tendency to be bioaccumulated and because of their possible adverse health effects (Oellerman and Pearce, 1995).

Phthalate esters : represent a large group of chemicals which are widely used as plasticisers in polyvinyl chloride (PVC) resins, adhesives and cellulose coatings (Department of Water Affairs and Forestry, 1992). A number of organisms have been found to be capable of metabolising phthalate esters under different environmental conditions.

Resin acids : are contained in compounds used in the manufacture of tar, pitch, turpentine and rubber (Department of Water Affairs and Forestry, 1992). They are normally insoluble in water and recalcitrant.

Surfactants : are organic chemicals which reduce surface tension in water and other liquids and are, therefore, used in soaps, laundry detergents and shampoos. They are compounds with both hydrophobic and hydrophilic groups. Because of these properties, surfactants tend to concentrate at the interfaces of aqueous mixtures. The anaerobic digestion of surfactant wastewaters is advantageous since severe foaming problems are often encountered with aerobic treatment.

Volatile fatty acids : the toxic effect of high concentrations of volatile fatty acids (VFA's) on methanogenic bacteria is important because VFA's are intermediates in the anaerobic digestion process (Zeikus, 1979). Their toxic effects in high concentrations are attributed either to the toxicity of the VFA's themselves or the reduction in alkalinity which they cause (Zeikus, 1979). Long-chain fatty acids such as palmitic, stearic and oleic acids can exert a toxic effect in anaerobic digestion if they are present in solution (Kugelman and Chin, 1971; Gunnerson and Stuckey, 1986).

Not all compounds are degradable. Many **xenobiotic** compounds, which are chemicals synthesised by humans that have no close natural counterparts, have molecular structures and chemical bond sequences that are not recognised by existing digestive enzymes (Cloete and Muyima, 1997). These compounds, e.g. pesticides, plastics and other synthetics, resist biodegradation or are metabolised incompletely with the result that some xenobiotic compounds accumulate in the environment (Cloete and Muyima, 1997). Xenobiotic organic compounds might be recalcitrant to biodegradation due to unusual substitutions, unusual bonds or bond sequences o excessive molecular size. In some cases, one portion of a molecule is susceptible to degradation while the other is recalcitrant. Thus, a diverse array of chemical modifications to a xenobiotic compound can occur as a result of microbial metabolism.

Thus, there are numerous industrial wastewaters which may be toxic to the anaerobic biomass due to the presence of xenobiotics or recalcitrant molecules. Fortunately, **acclimation** of the biomass facilitates the anaerobic biodegradation of many organic toxicants. It is well established that acclimated cultures can be induced to biodegrade highly toxic, or recalcitrant, compounds which had previously impaired metabolism (Speece, 1996). The time required for acclimation is dependent on the substrate structure, the inoculum source and the environmental conditions. Research has shown that the acclimated biomass does not require a constant presence of the toxicant since the *microbial memory* facilitates degradation of the toxicant when it is present (Speece, 1996). In an acclimated biomass there is no reduction in metabolic activity at concentrations of the toxicant that would normally be inhibitory.

The composition of the effluent is important in the identification of effluents which could be treated anaerobically. Concentration of an organic compound may be a significant factor affecting its susceptibility to microbial attack (Boethling and Alexander, 1979). The ultimate fate of the effluent is also important since treatment in available anaerobic digester volume may be more attractive, not only financially but also with regard to the protection of the environment.

4.3 Industrial Effluents in KwaZulu-Natal

The aim of this section was to identify industries producing high-strength or toxic organic effluents.

4.3.1 Effluent survey

A survey was conducted to identify industries which produced high-strength or toxic organic effluents. The survey incorporated a range of industries. The Durban Metropolitan Council provided information on those effluents monitored by them. Details of the effluents, for each region, are presented in **Appendix B**. These data include volumes of effluent produced and approximate strength (COD) based on monthly records. All effluents with a COD > 2 000 mg/ℓ were included.

Emphasis was placed on two particular regions due to the concentration of industry and the availability of anaerobic digester capacity. These two areas were Durban South and Pinetown. Effluents in the Durban South area could be treated in the idle digesters at the Southern Wastewater Treatment Works. Effluents produced in the Pinetown region have the potential for treatment at the Umbilo Sewage Purification Works or New Germany Wastewater Treatment Works. Industries in these regions were visited to gain familiarity with the processes and on-site pre-treatment methods.

4.3.2 Discharge of industrial effluent to sewer

The survey revealed the necessity for the identification of point source emissions within factories. This would, however, require an extensive survey in which researchers should become familiar with each process and be able to identify sources of high-strength or toxic organic components within a factory. These effluent sources could be segregated from the bulk effluent, concentrated on-site and then tankered to a nearby wastewater treatment works for treatment in the available anaerobic digester capacity. A study of such deptacilitate identification of possibilities for pollution prevention and waste minimisation. Segregation of the high-strength or toxic components of an effluent should facilitate compliance of the remainder of the effluent to the standards for discharge to sewer. The current draft bylaws, for the acceptance of trade effluent into a sewage disposal system, are presented (**Table 4.1**) (Durban Metropolitan Council, 1997).

TABLE 4.1 : Standards for the discharge of trade effluent into a sewage disposal system, according to the current draft bylaws.

General Quality Limits	Large Works (> 25 Mℓ/d)	Small Works (< 25 Mℓ/d)	Units
Temperature	<44	<44	°C
pH	6 to 10	6.5 to 10	pH units
Oils, greases, waxes of mineral origin	50	50	mg/ℓ
Vegetable oils, greases, waxes	250	250	mg/ℓ
Total sugar and starch (as glucose)	1 000	500	mg/ℓ
Sulphates in solution (as SO_4^{2-})	250	250	mg/ℓ
Sulphides (as S^{2-})	1	1	mg/ℓ
Chlorides (as Cl^-)	1 000	500	mg/ℓ
Fluoride (as F^-)	5	5	mg/ℓ
Phenols (as phenol)	10	5	mg/ℓ
Cyanides (as CN^-)	20	10	mg/ℓ
Settleable solids	Charge	Charge	mℓ/ℓ
Suspended solids	2 000	1 000	mg/ℓ
Total dissolved solids	1 000	500	mg/ℓ
Electrical conductivity	-	400	mS/m
Anionic surfactants	-	500	mg/ℓ
COD	Charge	Charge	mg/ℓ
Heavy Metal Limits			
Copper (as Cu)	50	5	mg/ℓ
Nickel (Ni)	50	5	mg/ℓ
Zinc (Zn)	50	5	mg/ℓ

General Quality Limits	Large Works (> 25 Ml/d)	Small Works (< 25 Ml/d)	Units
Iron (Fe)	50	5	mg/l
Boron (B)	50	5	mg/l
Selenium (Se)	50	5	mg/l
Manganese (Mn)	50	5	mg/l
Lead (Pb)	20	5	mg/l
Cadmium (Cd)	20	5	mg/l
Mercury (Hg)	1	1	mg/l
Total chrome (Cr)	20	5	mg/l
Arsenic (As)	20	5	mg/l
Titanium (Ti)	20	5	mg/l
Cobalt (Co)	20	5	mg/l
TOTAL METALS	100	20	mg/l

Industrial effluents from the Pietermaritzburg area are discharged to the Darvill Wastewater Treatment Works. Discharge standards are monitored by Umgeni Water. The major problem in this area is the disposal of effluent from the four vegetable oil refineries. The survey did not concentrate on this region since the Darvill Wastewater Treatment Works was operating almost at full capacity therefore additional loading of high-strength industrial effluents could be detrimental to the operation of the digesters.

The Durban Metropolitan Council was approached for information on the proposed establishment of new industry in the province. The main area demarcated for industrial development is Phoenix. High-strength or toxic organic effluents, produced in this region, could be treated in the idle digester at the Phoenix Wastewater Treatment Works. Thus, Phoenix would be a rational location for the development of new industries producing effluents of this nature. No other plans of extensive industrial development were divulged.

4.3.3 Source / digester matrix

A source / digester matrix (**Table 4.2**) was compiled with the digesters identified with available capacity and the industrial effluents for potential treatment. Individual factories are listed for the two regions covered by the survey. Potential for treatment of a specific effluent in a particular digester is identified by a tick. More detailed data are given in **Appendix B**.

What is evident from the matrix is that many of the industries in these two regions were agro-industrial. These industries often produce high-strength organic effluents which are monitored by the local authorities to ensure compliance to the stipulated discharge standards. To meet the standards, for discharge to sewer, the effluents are often diluted with excessive wastage of potable water. Another option for the disposal of effluents with a COD too high to be accepted at a sewage works, without either dilution or the imposition of high tariffs, is discharge to sea, e.g. CG Smith. Marine discharge standards are much lower than those for discharge to sewer since it is believed that the rapid turnover of water prevents adversity to marine ecosystems. The end result, with marine discharge, is a loss of water. Industries utilise fresh water from the rivers, however, when this is discharged to sea, the water can not be re-used. Co-disposal in municipal landfill sites is another option for high-strength or toxic organic effluents. A potential problem with co-disposal is the generation of excess leachate which, if the landfill is not properly lined, may cause contamination of the groundwater. The co-disposal of liquid effluents has even resulted in landfill subsidence e.g., the BulBul Drive landfill site, in Chatsworth, Durban, where a large mass of compacted waste collapsed on 8th September 1997 (Anon, 1997).

Examples of industries which produce high-strength organic effluents are dairies, bakeries, chemical and pharmaceutical manufacturers and yeast processors. Many of these effluents have been found to be amenable to anaerobic degradation (Van Der Merwe-Botha and Britz, 1997). Pesticide effluent is an example of an effluent which contains toxic organic molecules. Effluents of this nature are usually co-disposed in municipal landfill sites. They could, however, be treated by anaerobic digestion upon acclimation of the biomass. Also, implementation of waste minimisation practices and identification and segregation of point sources, would reduce the volumes of toxic effluent being produced. These lower volumes could then be treated in a digester without causing toxic shock.

TABLE 4.2 : Source / digester matrix illustrating the potential for the treatment of specific effluents in anaerobic digesters with available capacity.

DIGESTERS	Amanzimtoti	Cato Ridge	Mpophomeni	Mpumalanga	New Castle	New Germany	Northern	Phoenix	Southern	Tongaat	Umbilo	Umlazi	Umzinto	Verulam
INDUSTRIES														
Albany Bakery									✓					
Alex Cartage											✓			
Auto Armor											✓			
Associated Biscuits											✓			
Beacon Sweets									✓					
Beier Industries									✓					
Bromor Foods									✓					
Cargo Carriers									✓					
Cato Ridge region		✓												
CFC											✓			
Chemical Specialities									✓					
CHT South Africa						✓								
CG Smith									✓					
Coates Brothers	✓								✓					
Competition Motors									✓					
Dan Perkins											✓			
Distillers Corp.						✓								
Drum Services									✓					
Durban Confectionary									✓					
Durban South region									✓			✓		
Elida Ponds									✓					
Engen Refinery									✓					
Ferrobond											✓			
Fine Foods									✓					
Frametex						✓					✓			
Frame Textiles									✓					
Golden Lay Farms									✓					
Hammarsdale region				✓										
Huletts Refinery									✓					
Huls						✓					✓			
Ind. Oil Processors									✓					
Kohler Carton											✓			
Lever Bros./ Unifoods									✓					
Marachia Laundry									✓					
Mondi Paper									✓					
Nampak											✓			
NCD											✓			
NCP Umgeni							✓							
NCP/Sentrachem									✓					
NCP Yeast									✓					
Nelba											✓			
New Castle region					✓									
New Germany region						✓					✓			
Ninian & Lester											✓			
O.T.H. Beier									✓					
Paperkem									✓					
Pekay Chemicals											✓			
Phoenix region								✓						
Pinetown region						✓					✓			
Plascon Paints									✓					

DIGESTERS / INDUSTRIES	Amanzimtoti	Cato Ridge	Mpophomeni	Mpumalanga	New Castle	New Germany	Northern	Phoenix	Southern	Tongaat	Umbilo	Umlazi	Umzinto	Verulam
Pure Fresh Foods											✓			
Printpak									✓					
Prostruct											✓			
Qualichem											✓			
R&B Engineering											✓			
Rapidol											✓			
Rentokil											✓			
Republican Press	✓													
Resmed											✓			
Revertex									✓					
Robertsons	✓													
Sapref Refinery									✓					
Sarachem								✓						
S.A. Sugar Terminals									✓					
Springfield Park							✓							
Sorghum Breweries									✓					
South coast region													✓	
Staflex											✓			
Status Chemicals											✓			
Sunningdale							✓	✓						
Sunrise Dairies											✓			
Sybron Chemicals											✓			
Syndachem											✓			
Tanker Services									✓					
Tongaat region										✓				✓
Trek Express											✓			
Triumph Printers											✓			
Unitrans Natal									✓					
Verulam region														✓
Vision Creations									✓					
Waste Services									✓					
Waste Tron											✓			
Westmead						✓					✓			
Whiteheads										✓				

This matrix provides an indication of the potential for treatment of *problematic* effluents in available anaerobic digester capacity. A number of practical and logistical issues must be examined in each case. The matrix only includes those digesters which were identified with available capacity and those industries (in the 2 chosen regions) producing effluents with a COD > 2 000 mg/l. This matrix could be extended to incorporate a wider range of industries and digesters. What can be deduced from this survey and the compilation of the matrix is that there is definitely the potential for the utilisation of available resources to effectively stabilise effluents which otherwise may have an adverse effect on the environment.

Chapter 5

Laboratory-Scale Test Protocol

Assessment of the anaerobic degradability of an effluent, prior to its loading into a digester, is critical to prevent digester failure. This chapter focuses on organic industrial effluents and mechanisms for screening and assessing the feasibility of anaerobic treatment.

5.1 *Protocol*

A batch test protocol has been developed for simple effluent evaluation in the laboratory. The incubation time is short and the test functions as a screening mechanism to assess the anaerobic degradability and the potential toxicity of an effluent and its components.

5.1.1 Batch culture

Although experimental models greatly simplify the interactions between microbial populations and between the microbial community and the environment, the extent to which a model simulates the real ecosystem must be critically appraised. Laboratory-scale models attempt to simulate the conditions prevailing in the whole or part of the natural environment under study (Atlas and Bartha, 1993). In a batch culture, or model closed system, enrichment initially takes place under defined conditions, with no further input of growth substances or removal of metabolic end products (Parkes, 1982). Biological components and a supportive nutrient medium are added to the closed system. It is a self-sustaining system. As the biological process under the conditions of batch cultivation proceeds dynamically, but in the spatially closed and constant volume of the cultivation medium, it gradually changes with time. With gradual exhaustion of the nutrients and accumulation of metabolites in the living system a point is reached where exchange of free energy no longer occurs.

Anaerobic treatment has not always been an efficient and reliable treatment method since some potential residues for bioconversion are relatively recalcitrant and may contain materials which are toxic to methanogenic microorganisms (Owen, Stuckey, Healy, Young and McCarty, 1979). Bioassay techniques for measuring the degradability, as well as the pf inhibitory substances, could resolve anaerobic treatment problems.
Batch bioassay techniques facilitate the evaluation of a wide range of variables (Owen et al., 1979).

5.1.2 Biodegradability and toxicity assays

A number of experiments were made to determine the optimum assay conditions for laboratory-scale batch assessment of organic effluent biodegradability and toxicity to the biomass. The most effective technique is described.

Owen et al. (1979) described techniques for measuring the biodegradability (biochemical methane potential, BMP) and toxicity (anaerobic toxicity assay, ATA) of material subjected to anaerobic treatment. The bioassays were relatively simple and could be undertaken without the need for sophisticated equipment. Biochemical methane potential is a measure of substrate biodegradability and is determined by monitoring cumulative methane production from a sample which is anaerobically incubated in a chemically defined medium (Owen et al., 1979). The anaerobic toxicity assay measures the adverse effect of a compound on the rate of total gas production from a labile methanogenic substrate (Owen et al., 1979). Both techniques involved anaerobic serum bottles that contained samples, defined medium and seed inoculum. The serum bottles were incubated at the desired temperature and the respective gas productions were monitored volumetrically (Owen et al., 1979). The incubation period was typically 30 d which, in most cases, ensured mineralisation of biodegradable organic molecules (Owen et al., 1979). A protracted incubation period should provide more information on the degradation kinetics and allow for the acclimation of the biomass to inhibitory compounds.

The experimental method is described in **Appendix C**. For the BMP assay, controls, which contained only sludge and the mineral medium, were prepared in duplicate . The function of the control was to determine the volume of gas produced due to the microbial degradation of residual organic molecules in the inoculum. The measured gas volumes, for the experimental bottles, were corrected by subtracting the volume of gas produced in the controls to quantify the gas production as a result of the degradation of the substrate alone. In the ATA assay, the controls contained sludge, medium and sodium acetate-propionate solution. The working volume, in each serum bottle, was 100 ml, with a headspace of 25 ml.

The defined nutrient medium (**Appendix C**) contained nutrients and vitamins for anaerobic cultures. Resazurin was added to detect oxygen contamination. Sodium sulphide was incorporated to provide a reducing environment and sodium bicarbonate ($NaHCO_3$) to provide buffering which was important for alkalinity control. The final assay concentrations of nitrogen, phosphorous and alkalinity, respectively, were 122 mg/l as N, 19 mg/l as P and 2 500 mg/l as $CaCO_3$. The C : N ratio was 6 : 1.

The initial substrate concentration was calculated, based on the amount of COD added to each serum bottle. The bottles were incubated in a constant temperature room (37 °C) and shaken manually once a day to facilitate contact between the microorganisms and the substrate. The methods for gas volume sampling and removal are described in **Appendix C**. Gas production was measured daily for the first 10 d and periodically thereafter. Gas was vented as necessary to prevent inadvertent gas leakage and gas overpressure effects (Owen et al., 1979). The biogas compositions were determined by gas chromatography (**Appendix C**).

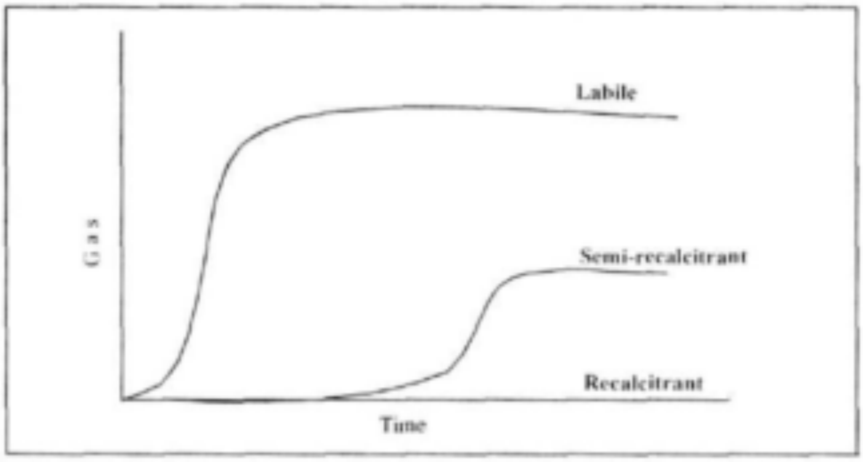

FIGURE 5.1 : Comparison of gas production curves for the degradation of labile, semi-recalcitrant and recalcitrant substrates.

Gas production is indicative of metabolic activity, thus the shape of the gas production curve indicates the degree of degradability of a substrate (**Figure 5.1**). A labile substrate should have a short lag period followed by the exponential growth phase. The gas production rate should be high due to the efficient metabolism of the available substrate. With a semi-recalcitrant substrate, the lag period would be protracted. During this time the biomass would metabolise more readily degradable compounds in the substrate and acclimate to the recalcitrant molecule, i.e., develop the necessary digestive enzymes. There would be not degradation of a recalcitrant substrate.

[illegible] important for the precision and accuracy of g/l in the assay liquid. This can be adjusted when toxicity and/or low degradability are anticipated. Multiple dilutions can be used when an estimate of degradability is not available. The headspace can be decreased, by increasing the liquid volume, to improve the accuracy of methane determinations when low gas production is expected.

The biochemical methane potential (BMP) assay provided an indication of the ultimate anaerobic degradability of an effluent. It also gave information on degradation rates and volumes and concentrations of an effluent that could be treated effectively. A detailed methane balance should be kept for each sample during the assay. Methane content isdetermined whenever gas was wasted. Biochemical methane potential is referenced either to sample volume (m^3 CH_4 /m^3 sample), sample mass (m^3 CH_4 /kg sample), or sample organic content (m^3 CH_4 / kg COD). The latter method permits direct transfer of results into percent organic matter converted to methane by the theoretical 0.350 m^3 CH_4 produced per kilogram COD catabolised (at STP) (McCarty, 1964).

Whilst toxicity is not often a problem in digesters operating on natural substrates, problems can often occur in treating industrial wastes. The anaerobic toxicity assay (ATA) indicates the inherent toxicity of an effluent, which was determined by a decrease in metabolic rate, relative to the control. The acetate-propionate solution was added to these assay bottles as a direct methanogenic precursor; i.e., as a labile source for the methanogens. Substrate was then added. If the substrate or its constituents were inhibitory to the methanogens, the metabolism would decrease and gas production would be lower than in the controls. Thus, anaerobic toxicity was determined as the adverse effect of a substrate on the predominant methanogens (Owen et al., 1979). The ATA is, typically, conducted under quiescent incubation conditions therefore periodic manual agitation is sufficient to facilitate contact. To test a substance, assay concentrations should be selected to provide a range from*non-inhibitory* to *severely toxic* (Owen et al., 1979). The first week of incubation is critical.

Total gas production data were employed for determining relative rates of metabolism of the sodium acetate-propionate solution. The maximum rate of gas production was computed for each sample over the same period and data were normalised by computing ratios between respective rates for samples and the average of the controls. This ratio was designated the maximum rate ratio (MRR) (Owen et al., 1979). Since measurement of gas production was relatively accurate, a MRR of < 0.95 suggested possible inhibition and one < 0.9 suggested significant inhibition.

5.1.3 Bioassay modifications

The laboratory-scale protocol was based on the method described by Owen et al. (1979). A few modifications were imposed to ensure the applicability of the bioassay in the least sophisticated laboratory. The aim was for the protocol to be implemented at the wastewater treatment works as a screening mechanism prior to the acceptance of an industrial effluent for anaerobic treatment.

Owen et al. (1979) used different bottle sizes for the BMP (200 mℓ) and ATA (125 mℓ) tests. The adapted protocol used only one bottle size (125 mℓ) for simplification of the method and to prevent increased expenses. The working volumes were kept constant, at 100 mℓ , in all the bottles.

The inoculumsize was 30 % (v/v) of the total working volume. Owen et al. (1979) used an inoculum size of 20 %. The important factor is that the volume of feed sludge is kept constant, in a particular trial, for comparison between different bottles.

Owen et al. (1979) designed an elaborate apparatus for the anaerobic transfer of the defined medium and substrate into the serum bottles. In the adapted protocol the components were simply measured in measuring cylinders and added to the serum bottles with as little oxygen contamination as possible. Once all of the components were added, the solutions were overgassed (OFN) to expel any oxygen contamination acquired during inoculation.

A gas mixture of 30 % (v/v) CO_2 and 70 % (v/v) N_2 was used by Owen et al. (1979) to overgas the solutions. This gas mixture was not readily available in KwaZulu-Natal resulting in an extended delivery period and the gas being expensive. Oxygen-free nitrogen (Fedgas) was, therefore, used for overgassing. This gas was readily available and inexpensive. The oxygen-free nitrogen could not be used to sparge the solutions since it would strip them of carbon dioxide. This restriction was not applicable with the carbon dioxide/nitrogen gas mixture. The oxygen-free nitrogen was, therefore, only used to overgas the headspace.

The serum bottles were incubated at 37 °C, as compared to 35 °C in the Owen assay. A temperature of 37 °C was chosen since, from the digester survey, it was established that most digesters were heated to this temperature which is optimal for mesophilic digestion. It is unlikely that there would be much difference in results between the two temperatures. What is important is that incubation should occur at the temperature at which the digester of interest is operated. Thus, if the digester is not heated then the bottles should be incubated at ambient temperature or slightly higher due to the exergonic nature of the methanogenic process.

5.1.4 Possible improvements of the protocol

At a wastewater treatment works, the raw sewage, or feed sludge, provides the necessary nutrients for anaerobic digestion and should, therefore, be incorporated into the batch tests to simulate the full-scale digester since the aim of these tests is to provide a screening mechanism for industrial effluents and to give an indication of the effects that a particular substrate may have on the operation of a full-scale digester. Constant volumes of feed sludge should, therefore be included in the serum bottles and realistic feed to effluent ratios calculated. The bioassays without the feed sludge are important as they provide information on the biodegradability of the effluent alone. When mixed with the feed sludge, distinction between metabolism of the feed and the industrial effluent would not be possible. Therefore, it is beli at both tests should be performed. The assay without the feed sludge provides an indication of the substrate degradability and identifies the inhibitory components and the concentrations at which the components may become inhibitory. Based on this information, incorporation of the feed sludge aims to simulate, on a batch-scale, what occurs in the full-scale digester. This facilitates scale-up directly from the batch test to full scale.

A possible improvement for the bioassay would be to have a syringe dedicated to the measurement of gas production in each serum bottle. This would prevent gas loss associated with the re-injection of gas into the bottle and the subsequent removal of the syringe to measure the gas production in another bottle. However, the cost and weight of the glass syringes would necessitate the use of plastic disposable syringes. The plastic syringes could be sealed to the septum with silicon sealant. This is not optimal as it was found that plastic syringes were not as accurate as glass syringes. The reason for this was that the plunger has a rubber seal on the end which tended to stick and a significant gas pressure was required to move the plunger. The glass syringe was, therefore, better for the accurate measurement of gas production.

Mixing the bottle contents could be improved by placing the bottles on a mechanical shaker. Manual shaking of the bottles, on a daily basis, was insufficient to prevent settlement of the contents.

The pH and alkalinity of the solution should be determined at the end of the test to provide an indication of the efficiency of the process.

The method used for COD determinations was based on the open reflux method presented in Standard Methods (American Public Health Association, 1989). This method is not suggested for samples containing solids. If the method is used, the samples should be homogenised. In these tests, the biomass contributed to the overall COD and, therefore, had to be incorporated in the calculations. The presence of solids or flocs can greatly affect the COD measurement. *In full-scale digesters, the organic fraction of the digester feed and effluent is quantified by* the determination of the volatile solids in each stream. This method could be applied in the laboratory tests and a reduction in the volatile solids, over the incubation period, would provide an indication of the substrate reduction. The COD could be determined on the soluble components, prior to inoculation, and the supernatant of the final effluent. This would provide an indication of COD reduction over the incubation period.

5.1.5 Batch vs continuous culture

Batch cultivation methods are not always suitable, especially when it is necessary to work under exactly defined conditions and biological material of constant properties is required (Malek and Fencl, 1966; Parkes, 1982). In batch cultivation, empirical knowledge with only a limited scientific basis is sufficient, whereas the continuous methods require fundamental knowledge of the process as well as its total kinetics.

A way of circumventing the short-comings of batch cultivation, which approaches the continuous-flow process, is **semi-continuous** cultivation, where a part of the fermented substrate is withdrawn at suitable time intervals and replaced by new substrate. The semi-continuous systems are transient forms between the batch and the continuous systems. If the intervals between the additions of fresh substrate and the removals are shortened, the semi-continuous systems approach fully continuous (Malek and Fencl, 1966).

The advantage of using batch tests to evaluate toxicity and biodegradability is that they can be easily set up, in any laboratory, can evaluate a wide range of variables and can investigate the influence of shock loads. The advantage of continuous screening tests would be the close simulation of full-scale operation although they are costly in terms of facilities, equipment, time and personnel (Owen et al., 1979). Batch tests do not simulate the effects of real systems very well, however, they are still useful for sorting out important variables and for the development of an efficient continuous-feed assay program.

5.2 Material and Energy Balances

According to the basic laws of thermodynamics, mass and energy are conserved within a system. The form may change but the total quantity remains constant. Material and energy balances can, therefore, be analysed for a system to give an indication of the process operation. This concept can be applied to the serum bottle tests, where material and energy balances provide an indication of the efficiency of the process within the bottle. This study investigated the response of a batch anaerobic system with a defined substrate, glucose. Glucose was selected because its biochemical fermentation pathways are well known (Sam-Soon, Loewenthal, Wentzel and Marais, 1990). The results obtained from the assay were used to establish a protocol for the calculation of material balances in an anaerobic batch test (**Appendix C**).

5.2.1 Carbon balance

To monitor sample decomposition and process efficiency, it is appropriate to perform a mass balance over the process. A **carbon balance** is particularly useful. A theoretical balance can be calculated from the Tarvin and Buswell equation (Eq. 2.2).

If the empirical formula of the substrate is known, then a carbon balance can be determined from the following relation:

Moles of carbon in - moles of carbon in biogas = moles of carbon remaining

The empirical formula of glucose was known ($C_6H_{12}O_6$), as well as the volume and concentration of glucose solution added to each sample. The carbon mass balance for the 5 g/ℓ assay was calculated (**Appendix C**) by determination of the amounts of carbon entering and leaving the system, incorporating the following components:

$$C_{glucose} + C_{biomass} + C_{nutrient\ medium} \rightarrow C_{CO_2} + C_{CH_4} + C_{biomass} + C_{final\ solution} \qquad [5.1]$$

The carbon balance was based on mass since mass is a conserved parameter. The mass of carbon added in the glucose solution was calculated at 80 mg/100 mℓ . This calculation was based on the chemical formula of glucose and the1Xtration of the glucose solution added to each serum bottle.

The volatile suspended solids of the inoculum sludge were determined by the Standard Method (American Public Health Association, 1989). This provided an estimate of the biomass concentration in the inoculum sludge (6.43 mg/ℓ). For fermentation with live cells, growth and other metabolic activity must be accomodated in the mass balance (Doran, 1995). There are several possible stoichiometric formulations for bacterial protoplasm although the formula most commonly accepted is $C_5H_7O_2N$ (Bailey and Ollis, 1986). The formula is a reflection of the biomass composition. Although microorganisms contain a wide range of elements, 90 to 95 % (m/v) of biomass can be accounted for by carbon, hydrogen, oxygen and nitrogen. The amount of carbon present in the biomass was determined from this empirical formula.

The nutrient medium was made up of trace elements and vitamins necessary for the metabolism of anaerobic cultures. An empirical formula of $C_{12}H_{14}O_3N_2$ was adopted. The nutrient medium contributed to the COD of the assay and was measured as 651 mg/ℓ. From the theoretical COD calculation (**Appendix C**), 1 g of medium had a COD equivalent to 10 g. The mass of nutrient medium added to the serum bottle was calculated based on the COD. The mass of carbon was then calculated from the chemical formula.

The biogas components containing carbon were carbon dioxide and methane. From the theoretical equation (Eq. 2.2), it was calculated that, under the set conditions, addition of 40 mℓ of a 5 g/ℓ glucose solution was equivalent to 0.001 moles of glucose. The theoretical volumes of carbon dioxide and methane production were calculated, based on the mineralisation of 0.001 moles of glucose. The theoretical gas production was 0.003 moles for both carbon dioxide and methane. The theoretical mass of each gas was calculated. These were calculated as 132 and 48 mg for carbon dioxide and methane, respectively. The reason for the greater mass of carbon dioxide relative to methane, when anaerobic biogas usually has a composition of ca. 60 % methane to 40 % carbon dioxide, is that the molecular mass of carbon dioxide is much greater than that of methane. From the experimental results, 84.4 mg of carbon dioxide was produced. This was 64 % (m/w) of the theoretical production. Methane production was only 51 % (w/w) of the theoretical, at 24.5 mg. These results suggested that the glucose was not completely degraded. The reason for this could have been that since glucose is a labile substrate, it was readily converted to volatile acids, by the acidogens. It is probable that the acids were not as efficiently converted to methane resulting in a build-up of acids within the serum bottle. This could have caused inhibition of the methanogens. The mass of carbon produced in each biogas component was calculated from the molecular masses.

The carbon contents of the individual components could not be determined upon termination of the assay since they were mixed together in the bottles. A total carbon analysis was thus performed on the final solution. This incorporated the biomass (including new biomass formed during the incubation period), undegraded substrate and un-utilised nutrient medium. The solutions were mixed to obtain representative samples for total carbon and inorganic carbon analyses. The residual total organic carbon was determined by subtracting the inorganic carbon from the total carbon. The carbon balance is presented in **Table 5.1**.

TABLE 5.1: Carbon balance for the 5 g/ℓ glucose assay.

	Carbon IN (mg)	**Carbon OUT (mg)**
Glucose solution	80.0	-
Biomass	0.1	-
Medium	1.2018	-
Carbon dioxide	-	23.0
Methane	-	18.38
Final solution	-	32.5
TOTAL	**81.3**	**73.88**
% Error : 9		

These calculations suggested that the carbon mass was not entirely conserved with a recovery of ca. 91 % (m/w). The carbon that was unaccounted for could have been lost in the form of biogas during measurement with the syringe. As stated above, this method is not optimal and may result in gas losses. Although, theoretically, mass is conserved, it is difficult to obtain a 100 % recovery under experimental conditions due to experimental error such as that described.

5.2.2 COD balance

Another means of performing a material balance is by measuring the COD of each assay sample before and after the incubation period. The chemical oxygen demand of a sample is an indication of the amount of organic matter present. Chemical oxygen demand is a conserved parameter in the anaerobic process. Degraded COD is transformed to COD in the form of methane in the biogas, thus recalcitrant COD contributes to the COD of the final solution and not the COD of the biogas.

The COD mass balance for the 5 g/ℓ glucose assay was calculated (**Appendix C**) by determination of the amounts of COD entering and leaving the system, incorporating the following components:

$$COD_{substrate} + COD_{biomass} + COD_{nutrient\ medium} \rightarrow COD_{CH_4} + COD_{final\ solution} \qquad [5.2]$$

The technique for determining the COD of a sample involved the oxidation of organic matter by a boiling mixture of chromic and sulphuric acids. The oxidation of organic material, by dichromate, follows the following reaction pathway (Sawyer, McCarty and Parkin, 1994):

$$C_n\, H_a\, O_b\, N_c + dCr_2\, O_7^{2-} + (8\,d + c)H^+ \rightarrow nCO_2 + \frac{a+8d-3c}{2} H_2O + cNH_4^+ + 2dCr^{3+} \quad [5.3]$$

where $d = 2n/3 + a/6 - b/3 - c/2$.

From this equation, the theoretical COD of a compound can be calculated based on the equivalent amount of oxygen required to oxidise it. The theoretical COD calculation was used as a mechanism to assess the accuracy of the COD method by comparing the theoretical COD values with the measured values. Potassium hydrogen phthalate was used as a standard in the COD test. The theoretical COD of this solution was 500 mg/l.

The COD balance for the 5 g/l glucose solution is described. The input COD values (substrate, biomass and nutrient medium) were measured. These values were summed to calculate the total COD entering the system (**Table 5.2**).

The amount of COD in the inoculated 40 ml of glucose solution was calculated from the measured COD. From the theoretical equation (Eq. 5.3) it was calculated that 1 g glucose had an equivalent COD of 1.067 g . This calculation has been reported by other researchers (Sam-Soon et al., 1990). A 40 ml sample of the 5g/l solution of glucose contained 0.0011 moles of glucose. From the theoretical equation, this should have had a COD of 213.4 mg. The measured COD was, however, much higher (443.6 mg) and could have been due to experimental error with the COD method.

The biomass contributed to the COD of the solution within the serum bottle. As stated, the open reflux COD test is not optimal for samples which contain solids and may result in inaccurate measurements. Although very little, the nutrient medium also contributed to the total input COD.

Methane production is directly proportional to COD reduction. Mineralisation of 1 g of COD results in the production of 0.350 l methane (at STP) (McCarty, 1964). The theoretical COD of a produced amount of methane can be calculated from Eq. 5.3. A total volume of 24.5 mg of methane was produced in the 5 g/l serum bottles.

For methane, $d = 1.33$

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2\,O \quad [5.4]$$

thus, 1 mole CH_4 requires 2 moles O_2

16 g CH_4 requires 64 g O_2

1 g CH_4 requires 4 g O_2

Therefore, 24.5 mg CH_4 = 98 mg COD

Carbon dioxide has a COD value of 0 (**Appendix C**).

The COD at the end of the incubation period was determined on the mixture of components in the assay solution. This incorporated the biomass, undegraded substrate and un-utilised nutrient medium. The solutions were mixed to obtain representative samples. The COD of the final, unfiltered sample, was determined. The sample could be filtered and the COD of the biomass and the filtrate measured separately. These values would then be added together to determine the total COD of the final solution if the relative volumes or masses were known. The COD balance is presented in **Table 5.2**.

TABLE 5.2 : COD balance for the 5 g/ℓ glucose assay.

	COD IN (mg)	COD OUT (mg)
Glucose solution	443.6	-
Biomass	80.3	-
Medium	19.53	-
Methane	-	98
Final solution	-	422.5
TOTAL	**543.4**	**520.5**
% Error : 4		

The COD reduction in the serum bottles was only 62 %. A greater reduces expected. This could be attributed to the possible inhibition of the methanogens, as described above. Increased COD reduction would have resulted in a lower COD for the final solution and a greater methane production. From **Table 5.2**, 96 % of the input COD was recovered.

The open reflux COD technique is relatively simple and can be done in most laboratories whereas not all laboratories have access to total carbon analysers. However, the carbon balance is recommended over the COD balance as it is believed to be more accurate and reproducible.

These balances could be transformed into energy balances. The organic matter present in the wastewater is an energy source for the digester biomass. In anaerobic digestion, methane and carbon dioxide are the major constituents of the evolved biogas. The organic matter is only transformed, i.e., the capacity for electron transfer is maintained in the methane which is produced.

5.2.3 Biomass yield

Despite its complexity and the many intracellular reactions involved, cell growth obeys the law of conservation of matter (Doran, 1995). When cell growth occurs, it is a product of the reaction and must be represented in the reaction equation. This requires knowledge of the growth stoichiometry.

Any increase in solids during the incubation time was attributed to cell growth. As cells grow there is, as a general approximation, a linear relationship between the amount of biomass produced and the amount of substrate consumed. Thus, an increased concentration of substrate should result in an increased rate of metabolism and more energy available for cell growth. Concurrently, with the increase in cell growth there shoulc be an increase in biogas production illustrating substrate utilisation.

Chapter 6

Case Study

The feasibility of the anaerobic digestion of a textile size effluent was investigated. The effluent was chosen due to its high organic strength (ca. 140 000 mg/ℓ) and because the mill producing it was located in the vicinity of the Umbilo Sewage Purification Works. The efficiency of the anaerobic digestion process at the Umbilo Works was assessed.

6.1 Evaluation Of the Umbilo Digesters

Efficient substrate degradation by anaerobic digestion is dependent on favourable digestion conditions. The performance efficiency of the anaerobic digesters at the Umbilo Sewage Purification Works was evaluated. The superficial evaluation (**Chapter 3**) identified the works as having available hydraulic and organic loading capacity.

6.1.1 Screening and grit removal

Raw wastewater contains solids which, if not removed, accumulate in the digester and reduce the efficiency by reduction of the active volume. The removal of these materials is important to extend the operational periods between digester shutdown for maintenance. Larger particles are removed by screens while grit is removed by the grit removal system. If these materials are not removed they could cause problems such as blockage of pipes and pumps and accumulation in the digesters.

The screen at the Umbilo works consists of a series of bars spaced across the inflow channel at the inlet to the works. The screens are raked periodically and the screenings disposed. The Umbilo works has a second screen positioned between the primary settling tanks and the digester sludge sump, thus the sludge fed to the digesters is screened twice to remove large materials. An average of 4.1 m^3 of screenings is removed per month which is equivalent to ca. 0.14 m^3/d.

Grit removal is essential as it can cause mechanical malfunctions and reduce the effective volume of the digesters. Grit removal channels at the inlet to the works allow for settlement of the grit which is manually removed. A monthly average of 8.5 m^3 grit is removed with a daily removal of ca. 0.28 m^3.

6.1.2 Process evaluation

The Umbilo Sewage Purification Works (USPW) was designed (1992) to treat a flow of 23.2 Mℓ/d (10 Mℓ in the activated sludge plant and 13.2 Mℓ in the biofilter plant). Currently, 17.4 Mℓ is treated per day which is 75 % (v/v) of the design load. The USPW does, therefore, have the capacity to treat a higher hydraulic load. The biofilter plant was operating at 73 % (v/v) of its capacity at 9.67 Mℓ/d and the activated sludge plant at 77 % (v/v) of its design capacity at 7.71 Mℓ/d.

At the USPW the primary sludge is fed straight to the digesters. Since there is no thickener, the concentration, or percentage total solids, of the feed sludge is relatively low. The concentration of solids should be as high as possible to promote effective digestion but not too high to adversely affect pumping and mixing of the sludge (Ross et al., 1992). The feed sludge to the Umbilo digesters had an average concentration of 3.6 %.

Continuous or near continuous feeding should eliminate any abrupt flow rate or organic loading change which could result in shock loading. The Umbilo digesters had 2 main feeds per day. One at 08h00 and the second at 16h30. During these feeds the sludge from the primary sedimentation tanks was pumped to the anaerobic digesters. There were, on average, an additional 2 to 3 feeds per day. These consisted of sludge overflow from the activated sludge plant and the dissolved air flotation (DAF) unit. This feeding schedule could be improved to have more frequent feeds at lower flowrates. The distribution box ensured that each of the four digesters received an equal volume of feed.

According to the design drawings, the feed sludge is added at the top of the draft tube (**Figure 6.1**). The digester sludge is drawn up the draft tube, thus the feed sludge is fed in the opposite direction. The advantage of this is that the feed sludge enters the digester at a point of great turbulence thus ensuring mixing. The feed is drawn into the sludge pathway. The digester level is kept constant and there is positive displacement of sludge, i.e., addition of sludge resulted in a sludge overflow, of an equal volume.

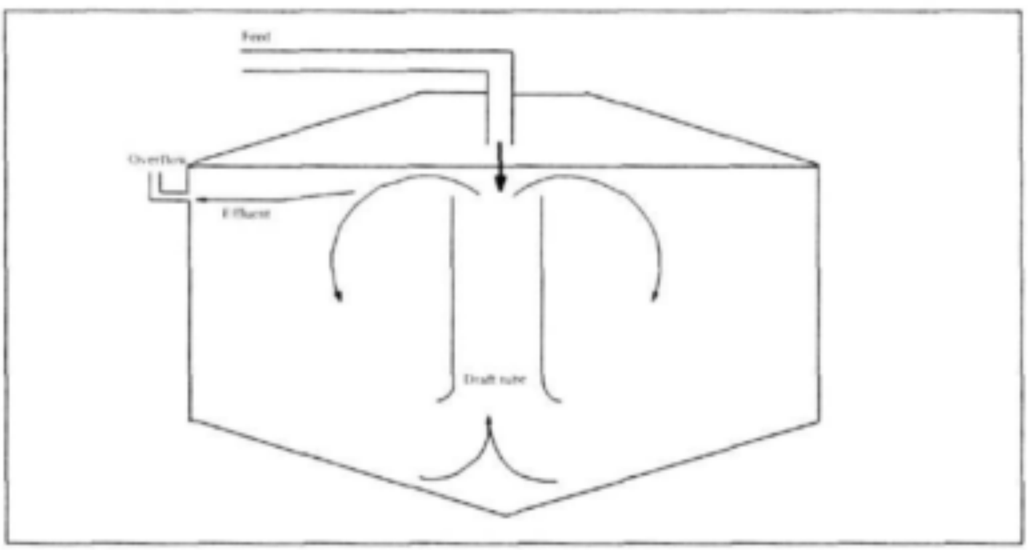

FIGURE 6.1 : Schematic diagram of the Umbilo digester feed and overflow streams .

The average loading to the digesters was calculated at 1.12 kg VS/m^3.d. The recommended loading rate for a high rate digester (with mixing and heating) is between 1.5 and 3.0 kg VS/m^3.d. Thus, the Umbilo digesters were under-loaded.

The USPW has a laboratory on-site for analysis of samples taken from the plant. Under balanced conditions, the volatile acid concentration of the digesting sludge is usually in the range of 50 to 300 mg/l. The average VFA content of the Umbilo digester sludge was within this range (169 mg/l). The alkalinity (2 026 mg/l) of the Umbilo digester sludge also indicated that it was healthy. These values gave a volatile acids : total alkalinity ratio (Ripley ratio) of 0.08. A ratio < 0.3 indicates an efficient degradation process (Ross et al., 1992). The VFA to alkalinity ratio was plotted over a one year period from May 1996 to May 1997 (**Figure 6.2 (a)**). The plot shows that the ratio was relatively constant which suggested that the sludge was stable. The average is indicated by the solid line.

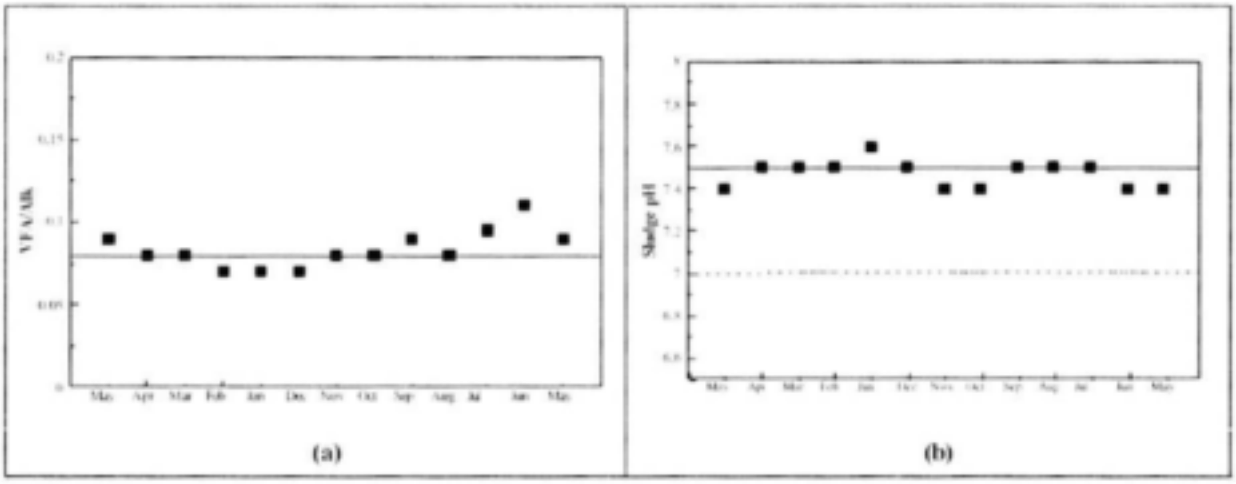

FIGURE 6.2 : Plots of the Umbilo digester sludge VFA/Alkalinity ratio and pH over a one year period.

The average pH of the Umbilo sludge was 7.5 (**Figure 6.2 (b)**) which indicated that the buffering capacity of the digesters could be improved. This pH still facilitates digestion. The plot shows that the sludge pH was relatively constant over the one year period, which verified that the process was stable. The broken line indicates the optimal digestion pH of 7.

The average COD reduction over the works was 71 %. The COD reduction was not calculated for the anaerobic digesters. The reduction in volatile solids within the digesters (72 % or 1 081.5 kg/d) provided an indication of the extent of organic degradation.

Effective anaerobic digestion occurs with the stoichiometric production of biogas. Based on the fact that 1 m^3 biogas is produced per kg volatile solids reduced, the biogas production rate of the USPW anaerobic digesters was calculated to be 1 082 m^3 which gave a biogas production rate of 1 m^3/kg VS. The methane content of the biogas was approximately 65 % thus the methane production was 0.65 m^3/kg VS.

A solids mass balance was calculated for each digester (for the period May 1996 to May 1997), based on the method described by Ross et al. (1982) (**Table 6.1**). This provided an indication of the process efficiency.

TABLE 6.1 : Mass balance of the Umbilo anaerobic digesters.

Mass (kg/d)	Feed sludge	Digested sludge	Biogas
Volatile mass	1 505	424	-
Ash mass	450	228	-
Biogas	0	0	1 000
Total	1 955	652	1 000

The mass of biogas produced was calculated from the theoretical density of 1 kg/m^3. The total mass in (feed sludge) was ca. 15 % (m/m) greater than the total mass out (digested sludge and biogas). This error in the mass balance could be attributed to sampling or analytical inaccuracies as it is unlikely that 222 kg/d of solids built up in the digester. The poor balance could be due to the erratic feed flows to the digesters. The periodic high flows could have been due to longer pumping times if the solids concentration of the feed sludge was low. A more accurate mass balance would be a total carbon balance across the digester, incorporating alkalinity and CO_2.

6.1.3 Mixing

Although mixing is only one factor which affects digester performance, it increases the overall rate of biological activity by promoting contact between the substrate and microorganisms. The degree of mixing of the primary digester is important to prevent dead volume.

Mixing efficiency can be measured by a vertical traverse of the temperature or solids concentration in the digester or by tracer techniques (United States Environmental Protection Agency, 1987). A tracer test was performed on one of the Umbilo anaerobic digesters to evaluate the mixing efficiency and to identify any dead volume. These results are presented in **Section 6.1.6**.

Mixing of the Umbilo digesters is achieved by mechanical mixers. Each mixer is mounted above a draft tube to direct the flow within the digester (**Figure 6.3**). Each impeller is driven by an electric motor. The sludge is drawn into the bottom of the draft tube and discharged at the top. This ensures that the heavier sludge is mixed throughout the digester. If the motor is operated in the opposite direction, the light sludge and scum layer from the top of the digester is forced down the draft tube to the bottom of the digester. It is generally recommended that for adequate mixing the entire contents of the digester should be turned over at least once every 24 h. From the design specifications, the power of the motor running each mixer was 11 kW. The mixer speed was 960 rpm, with a duty of 250 l/s. The pump is operated continuously so there are 16 volumetric displacements of the digester contents per day.

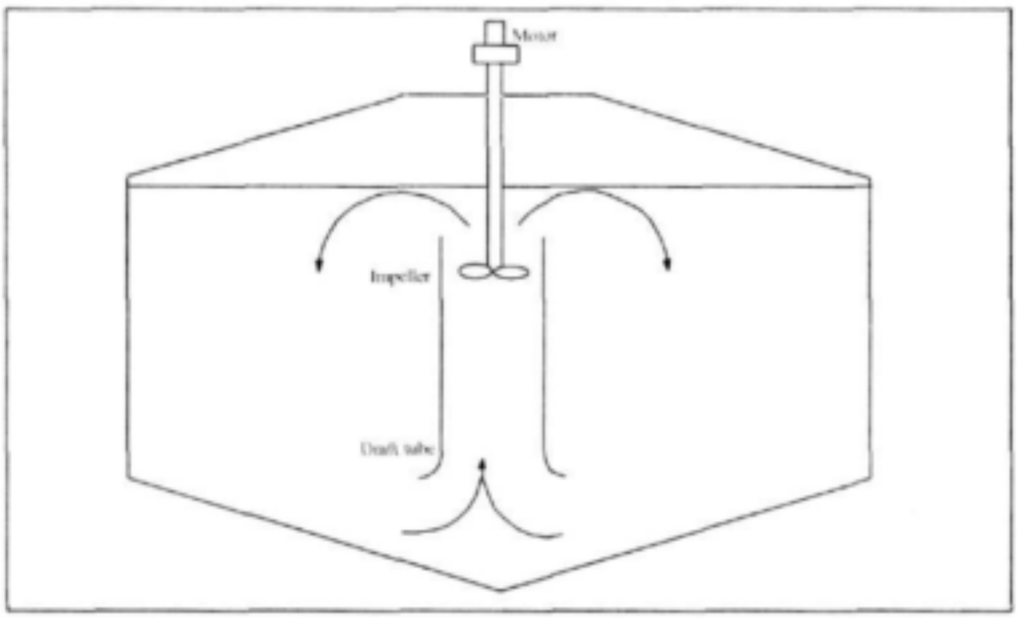

FIGURE 6.3 : Schematic diagram showing the mixing of the anaerobic digester contents at the Umbilo Sewage Purification Works.

Mixing of the Umbilo digesters was efficient as verified by the residence time distribution study (**Section 6.1.6**). A drawback of this mixing system is that impellers tend to wear from sludge abrasiveness and build-up of dirt and rags on the vanes. A decrease in the current of the motor is an indication that the impeller should be replaced.

6.1.4 Heating

The Umbilo digester sludge temperature is maintained at 36 ± 1 °C by a process of steam injection. A portion of the biogas, from the anaerobic digesters, is used to heat water in a tube boiler. The gas pressure of the boiler is regulated to 1 000 kPa. Steam from the boiler is injected through 15 mm steam lances mounted on top of each digester. Temperature probes in the digesters are set at 36 ± 1 °C and the temperature of the digester sludge is maintained at this temperature by the control of the steam inlet valve on the steam manifold. When this temperature is reached the valve closes and the gas burner shuts down. The boiler pump has a gas firing rate of 89.9 m^3/h. The heating surface of the boiler is 11 148 m^2. The evaporation rate is 626 kg s t 100 °C. Water is fed to the boiler from a 2 000 l tank.

A disadvantage of this system is that the steam causes the liquid to rise, resulting in a counter-current with the sludge recirculating through the draft tube (**Figure 6.4**). Injection of the steam may also be detrimental to the biomass in the vicinity of the point of injection. The process does, however, seem to be efficient to maintain a constant digester sludge temperature.

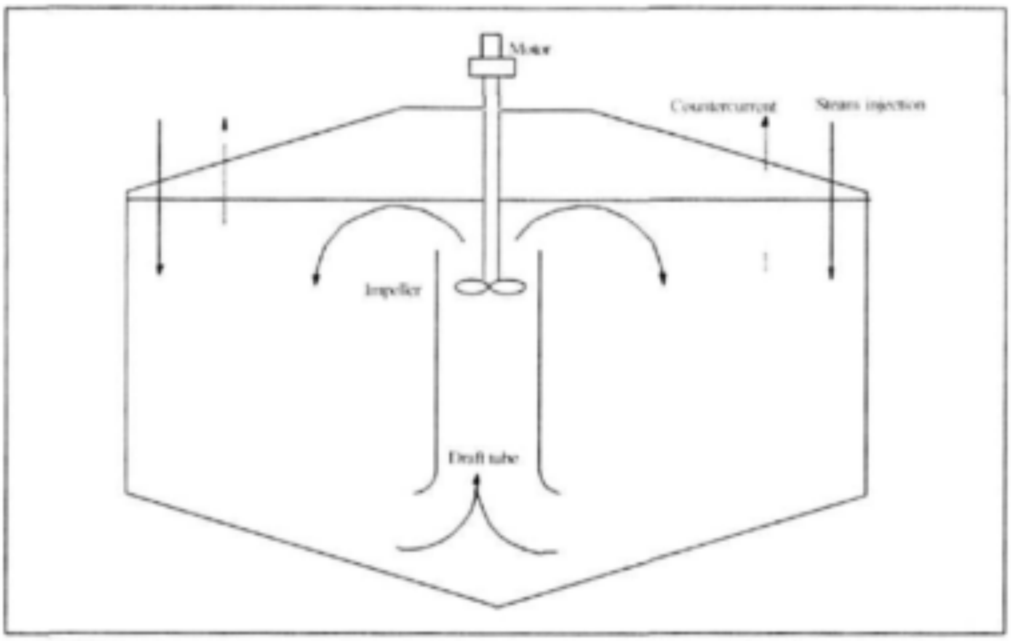

FIGURE 6.4 : Schematic diagram showing the mixing and heating flows in each digester.

6.1.5 Gas system

The digesters have fixed covers with a space for gas collection between the cover and the liquid surface of the digester contents. Each digester has a pressure relief valve mounted on top to relieve excess pressure and prevent damage to the digester cover. The vacuum relief valve functions in the opposite manner and allows air to enter the digester in the event of the sludge being withdrawn too rapidly.

The biogas produced in the digester is collected in the cone above the digester contents and then flows through the gas line. The gas pressure should be constant at all points in the gas system. The gas lines from all four digesters joins onto the main gas line. Gas leaving the digester is almost saturated with water vapour. As the gas cools, the water vapour condenses. The water trap functions to remove the water from the gas system and thereby prevents corrosion in the valves and regulators.

Flame traps are emergency devices which are installed in gas lines to prevent flames travelling back up the gas line and reaching the digester. The flame trap usually consists of a box filled with stone or a metal grid. If a flame develops in the gas line, the temperature of the flame is reduced below the ignition point as it passes through the trap and the flame is extinguished. Non-return valves are installed in the gas line to allow gas flow in one direction only, i.e. out of the digester. Pressure regulators are used when a lower pressure than the system operating pressure is required for a specific device such as the boiler. The gas system at the USPW is illustrated in **Figure 6.5**.

The Umbilo gas holder has a volume of 500 m^3. The upper half of the steel dome moves freely by means of guide rails attached to the concrete structure and rollers attached to the steel dome. The holder is filled with water and the gas is collected in the headspace above the water. This results in a build up of pressure which causes the dome to rise. There is a pressure relief valve on top of the dome for pressure control. Excess gas is flared to the atmosphere at the gas burner.

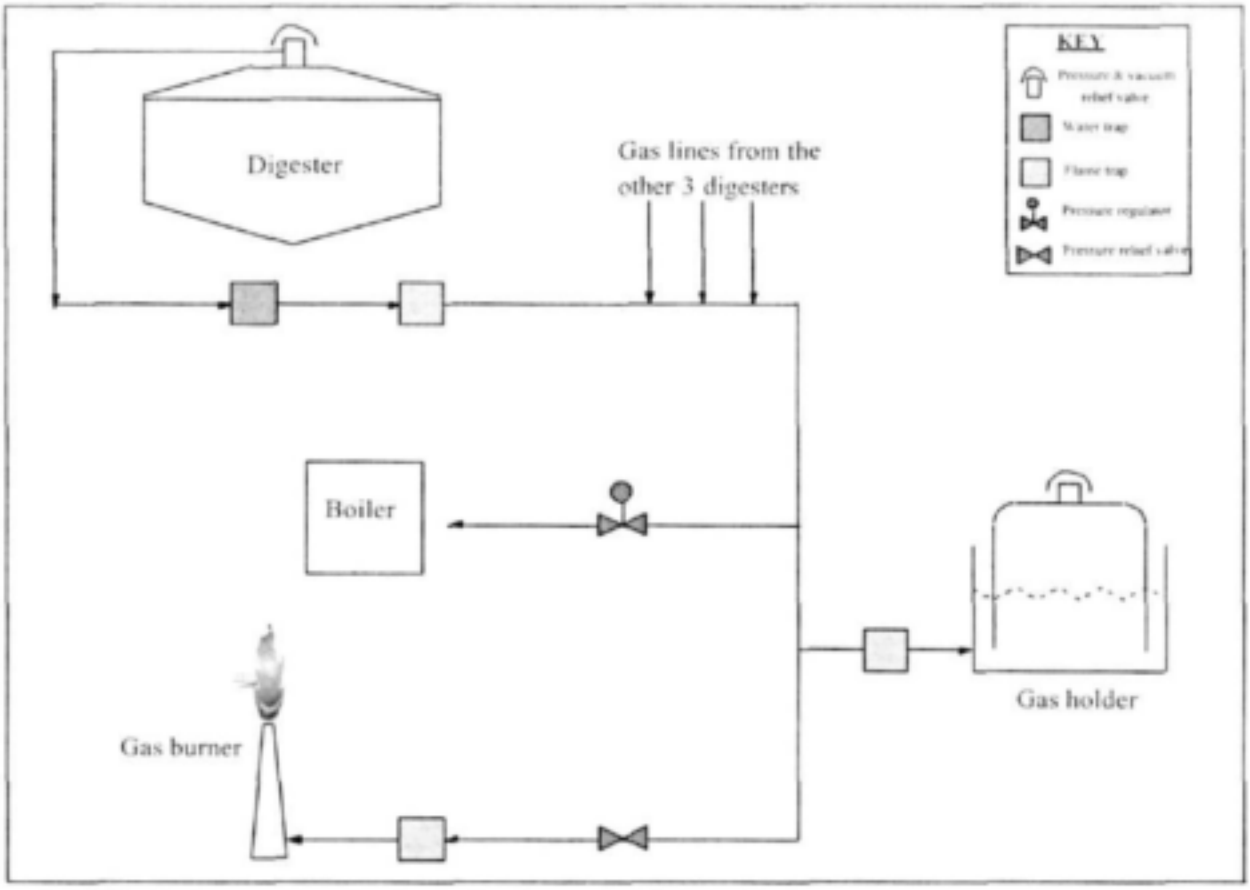

FIGURE 6.5 : Biogas system at the Umbilo Sewage Purification Works.

There is no gas flow meter at the USPW, thus the rate of gas production is not be measured. This should be rectified since the rate of gas production is an important process control indicator.

6.1.6 Residence time distribution test

A technique for determining the flow model of processes is the residence time distribution method. Danckwerts (1953) developed the residence time distribution concept to characterise the overall flow behaviour in a process. The effluent stream from a continuous flow process is a mixture of fluid elements which have resided in the process for different lengths of time. The distribution of these residence times is an indicator of flow patterns within a process. Analysis of these data allows calculation of the actual hydraulic retention time in the digester, a parameter which is controlled by the extent of mixing (Tenney and Budzin, 1972).

The flow patterns found in real processes usually lie between the two extremes of perfect mixing (complete mixing of the fluid) and plug flow (no mixing in the direction of flow). This is due to bypassing, channelling, dead space, dispersion and recycling (Barnett, 1995). In a digester, the active decomposition of organic material occurs in the volume that is mixed. Conversely, the zones that are not mixed remain stagnant and are, essentially, lost to the digestion process (Tenney and Budzin, 1972).

The residence time distribution (RTD) is determined experimentally by injecting an inert chemical, called a tracer, into the reactor at some time $t = 0$ and then measuring the tracer concentration, C, in the effluent stream as a function of time (Nachaiyasit, 1995). Introducing tracer into the inlet stream of a process and measuring the concentration-time relationship of the tracer in the effluent stream provides an indication of the distribution of the residence times of the tracer (Barnett, 1995).

A computer program, IMPULSE, was written by Baddock, Barnett, Brouckeart and Buckley (1993) which allows easy modelling of systems using curves obtained from tracer response tests. The user assumes a flow model for the system. The program determines the theoretical response for the model and optimises a chosen set of parameters of the model to fit the experimental curve.

To determine the residence time and mixing patterns of the digester of interest, a tracer test was performed on Digester 2 at the USPW to determine the residence time distribution (RTD). Lithium chloride was chosen as the tracer. The method is presented in **Appendix D**.

Results and discussion

Previous work showed that lithium did not adsorb onto sludge particles and was not assimilated by the microorganisms as a nutrient (Grobicki, 1989). This was verified with the Umbilo digester sludge (Barclay, 1996). The background levels of lithium, in the digester sludge, were measured and found to be ca. 0.006 mg/ℓ. The raw data were corrected for this and entered into IMPULSE as the experimental data.

The results from the experimental analysis, referred to as the experimental data (**Annexure 1**), are presented in **Figure 6.6**.

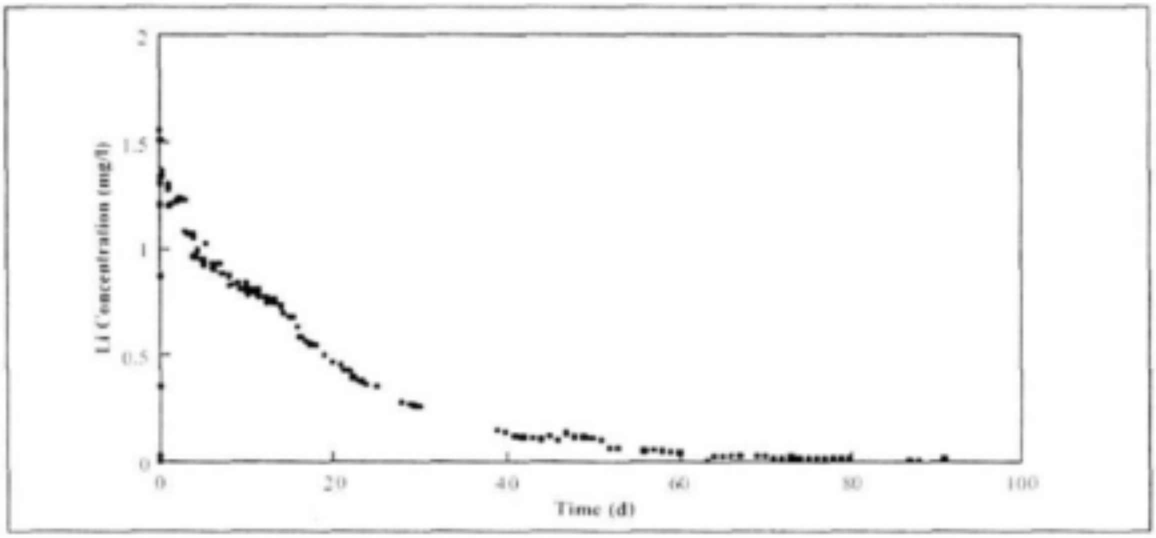

FIGURE 6.6 : Diagram of the experimental data for the residence time distribution study

The lithium concentration peak was ca. 1.2 mg/l which was the concentration calculated from the design digester volume (1 340 m^3). This suggested that the entire design volume was active, i.e. there was negligible dead volume. Based on this assumption, the design digester volume (1 340 m^3) was entered into IMPULSE as a constant input. The digester was modelled as a tanks-in-series CSTR with a variable number of tanks which accounted for the apparent sludge bypass. The resolution time was set at 0.1 d. The input flows were variable.

The average residence time is the calculated residence time of the liquid component in the reactor. The normalised distribution function, C(T) is a dimensionless plot of the residence time distribution. Based on the set parameters, the following results were obtained from the IMPULSE model fit:

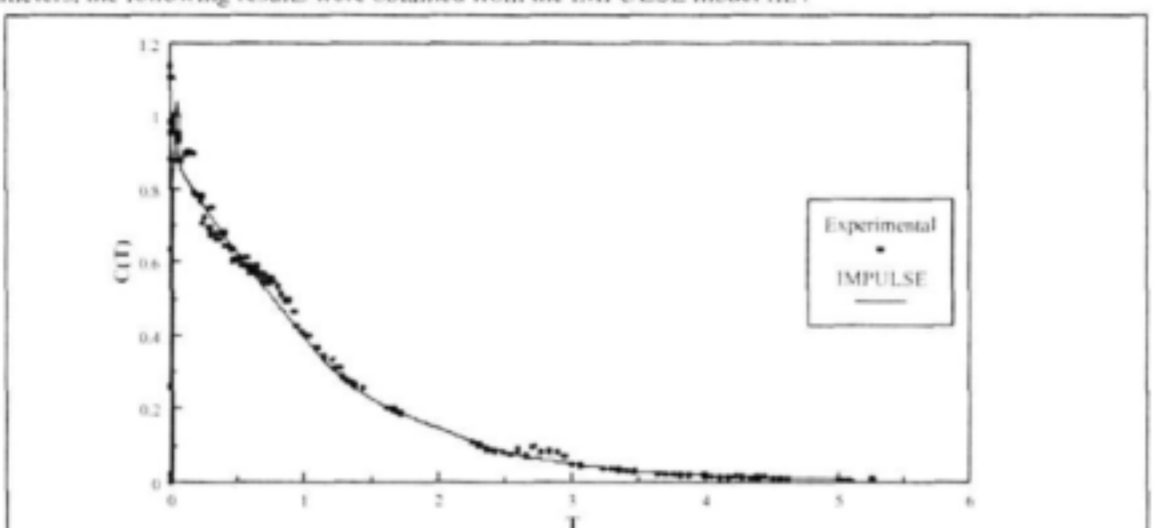

FIGURE 6.7 : Diagram of the normalised residence time distribution curve for the experimental data and the IMPULSE model.

IMPULSE produced a close fit to the experimental data. In the model, the digester volume was fixed which forced the flows and the bypass split ratio to vary, to fit the experimental data. The IMPULSE output (**Appendix D**) indicated that the split to the sludge bypass was ca. 1.94 % of the flow to the digester. Although this volume was small, it was not insignificant and effectively meant that undegraded substrate was leaving the digester. This could be detrimental if high-strength effluents were added to the feed. The bypass could be overcome by changing the position of the feed inlet. If the feed was added at the bottom of the digester, it would be drawn into the draft tube and the bypass would be alleviated. Another option would be to uncouple digested sludge withdrawal and raw sludge feed.

In the model, the digester volume was fixed based on the assumption that the entire volume was being utilised. If the output lithium concentration had been higher than expected, it would have suggested reduced digester volume since the tracer would have been less diluted. A reduction in volume of the digester would have been indicative of dead volume which is volume where there is no, or little, active mixing. In the active volume, the solids are suspended, by the mixing action, thus facilitating contact between the substrate and the microorganisms. In the dead volume, there is no active movement since these regions are, essentially, stagnant and do not contribute to substrate degradation (Barona and Prengle, 1973). These results indicate that, apart from the initial sludge bypass, the digester mixing, i.e. by draft tube, was efficient and there were no stagnant areas within the digester.

This model assumed that the digester was operating as an ideal CSTR. The real average residence time of the reactor was calculated from the experimental data, by a numerical integration method, as **17.29 d**. The average residence time, as calculated from the IMPULSE model, can be used to assess the accuracy of the model. The average residence time, as calculated from the IMPULSE output, was **17.59 d** which indicated that the model was a close representation of the system. The IMPULSE output indicated that the flows were under estimated by 34.6 %. Thus, correction of the measured flows by this scaling factor, resulted in an estimated residence time of ca. **20 d**. This was within the recommended range of 15 to 25 d for a high-rate reactor (Ross et al., 1992), thus verifying the accuracy of the model and the operation of the reactor.

From a mass balance of lithium (**Annexure 1**), the percentage of recovered lithium was determined. For each time step, the area under the curve (**Figure 6.6**) was calculated. These were summed to obtain the total amount of lithium recovered which was **1.5407 kg**, compared to the dosed 1.65 kg. This equated to **93.4 %** recovery of the lithium. The calculation for lithium recovery was based on flowrates and measured concentrations at the outlet. The flowrates were corrected by a factor of 1.34 as calculated from the IMPULSE output, thus the efficient lithium recovery also provided verification of the model.

From these results, if the IMPULSE model was correct and the flows were under-estimated by 34.6 % then the digester was operating at its full capacity, i.e. there was no dead volume and the average residence time was 17.29 d. If, however, the flow data were accurate, then the system would be modelled with constant flows and a variable digester volume. To assess this scenario the model parameters were altered to set the flows constant and the digester volume variable. This model showed that the digester volume would decrease by ca. 27 % to fit the experimental data. This would suggest that the digester had a dead volume of 27 %. The lithium recovery for the uncorrected flows was, however, only 69 % compared to 93 % obtained for the corrected flows. This suggested that the IMPULSE model was correct and that the measured flows were under-estimated.

6.2 *Evaluation Of a Textile Size Effluent*

The focus of this section is the assessment of the anaerobic treatment of a textile size effluent, by application of the strategy described in **Chapter 1**. The choice of effluent was justified by its high COD content, its problematic disposal and the location of the mill, which was in the vicinity of available digester capacity.

Increasingly strict environmental legislation has led inishing industries being labelled as high priority industries with respect to pollution (Carliell, 1993). Size effluents represent the main component (ca. 60 %) of the organic load of the effluents from textile finishing mills (Schluter, 1991). In the sizing operation, the individual yarns are coated with a protective film of size in order to resist the abrasive effects of the weaving loom; the size strengthens the yarn (Water Research Commission, 1983). The quality of the sizing treatment influences not only the efficiency of the weaving process but also the quality of the cloth, both in the loom state and after finishing (Smith, 1964). The traditional sizing agent was starch thus the effluent originating from the size kitchen and size slashers, in the mill, was a high-strength organic effluent. When mixed with the remainder of the mill effluent, it increased the COD of the final trade effluent thereby introducing disposal problems.

The described strategy (**Figure 1.1**) was applied to determine the feasibility of the anaerobic digestion of the textile size effluent produced by a mill in New Germany. The mill was located within 10 km of the Umbilo Sewage Purification Works and produced a total of 110 m^3 of effluent per day; of which 10 m^3 was size effluent. The size effluent was segregated, at the mill. However, for disposal, all of the effluent was mixed and the total effluent was tankered 40 km for marine discharge, at the Southern Wastewater Treatment Works submarine pipeline. The segregation of the size effluent allowed for the investigation of its degradability and would facilitate the concentration of the high-strength effluent on site. Depending on the colour component of the remainder of the effluent, it could then be discharged directly to sewer.

6.2.1 Textile size

Starch has been the traditional sizing material used in textile manufacturing, however, in recent years the trend has been towards synthetic sizes because of the increased demand for synthetic fibres. To overcome the deficiencies of single component sizes, size blends are commonly used (Water Research Commission, 1983). Some of the components of size blends are outlined below.

Starch : starches are flours without the glutens (Seydel, 1972; Water Research Commission, 1983). Starch granules consist of α- and β-amylose; the former is insoluble in water. The β-amylose is contained within a membrane of the α-amylose. On heating the water permeates through the outer membrane causing the β-amylose to dissolve and swell. The granules expand and the viscosity increases (Water Research Commission, 1983). The qualities which give starch its usefulness as a sizing agent are its ability to form a pliable film and its ability to adhere and provide a good coating without excess penetration into the yarn (Seydel, 1972). Since the prime function of sizing is to produce weavability in the warp, the essential part of the size formula is the film-forming ingredient. Modified starches are formed by substituting acetyl or hydroxy-ethyl groups for hydrogen or hydroxide groups on the starch molecule (Water Research Commission, 1983). An example is **oxidised modified starch (OMS)**, which is prepared by treating starch in an alkaline, aqueous medium with hypochlorite (Kirk-Othmer, 1982). The oxidising action introduces zig-zag discontinuities into the linear molecules, which decreases the gelling characteristic of starch (Seydel, 1972).

Carboxymethyl cellulose (CMC) : is generally a sodium salt and is formed by treating cellulose with sodium hydroxide and mono-chloroacetic acid (Water Research Commission, 1983). Carboxymethyl cellulose tends to absorb and hold moisture and its value in textiles hinges on its water-binding ability as this reduces the need for high humidity conditions in the weaving shed (Seydel, 1972).

Polyvinyl alcohol (PVA) : is a synthetic polymer resin and is produced by acid or alkaline hydrolysis of polyvinyl acetate (Water Research Commission, 1983). The viscosity and hydrolysis of PVA are controlled in the manufacturing process and are important in determining end-product sizing characteristics (Seydel, 1972).

Polyvinyl alcohol is an excellent textile warp size because of its strength, adhesion, flexibility and film-forming properties (Kirk-Othmer, 1982). Polyvinyl alcohol can be recovered from wash-waters by ultrafiltration (Groves et al., 1978).

Acrylate : polymeric methyl acrylate is used principally as the soldium salt. It is hydroscopic and cannot be used under high humidity conditions (Sharp, 1990).

Waxes : the term wax includes almost any lubricant of a solid nature. The chemical composition varies widely, but is generally based on a long-chain hydrocarbon molecule or a derivative, such as fatty acid or fatty alcohol (Seydel, 1972).

Plystran : is a commercial blend of a number of size components, made up of ca. 58 % (w/v) modified potato starch, 40 % (w/v) PVA and 2 % (w/v) wax. This component is often difficult to dissolve because of the wax content.

Biocide: the purpose of which is to prevent bacterial or algal growth in the highly organic size solutions. Microbial growth could impair the efficacy of the yarn treatment and could also stain the material. It was expected that the biocide would prove problematic during the microbial treatment of the effluent. The disinfectant added to the investigated size was a water-soluble Dodigen 2451 (Hoechst), which was composed of alkyl dimethylbenzyl ammonium chloride.

For a size formula to approach perfection it should have several basic characteristics which will serve to eliminate warp breaks during weaving (Seydel, 1972). These include the ability to increase the tensile strength of the yarn, adhere to the fibre structure and protect the warp yarn, and provide flexibility to the yarn as it must withstand repeated and extensive bending during the weaving operation.

The COD of the size effluent, sampled at the New Germany Frametex mill, was measured at 112 000 mg/ℓ .

6.2.2 Assessment of anaerobic degradability

The laboratory-scale batch test protocol was applied to assess the biodegradability of each component of the textile size solution (**Appendix D**). The solution was synthesised in the laboratory according to the mass of each component utilised by the mill. A synthetic effluent was chosen, over a real effluent, so that components were concentrated and not diluted by wash-waters. It also avoided variability in the composition which facilitated accuracy in the calculations.

A detailed description of the results is presented in **Annexure 1**. These tests investigated the anaerobic degradability of each component alone since no other substrate, such as feed sludge, was added to the serum bottles. The tests also investigated undiluted samples although the relative concentrations in the size effluent would be much lower due to dilution by wash waters, etc.

Measurement of gas production provided an indication of the metabolic activity and the degradability of each component. The ability to metabolise many substrates simultaneously is clearly an important survival strategy, especially in natural environments where often a mixture of organic compounds occurs. The result is the development of generalist and specialist species or populations. A generalist microorganism can metabolise more than one substrate whereas specialist microorganisms develop the necessary complement of enzymes (they acclimate) for a particular substrate. Gas production results of the synthetic size solution did not follow first order kinetics which suggested that the degradation of the multi-component size solution involved a complex microbial community with specific interspecies interactions.

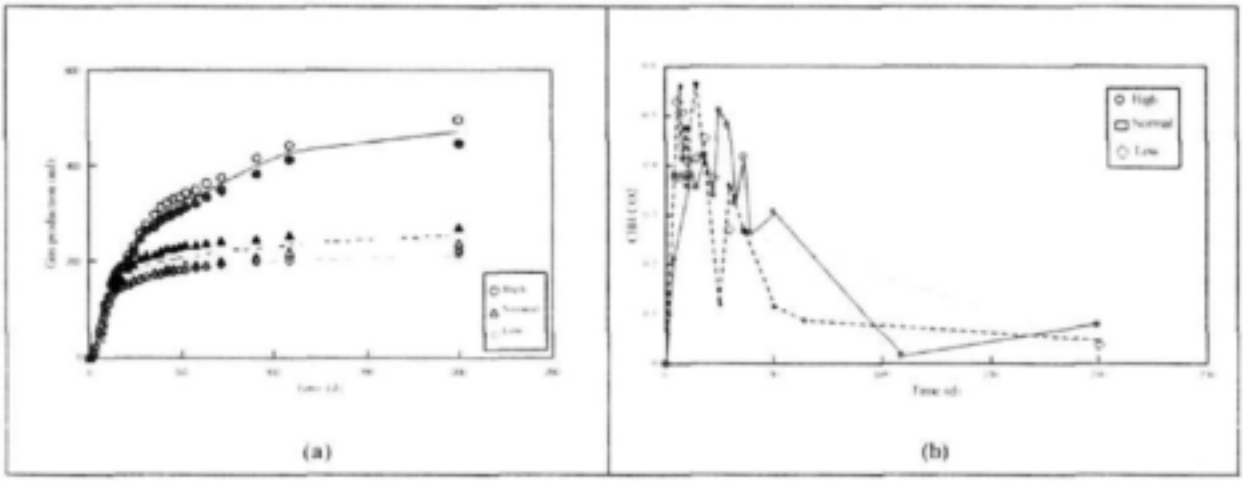

FIGURE 6.8 : Plots of the cumulative gas production (a) and the ratio of methane to carbon dioxide in the biogas (b) for the synthetic size solution.

From the results it was concluded that the size solution could be degraded by the microorganisms in the anaerobic digester sludge. Caution would have to be taken to prevent overloading of the digester as these results suggested decreased degradation with increased concentration of the substrate. Methane production was relatively low which suggested that the degradation of the substrate was achieved by an interacting microbial association. It is likely that the substrate was co-metabolised, i.e. different components of the size solution were degraded by different populations and the intermediates produced became substrates for other populations. Labile components would have been degraded initially with concurrent acclimation of the biomass to the more recalcitrant molecules. It is due to these interactions, and co-metabolic pathways, that the degradation of the combined size solution could not be predicted from the results obtained with the individual components. The results did, however, give an indication of the inhibitory and labile components of the size solution.

Investigation of the individual components identified those with an inherent inhibitory effect on the anaerobic biomass and the concentrations at which each component could be effectively degraded. The PVA was found to become inhibitory at concentrations greater than 30 g/ℓ. Plystran was inhibitory at concentrations > 10 g/ℓ, acrylic at concentrations > 4 g/ℓ and the biocide became inhibitory at concentrations > 0.5 mg/ℓ and toxic at a concentration of 50 mg/ℓ.

The tests were run for a protracted incubation period (200 d). The tests would normally only run for ca. 30 to 60 d. The extended period may have caused the observed decrease in methane production due to the cessation of degradation. Exhaustion of the substrate could have resulted in the bacteria utilising the methane as a carbon source during the endogenous respiration phase. The extended incubation period did, however, allow for the observation of biomass acclimation to the inhibitory substrates.

6.2.3 Acclimation

Anaerobic organisms, particularly methanogens, are susceptible to a large variety of compounds. However, even severely inhibitory compounds (1Xoroform) can be degraded by anaerobic associations following acclimation (Lettinga, 1995). The acclimation of an anaerobic sludge to a specific molecule effects significant changes to its microbial population (Gavala and Lyberatos, 1997).

Tests were conducted to assess the biomass acclimation to the Plystran and biocide components of the textile size solution. In these tests the acclimated sludge from the serum bottles, previously containing the Plystran and biocide solutions, was used to inoculate new serum bottles. The objective of the test was to determine whether there was a change in the degradation rate and in the length of the lag period with the acclimated sludge. The experimental method is described in **Appendix D**.

The gas production results were compared to those of the unacclimated sludge. The initial gas production rates were compared to provide an indication of the improved degradation ability of the acclimated sludge (**Appendix D**). The lag periods were reduced. In the lower Plystran concentrations (16 and 8 g/ℓ) degradation was immediate whereas with the unacclimated sludge there was a lag period of ca. 20 to 30 d. With the 24 g/ℓ concentration the lag period was reduced from ca. 80 d to ca. 5 d.

The initial biogas production rates were compared (**Table 6.2**). The results showed higher biogas production rates with the acclimated sludge.

TABLE 6.2 : Comparison of biogas production rates between the unacclimated and acclimated Plystran sludges.

		Unacclimated	Acclimated
Plystran concentration (g/l)	**Digestion phase**	**Rate (ml/d)**	**Rate (mℓ/d)**
24	Initial	0.02	0.103
16	Initial	0.03	0.101
8	Initial	0.08	0.098

The 50 mg/ℓ biocide concentration was not investigated as, from the previous assays, it was deduced that this concentration was completely inhibitory to the biomass. In the previous assay, the 5 mg/ℓ biocide concentration was labile thus this concentration was not investigated with the acclimated sludge. With the unacclimated sludge, the lag period of the 5 mg/ℓ biocide concentration was ca. 25 d. This was reduced to ca. 5 d with the acclimated sludge which showed that the biocide was more readily degraded after acclimation (**Appendix D**). The initial reaction rate was calculated at 0.06 mℓ/d whereas in the assay with the unacclimated sludge, the biogas production rate was zero until ca. day 25.

These tests showed that biomass can be acclimated to a potentially toxic, or inhibitory, substrate. Acclimation facilitates degradation of the substrate in concentrations that were previously inhibitory, with reduced lag periods and increased reaction rates.

6.3 *Implementation*

Batch tests are a screening mechanism to provide an indication of the anaerobic degradability and potential toxicity of a molecule. These results could be used to predict digester operation and process efficiency in full-scale treatment. Conditions change during scale-up and these should be taken into consideration when predicting full-scale operation. To provide a more accurate indication, the serum bottle tests could first be scaled up to a larger semi-continuous or continuous laboratory-scale reactor. This would facilitate prediction of the kinetic parameters in the semi-continuous or continuous feed mode of the full-scale digester.

There are problems associated with process scale-up, e.g. mixing, mass transfer and heat transfer (Luyben, 1997). These factors could result in the microorganism being exposed to a different micro-environment. Essentially, the problem with scaling up is a problem of transfer (mass, momentum or heat) and a lack of knowledge with respect to the interaction of hydrodynamics and other relevant sub-processes in a large-scale process. The best approach is to develop an adequate scale-up methodology based on the results obtained at experimental scale (Luyben, 1997).

To achieve this, a 20 ℓ laboratory-scale reactor could be set up. Such a set-up and operation are described in **Appendix E**.

6.3.1 Full-scale prediction

The laboratory-scale tests should facilitate the prediction of the feasibility of treatment of a particular molecule in a full-scale anaerobic digester, with indication of the volumes and concentrations that could be treated effectively.

At the commencement of the treatment process the volume of effluent in the feed should be low with a gradual increase to allow for acclimation of the biomass. If possible, the effluent should not be mixed with the feed sludge prior to feeding the digesters as the high concentrations could be detrimental to the bacteria present in the feed sludge. The effluent should be fed separately.

A thorough process evaluation and performance efficiency assessment should be carried out prior to the loading of an additional molecule in a digester. High-strength or toxic organic effluents should only be fed to digesters that are operating efficiently. The digester sludge should be monitored regularly and biogas should be measured to assess the efficiency of the degradation process.

The serum bottle tests identified inhibitory components of the textile size effluent. Although the synthetic size solution was degraded, the batch tests indicated that high concentrations of the size solution could result in an organic d of the digesters. The Frametex mill produced ca. 10 m^3 size effluent per day, with a measured COD of ca. 112 000 mg/ℓ. If all 10 m^3 of the size effluent were loaded into an anaerobic digester at the Umbilo Sewage Purification Works (1 340 m^3), the additional organic load would be 0.8 kg COD/m^3.d. This load is relatively high and could shock the microorganisms if they were not introduced to the substrate gradually. Treatment of this load is however feasible since in the serum bottle tests the equivalent load was 23.7 kg COD/m^3 and 35.6 kg COD/m^3 for the more concentrated size solution. Both of these concentrations were degraded by the biomass. Thus, the textile size effluent has the potential for treatment by anaerobic digestion.

Chapter 7

Conclusions

From this investigation of the anaerobic digestion of high-strength or toxic organic effluents in available anaerobic digester capacity, the following can be concluded:

1. The implementation of **cleaner production** and waste minimisation strategies should facilitate the identification of point source emissions. The high-strength or toxic organic components of the effluent could then be segregated from the bulk effluent and concentrated on-site. These concentrated components could be recycled in the process. Upon segregation, the remainder of the trade effluent should meet the General Standards for disposal to sewer. The concentrated wastes could be tankered separately for treatment in available anaerobic digester capacity.

2. A survey of 24 wastewater treatment plants was undertaken which included a total of 56 anaerobic digesters. The survey identified the availability of hydraulic or organic capacity. It was proposed that this available capacity could be utilised for the treatment of high-strength or toxic organic effluents, produced by industries in the vicinity of the wastewater treatment works. Six of the investigated treatment plants had digesters that were not utilised at all with a total available volume of 21 223 m^3. The average residence time of all of the investigated digesters was 61 d which was 36 d longer than the nominal retention time of 25 d. This indicated that the digesters were under-loaded. Using the design criteria of 25 d hydraulic retention time and 3 kg VS/m^3.d organic load, on average the digesters were 32 % hydraulically under-loaded and 58 % organically under-loaded.

3. Industries producing high-strength or toxic organic effluents were identified and selected industries were visited. Disposal of these types of effluent is problematic if the General Standards for disposal into a sewer system are not met. The solution generally involves costly tariffs, dilution of the wastewaters with valuable potable water, marine discharge or co-disposal into municipal landfill sites. Anaerobic digestion has been shown to have the potential to treat effluents of this nature. Microorganisms have the ability to acclimate to xenobiotic or toxic substrates which provides the potential for the anaerobic degradation of most substrates. The survey concentrated on two regions, viz. Durban South and Pinetown, due to the availability of anaerobic digestion capacity at the Southern, and Umbilo and New Germany Works, respectively. Industries producing an effluent with a COD > 2 000 mg/l were included in the survey. A matrix was compiled in which available digestion capacity was matched with potential effluents for treatment. From the investigation of the industries and the composition of effluents it was concluded that there was the potential for the utilisation of available resources to effectively stabilise effluents which otherwise could have an adverse effect on the environment.

4. The laboratory-scale screening test was based on the method of Owen et al. (1979) which was found to be a suitable method for the easy assessment of the anaerobic degradability and potential toxicity of a compound. These assays facilitated the determination of whether the loading of a substrate into an anaerobic digester would be detrimental to its operation and provided information on volumes and concentrations of an effluent that could be treated effectively. Material and energy balances provided an indication of the efficiency of the digestion process in the serum bottles.

5. The batch tests should run for a period of ca. 30 d. The method is simple to apply and is no more time-consuming than standard analytical procedures e.g. COD determination. No specialised equipment is necessary, apart from a gas chromatograph for gas composition analyses.

6. Detailed evaluation of the anaerobic digesters at the Umbilo Sewage Purification Works (USPW) identified available capacity in terms of both hydraulic and organic load. This was determined by investigation of the flow to the digesters and the properties of the feed sludge. The hydraulic load to the USPW was 75 % of the design capacity (it was designed to treat a flow of 23.2 Mℓ/d but was only treating 17.38 Mℓ/d) hence the load the anaerobic digesters was below capacity. The anaerobic digesters were high-rate digesters in that they were heated and mixed. They could, therefore, receive an organic load of between 1.5 and 3 kg VS/m^3.d. The annual average feed to the digetsers was 1.12 kg VS/m^3.d which indicated that the digesters were organically underloaded.

7. The stability of the Umbilo digestion process was assessed by analysis of the characteristics of the digester sludge. Operation of the digesters was efficient. Similar analyses were performed at the other wastewater treatment works to determine the performance efficiency and highlight under-performance. This facilitated the recommendation for remedial action and the ultimate improvement of utilisation of digestion facilities.

8. Tracer tests are useful to assess the mixing and flow patterns within an anaerobic digester as well as the quantification of a1x2972Y A residence time distribution test was performed on an anaerobic digester at the USPW. The tracer test indicated that the entire digester volume was utilised thus indicating the absence of dead volume. The mixing process was efficient with the reactor approximating a perfect completely stirred tank reactor (CSTR). A sludge bypass of 1.94 % of the flow was detected. This should be remedied to prevent the presence of undegraded substrate in the final effluent.

9. The laboratory-scale test protocol was applied to assess the anaerobic degradability of a textile size solution. The size solution was chosen due to its high organic strength (ca. 120 000 mg/ℓ) and because the textile mill producing the effluent was located in the vicinity of the USPW. The effluent was being tankered approximately 40 km for marine discharge. The serum bottle tests showed that the size solution was anaerobically degradable. Interactions between microbial populations together with co-metabolism resulted in the efficient degradation of the substrate even though components of the size solution were found to be inhibitory to the biomass. Acclimation experiments were undertaken with the inhibitory size components since it is known that microorganisms have the ability to acclimate to inhibitory substrates so that they can be degraded at concentrations which were previously inhibitory. These results indicated the potential to treat of the textile size effluent in the available anaerobic digester capacity at the Umbilo Sewage Purification Works.

10. Implementation of cleaner production strategies such as raw material substitution could alleviate the need for extended digestion time due to the presence of inhibitory components in the effluent. The recalcitrant components could be replaced with labile substitutes. This was observed during the investigation. The Plystran component of the textile size was found to be inhibitory to the anaerobic biomass. The mill substituted the Plystran with PVA and starch, with a reduced cost to the mill.

Chapter 8

Recommendations

1. The anaerobic digester performance evaluation should be extended throughout the country. The utilisation of these available resources would generate income which could be used for social improvement such as the provision of sanitation.

2. A thorough survey of industries with emphasis on the identification of point source emissions within the factories should be undertaken. This would facilitate the segregation and concentration of the high-strength or toxic effluent components on-site. These could then be tankered to a nearby wastewater treatment works for anaerobic treatment in available capacity.

3. Segregation of high-strength or toxic components on-site would promote cleaner production strategies such as recycling. Raw material substitution could also be implemented. This involves the replacement of recalcitrant components with biodegradable substitutes.

4. The information from the effluent survey could contribute to the proposed national database on effluent production and characteristics.

5. Assessment of the cost-effectiveness of the proposed treatment option and logistical considerations, such as road quality and maintenance with increased usage by tankers, should be undertaken.

6. There should be long-term monitoring of effluent degradation by the staff at the wastewater treatment works.

7. Research into the concentration, or thickening, of digester sludge for the efficient utilisation of digester volume should be carried out. Investigation of the computational fluid dynamics of an under-performing digester could also contribute to improved process efficiency.

8. Detailed research in anaerobic modelling systems should be undertaken.

9. The serum bottle test should be scaled up to a 20 ℓ laboratory-scale reactor to provide more accurate information for prediction of operation in a full-scale digester. The set-up and operating procedure for these tests are presented in **Appendix E.**

10. The described protocol should be employed in the laboratories at the respective wastewater treatment works for the assessment of effluents prior to their acceptance for anaerobic digestion.

11. The closure of the Bulbul Road landfill site to co-disposal has necessitated the co-disposal of toxic wastes onto the unlined Bisasar landfill site, in Springfield Park. Approximately 200 m^3 of liquid wastes are being discharged to this site per day. This poses grave environmental problems in terms of contamination of the groundwater and rivers. There is the potential for these effluents to be treated in available anaerobic digester capacity thereby safeguarding the environment. This recommendation was supported by Durban Solid Waste.

12. The implementation of anaerobic digestion of liquid wastes, instead of co-disposal, should promote a reduction in the leachate production problems experienced at the landfill sites.

13. Dedicated or specialised digesters could be developed to treat the toxic effluents on-site. Acclimation of the biomass would facilitate efficient pre-treatment of the effluent, which could then be discharged to sewer. The digesters would be under the control of the local authority who would monitor the effluent quality. This would reduce transportation risks.

Chapter 9

Technology Transfer

9.1 Interaction With Other Projects

1. The residence time distribution test carried out on the Umbilo digester was modelled using IMPULSE, which was developed during the course of WRC Project No. 363 entitled *The Development and Evaluation of Small-scale Potable Water Treatment Equipment.*

2. The project was motivated by conclusions reached during the course of WRC Project No. 456 entitled *The Regional Treatment of Textile and Industrial Effluents* which identified the under-utilisation of anaerobic digestion facilities in the KwaZulu-Natal Region.

3. An Honours project (Department of Microbiology and Plant Pathology at the University of Natal, Pietermaritzburg) to isolate bacterial populations targeting selected industrial wastewaters.

4. A student laboratory project (Department of Chemical EnUniversity of Natal, Durban) applied the biodegradability and toxicity assays to ascertain the anaerobic treatability of ice cream waste.

5. The biodegradability and toxicity protocol will be applied by a number of B-Tech students (Natal Technikon) in order to assess a number of identified effluents.

6. A student laboratory project (Department of Chemical Engineering, University of Natal, Durban) assessed the baffled (compartmentalised) anaerobic digester for the treatment of a high strength organic effluent.

7. An effluent survey conducted by a research team at Natal Technikon.

9.2 KwaZulu-Natal Water Research Network

The establishment of the KwaZulu Natal Water Research Network and the frequent meeting of its members has facilitated the exchange of ideas and collaborative research as well as the ability to use equipment in other laboratories.

9.3 Publications

Papers presented : (Annexure 2)

1. **J SACKS, CA BUCKLEY, E Senior and H Kasan**. (1997). The utilisation of available anaerobic digester capacity, in the KwaZulu Natal region, for the treatment of high strength or toxic organic effluents. *SAIChE '97*. Cape Town, South Africa.

2. **J SACKS, CA BUCKLEY, E Senior and H Kasan**. (1997). The utilisation of available anaerobic digester capacity, in the KwaZulu Natal region, for the treatment of high strength or toxic organic eflfuents. *Regional Meeting of the KwaZulu Natal Branch of SAIChE*. Durban.

3. **J SACKS, CA BUCKLEY, E Senior and H Kasan**. (1997). Anaerobic digestion of a high strength organic effluent. *Joint KwaZulu Natal Biochemistry and Microbiology Symposium*. Durban, South Africa.

Poster presentations : (Annexure 2)

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Appendix A

Anaerobic Digester Survey

	AMANZIMTOTI	CATO RIDGE ABATTOIR	DARVILL
Total flow to works (*Ml/d*)	19.4	1	55
Screen performance (*m^3/d*)	0.13	0.5	0.9
Grit removal (*m^3/d*)	1.5	0.5	3
Feed sludge (*% TS*)	3.8	3	5.75
Anaerobic Digestion Reactor	CSTR	CSTR	CSTR
Digester volume (*m^3*)	(1.2 &3) 2 012 : idle (4) 2 068; (5&6) 3 640	2 866 (x2)	4 500 (x2)
Feed schedule	Batch (7m^3/h)	Continuous	Batch
Volume of feed sludge (*m^3/d*)	80	1 230.4	227
VS loading rate (*kg VS/m^3/d*)	0.25	4.1	2.03
Temperature (°C)	Ambient	Ambient	35
Type of mixing	Draft tube	Sludge recycle	Sludge recycle
Power for mixing (*W/m^3*)	Not determined	Not determined	Not determined
Mixing efficiency (*vol. displ/d*)	Not determined	Not determined	0.4
Retention time (*d*)	46	5	20
Sludge pH	7.4	7.2	7.3
Sludge VFA (*mg/l*)	566	213	100
Sludge alkalinity (*mg/l*)	3 343	891	3 700
Ripley ratio	0.17	0.24	0.03
VS reduction (%)	60	72	64.6
Works COD reduction (%)	90	95	95
Total gas prodn (*m^3/d*)	Not determined	Not determined	10 000
Efficiency (*m^3 CH_4/kg VS destroyed*)	Not determined	Not determined	1.01
Gas storage on site (*m^3*)	2 000	None	None
CH_4 utilisation	None	None	Digester heating
Secondary digesters	Closed settling tanks (x3)	Clarifiers	Open settling tank
Sludge dewatering	Belt press	None	Flood irrigation
Sludge disposal	Municipal landfill	Land conditioner	Land conditioner

	ESCOURT	KWA MAKUTHA	KWA MASHU
Total flow to works (*Ml/d*)		3.5	65
Screen performance (m^3/d)		0.3	2.2
Grit removal (m^3/d)		0.5	2
Feed sludge (*% TS*)		5.5	3.8
Anaerobic Digestion			
Reactor		CSTR	CSTR
Digester volume (m^3)		1 650	1 750 (x2)
Feed schedule		Batch	Batch
Volume of feed sludge (m^3/d)		90	130
VS loading rate ($kg\ VS/m^3/d$)		2.1	1.09
Temperature (°*C*)		Ambient	37
Type of mixing		Draft tube	Sludge recycle
Power for mixing (W/m^3)		Not determined	Not determined
Mixing efficiency (*vol. displ/d*)		Not determined	0.8
Retention time (*d*)		18.3	27
Sludge pH		7	7.2
Sludge VFA (*mg/l*)		102	85
Sludge alkalinity (*mg/l*)		4 410	2 579
Ripley ratio		0.02	0.03
VS reduction (%)		56	59.1
Works COD reduction (%)		86	69.8
Total gas prodn (m^3/d)		Not determined	3 500
Efficiency ($m^3\ CH_4/kg\ VS$)		Not determined	0.76
Gas storage on site (m^3)		None	1 200
CH_4 utilisation		None	Heat digesters
Secondary digesters		None	Open settling tank
Sludge dewatering		Drying beds	Centrifuge/ dry beds
Sludge disposal		Land conditioner	Stock piled

	KWA NDENGEZI	MPOPHOMENI	MPUMALANGA
Total flow to works (*Ml/d*)	2.9	1.8	3.26
Screen performance (m^3/d)	-	Not determined	0.6
Grit removal (m^3/d)	1.4	Not determined	2
Feed sludge (*% TS*)	3.51	7	4.5
<u>Anaerobic Digestion</u> Reactor	CSTR	CSTR	CSTR
Digester volume (m^3)	1 550	683 (x2)	1 052 (x4)
Feed schedule	Batch	Batch	Batch
Volume of feed sludge (m^3/d)	29	45	45
VS loading rate ($kg\ VS/m^3/d$)	0.5	3.2	0.34
Temperature (°C)	Ambient	Ambient	Ambient
Type of mixing	Sludge recycle	Draft tube	Draft tube
Power for mixing (W/m^3)	Not determined	Not determined	0.01
Mixing efficiency (*vol. displ/d*)	Not determined	Not determined	N/D
Retention time (*d*)	53	15	94
Sludge pH	7.1	7	7.1
Sludge VFA (*mg/l*)	150	98	97
Sludge alkalinity (*mg/l*)	3 966	2 747	3 167
Ripley ratio	0.04	0.04	0.03
VS reduction (%)	26	33	34.5
Works COD reduction (%)	92.9	94	94
Total gas prodn (m^3/d)	Not determined	Not determined	Not determined
Efficiency ($m^3\ CH_4/kg\ VS$)	Not determined	Not determined	Not determined
Gas storage on site (m^3)	None	None	None
CH_4 utilisation	None	None	None
Secondary digesters	None	Closed tank	Closed settling tanks
Sludge dewatering	Drying beds	None	Drying beds
Sludge disposal	Land conditioner	Land conditioner	Land conditioner

	NEWCASTLE	NEW GERMANY	NOODSBURG (Illovo Sugar)
Total flow to works (*Ml/d*)	Not determined	3.5	800
Screen performance (m^3/d)	Not determined	0.3	Not determined
Grit removal (m^3/d)	Not determined	0.17	Not determined
Feed sludge (*% TS*)	-	4.1	Not determined
Anaerobic Digestion			
Reactor	CSTR	CSTR	Lagoon
Digester volume (m^3)	850	1 000 (x2)	11 700
Feed schedule	-	Batch	Continuous
Volume of feed sludge (m^3/d)	-	5	800
VS loading rate ($kg\ VS/m^3/d$)	-	0.08	0.05
Temperature (°*C*)	-	37	35
Type of mixing	Sludge recycle	Sludge recycle	Recirculation
Power for mixing (W/m^3)	-	Not determined	Not determined
Mixing efficiency (*vol. displ/d*)	-	Not determined	Not determined
Retention time (*d*)	-	200	15
Sludge pH	-	6.6	Not determined
Sludge VFA (*mg/l*)	-	3 567	Not determined
Sludge alkalinity (*mg/l*)	-	2 657	Not determined
Ripley ratio	-	0.1	Not determined
VS reduction (%)	-	24	Not determined
Works COD reduction (%)	90	95	25
Total gas prodn (m^3/d)	Not determined	Not determined	Not determined
Efficiency ($m^3\ CH_4/kg\ VS$)	-	Not determined	Not determined
Gas storage on site (m^3)	None	250	None
CH_4 utilisation	None	Heat digesters	None
Secondary digesters	-	Open settling tank	None
Sludge dewatering	-	None	None
Sludge disposal	Land conditioner	Land conditioner	None

	NORTHERN	PHOENIX	SCOTTBURGH
Total flow to works (*Ml/d*)	42	11	1.1
Screen performance (*m^3/d*)	2.5	0.3	Not determined
Grit removal (*m^3/d*)	1.7	0.7	Not determined
Feed sludge (*% TS*)	6	3.9	2
Anaerobic Digestion			
Reactor	CSTR	CSTR	CSTR
Digester volume (*m^3*)	2 350 (x3)	2 600 (x2)	1 130
Feed schedule	Continuous	Batch	Batch
Volume of feed sludge (*m^3/d*)	(1&2) 65; (3) 100	85	10.5
VS loading rate (*kg VS/m^3/d*)	1.6	1.06	0.14
Temperature (*°C*)	37	37	Ambient
Type of mixing	Sludge recycle	Sludge recycle	Sludge recycle
Power for mixing (*W/m^3*)	Not determined	Not determined	Not determined
Mixing efficiency (*vol. displ/d*)	0.5	0.28	Not determined
Retention time (*d*)	(1&2) 36; (3) 24	31	108
Sludge pH	7.4	6.8	7
Sludge VFA (*mg/l*)	187	130	800
Sludge alkalinity (*mg/l*)	3 700	2 823	1350
Ripley ratio	0.05	0.05	0.6
VS reduction (%)	62	66	50.3
Works COD reduction (%)	72	76	92
Total gas prodn (*m^3/d*)	3 550	1 514	Not determined
Efficiency (*m^3 CH_4/kg VS*)	0.3	0.55	Not determined
Gas storage on site (*m^3*)	3 500	2 000	None
CH_4 utilisation	Heat digesters	Heat digesters	None
Secondary digesters	Open settling tank	Open settling tank	Closed settling tank
Sludge dewatering	Belt press	None	Drying beds
Sludge disposal	Land conditioner	Land conditioner	Land conditioner

	PROSPECTON (S.A.B)	**SOUTHERN**	**SUNDUMBILI**
Total flow to works (*Ml/d*)	4.5	100	11.9
Screen performance (*m^3/d*)	1	Not determined	0.15
Grit removal (*m^3/d*)	-	Not determined	0.1
Feed sludge (*% TS*)	8.8	-	2
Anaerobic Digestion Reactor	UASB	CSTR	CSTR
Digester volume (*m^3*)	1 700	4 620 (x2)	1 387 (x4)
Feed schedule	Continuous	Continuous	Batch
Volume of feed sludge (*m^3/d*)	3 303	Not determined	100
VS loading rate (*kg VS/m^3/d*)	3.3	58	1.01
Temperature (*°C*)	37	37	Ambient
Type of mixing	Spargers	Sludge recycle	Draft tube
Power for mixing (*W/m^3*)	Not determined	Not determined	Not determined
Mixing efficiency (*vol. displ/d*)	Not determined	Not determined	Not determined
Retention time (*d*)	0.51	30	14
Sludge pH	6.5	-	6.9
Sludge VFA (*mg/l*)	1 475	-	3 000
Sludge alkalinity (*mg/l*)	1 300	-	5 100
Ripley ratio	1.1	-	0.6
VS reduction (%)	66	55	36
Works COD reduction (%)	96	-	94
Total gas prodn (*m^3/d*)	4 913	-	Not determined
Efficiency (*m^3 CH_4/kg VS*)	1.3	1.2	Not determined
Gas storage on site (*m^3*)	None	2 500	None
CH_4 utilisation	Heat digester	Heat digesters	None
Secondary digesters	Closed settling tank	Closed settling tank	Closed settling tanks
Sludge dewatering	None	Portius treatment	Drying beds
Sludge disposal	Cattle feed	Land conditioner	Stock piled

	TONGAAT	UMBILO	UMBOGINTWINI (AECI)
Total flow to works (*Ml/d*)	3	17.38	0.5
Screen performance (*m^3/d*)	0.02	0.14	Not determined
Grit removal (*m^3/d*)	0	0.28	Not determined
Feed sludge (*% TS*)	4	3.6	Not determined
<u>Anaerobic Digestion</u>		Reactor C	CSTR
Digester volume (*m^3*)	2 000 (x2)	1 340 (x4)	103 (x1)
Feed schedule	Batch	Batch	Batch
Volume of feed sludge (*m^3/d*)	40	54.3	4
VS loading rate (*kg VS/m^3/d*)	0.28	1.12	Not determined
Temperature (*°C*)	Ambient	36	Ambient
Type of mixing	Sludge recycle	Draft tube	Mechanical stirrer
Power for mixing (*W/m^3*)	Not determined	8.2	Not determined
Mixing efficiency (*vol. displ/d*)	0.13	16	Not determined
Retention time (*d*)	100	22.3	26
Sludge pH	7.1	7.5	Not determined
Sludge VFA (*mg/l*)	30	169	Not determined
Sludge alkalinity (*mg/l*)	600	2 026	Not determined
Ripley ratio	0.05	0.08	Not determined
VS reduction (%)	45	72	Not determined
Works COD reduction (%)	93	71	75
Total gas prodn (*m^3/d*)	Not determined	1 200	Not determined
Efficiency (*m^3 CH_4/kg VS*)	Not determined	0.63	Not determined
Gas storage on site (*m^3*)	None	500	None
CH_4 utilisation	None	Heat digesters	None
Secondary digesters	None	Closed settling tanks	None
Sludge dewatering	Drying beds	Belt press	Drying beds
Sludge disposal	Stock piled	Land conditioner	Land conditioner

	UMLAZI	UMZINTO	VERULAM
Total flow to works (*Ml/d*)	12	0.002	4
Screen performance (*m^3/d*)	0.75	Not determined	0.3
Grit removal (*m^3/d*)	2	Not determined	0.6
Feed sludge (% *TS*)	3.7	Not determined	4
Anaerobic Digestion Reactor	CSTR	Settling tank	CSTR
Digester volume (*m^3*)	964 (x6)	705	(1) 4 120; (2;3) 8 200
Feed schedule	Batch	Batch	Batch
Volume of feed sludge (*m^3/d*)	300	Not determined	103
VS loading rate (*kg VS/m^3/d*)	1.7	Not determined	0.14
Temperature (°C)	Ambient	Ambient	Ambient
Type of mixing	Draft tube	Biogas	Stirrer
Power for mixing (*W/m^3*)	Not determined	Not determined	Not determined
Mixing efficiency (*vol. displ/d*)	0.1	Not determined	0.03
Retention time (*d*)	16.1	200	240
Sludge pH	7.3	7.4	7.2
Sludge VFA (*mg/l*)	145	Not determined	130
Sludge alkalinity (*mg/l*)	3 300	Not determined	3 200
Ripley ratio	0.04	Not determined	0.04
VS reduction (%)	62.5	Not determined	57
Works COD reduction (%)	90	87	80
Total gas prodn (*m^3/d*)	Not determined	Not determined	Not determined
Efficiency (*m^3 CH_4/kg VS*)	Not determined	Not determined	Not determined
Gas storage on site (*m^3*)	None	None	None
CH_4 utilisation	None	None	None
Secondary digesters	Closed settling tank	None	Open settling tank
Sludge dewatering	Drying beds	Drying beds	Drying beds
Sludge disposal	Land conditioner	Land conditioner	Stock piled

Appendix B

Effluent Survey

Effluent information was provided by the Durban Metropolitan Council on all the industrial effluents with a COD > 2 000 mg/l. For each region, the industries are listed in descending order of organic mass produced.

Amanzimtoti

Company	COD mass (kg /month)	Volume (m^3/month)	COD (mg/l)	Current Treatment
S.A. Breweries	55 815	111 853	499	UASB on site. Discharged to Toti WWTW.
Coates Brothers	5 958	698	8 536	N/D
Robertsons	4 702	1 004	4 683	N/D
Republican Press	3 002	1 341	2 239	N/D

N/D: Not determined

New Germany

Company	COD mass (kg /month)	Volume (m^3/month)	COD (mg/l)	Current Treatment
Frametex	41 550	300	138 500	Marine outfall
Distillers Corp.	1 336	415	3 220	N/D
CHT South Africa	424	130	3 260	N/D
Huls	358	600	596	N/D

North Coast

Company	COD mass (kg /month)	Volume (m^3/month)	COD (mg/l)	Current Treatment
NCP	2.6e05	17 627	14 621	Marine outfall
Mondi Board Mills	61 711	35 223	1 752	Marine outfall
Sappi (Mandeni)	22 500	45 000	500	Marine outfall
David Whiteheads & Sons	17 795	5 000	3 559	Marine outfall

Durban South

Company	COD mass (kg / month)	Volume (m³/month)	COD (mg/l)	Current Treatment
CG Smith	2.8e06	70 000	40 000	Marine outfall
Mondi Paper	1.4e06	800 000	1 752	Marine outfall
Engen Refinery	1.2e05	170 757	719	Pre-treatment on site. Marine outfall.
Durban Confectionary	173 279	24 779	6 993	N/D
Sapref Refinery	78 238	139 214	562	Pre-treatment on site. Marine outfall.
Lever Bros./ Unifoods	57 668	17 799	3 240	Pre-treatment on site. Marine outfall.
Waste Services	27 715	4 597	6 029	N/D
Ind. Oil Processors	23 831	4 379	5 442	Landfill
O.T.H. Beier	20 789	8 731	2 381	N/D
NCP/Sentrachem	18 391	3 741	4 916	Marine outfall
National Sorghum Breweries	17 177	7 031	2 443	Pre-treatment on site. Marine outfall
Cargo Carriers	13 994	4 398	3 182	N/D
Frame Textiles	10 832	117 741	92	Balancing pond on site. Partially treated effluent used at Mondi.
Paperkem	10 606	1 552	6 834	N/D
Drum Services	9 705	498	19 488	Marine outfall
Revertex	9 151	1 235	7 410	N/D
Beacon Sweets	8 395	3 150	2 665	N/D
Huletts Refinery	5 685	15 000	379	Pre-treatment on site. Marine outfall
Vision Creations	5 646	1 735	3 254	N/D
Unitrans Natal	4 769	1 862	2 561	N/D
NCP Yeast	4 659	4 843	962	Landfill
Tanker Services	4 513	4 385	1 029	N/D
Chemical Specialities	3 610	761	4 744	N/D
Elida Ponds	3 419	967	3 536	N/D
Golden Lay Farms	2 519	693	3 635	N/D
Fine Foods	1 946	453	4 295	N/D

Company	**COD mass (kg /month)**	**Volume (m³/month)**	**COD (mg/l)**	**Current Treatment**
Bromor Foods	1 741	393	4 431	Marine outfall
Albany Bakery	1 595	1 013	1 575	N/D
Competition Motors	1 400	324	4 320	N/D
Printpak	1 187	280	4 240	N/D
S.A. Sugar Terminals	433	198	2 186	N/D
Marachia Laundry	328	92	3 560	N/D
Plascon Paints	106	33	3 200	Pre-treatment on site. Marine outfall
Beier Industries	N/D	174	N/D	N/D

The cumulative COD mass was plotted against the number of factories in the region (**Figure B.1**). This plot showed that the majority of the COD came from the first three industries in the above list.

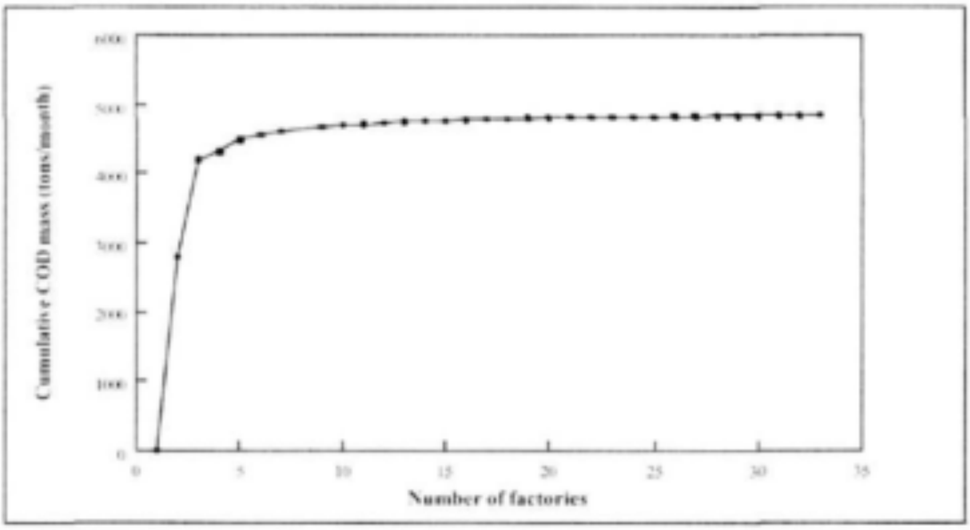


FIGURE B.1 : Indication of the number of industries producing the majority of the COD load in the Durban South region.

Pinetown

Company	COD mass (kg / month)	Volume (m^3/month)	COD (mg/l)	Current Treatment
NCD	1.5e05	34 293	4 301	Dilution and disposal to sewer.
Ninian & Lester	1.2e05	50 081	2 321	Pre-treatment on site. Disposal to sewer.
Pure Fresh Foods	1.2e05	21 907	5 391	N/D
Sunrise Dairies	13 499	1 892	7 135	N/D
Alex Cartage	10 078	978	10 305	N/D
Nampak	9 403	1 915	4 910	N/D
Dan Perkins	8 142	172	47 337	N/D
Rapidol	7 803	531	14 694	N/D
Associated Biscuits	6 322	1 795	3 522	Landfill
Kohler Carton	4 872	570	8 547	N/D
Nelba	4 144	395	10 491	N/D
Waste Tron	2 597	339	7 661	N/D
CFC	2 327	100	23 267	N/D
Triumph Printers	1 848	696	2 655	N/D
Trek Express	1 463	293	4 992	N/D
R&B Engineering	1 248	382	3 267	N/D
Auto Armor	1 118	332	3 368	N/D
Prostruct	828	320	2 586	N/D
Ferrobond	725	183	3 961	N/D
Syndachem	658	34	19 366	N/D
Pekay Chemicals	561	34	16 494	N/D
Sybron Chemicals	328	65	5 047	N/D
Qualichem	0	0	53 593	N/D
Resmed	0	0	12 525	N/D
Status Chemicals	0	0	16 220	N/D

Figure B.2 shows that the majority of the COD load was contributed by the three major industries listed at the top of the above list.

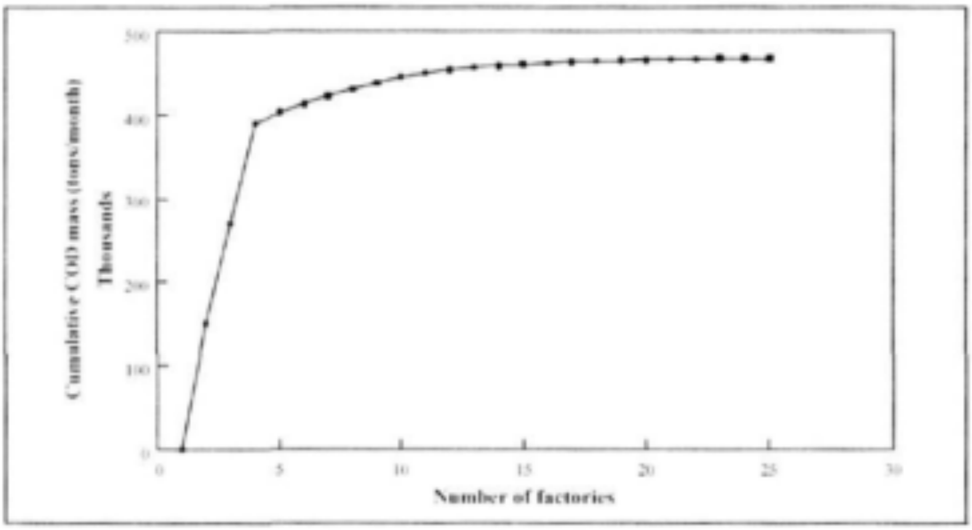


FIGURE B.2 : Indication of the number of industries producing the majority of the COD load in the Pinetown region.

Appendix C

Batch Test Protocol

The experimental procedure for the laboratory-scale test protocol is described. Experiments were performed in 125 ml glass serum bottles (Supelco, Inc.) which were sealed with butyl rubber septa and aluminium crimp seals.

C.1 Materials

Mineral salts solution

A defined solution containing trace elements, minerals and vitamins was prepared according to Owen et al. (1979). The stock solutions for preparation of the nutrient medium are presented in **Table C.1** and the method for preparation is presented in **Table C.2**.

TABLE C.1: Stock solutions for preparation of mineral salts solution.

Stock solution	Composition	Concentration (g/l)
S2	Resazurin	1
S3	$(NH_4)_2HPO_4$	26.7
S4	$CaCl_2.2H_2O$	16.7
	NH_4Cl	26.6
	$MgCl_2.6H_2O$	120
	KCl	86.7
	$MnCl_2.4H_2O$	1.33
	$CoCl_2.6H_2O$	2
	H_3BO_3	0.38
	$CuCl_2.2H_2O$	0.18
	$Na_2MoO_4.2H_2O$	0.17
	$ZnCl_2$	0.14

Stock solution	Composition	Concentration (g/ℓ)
S5	$FeCl_2.4H_2O$	370
S6	$Na_2S.9H_2O$	500
S7	Biotin	0.002
	Folic acid	0.002
	Pyridoxine hydrochloride	0.01
	Riboflavin	0.005
	Thiamin	0.005
	Nicotinic acid	0.005
	Panthothenic acid	0.005
	p-aminobenzoic acid	0.005
	Thioctic acid	0.005

TABLE C.2 : Preparation of the defined mineral salts solution.

Step	Method	Volume (mℓ)	Mass (g)
1	1 ℓ of deionised water was added to a 2 ℓ yrex vessel		
2	The following were added :		
	Stock solution S2	1.8	
	Stock solution S3	5.4	
	Stock solution S4	27.0	
3	Deionised water was added up to 1.8 ℓ		
4	Boiled for 15 min whilst flushing with OFN gas (1 ℓ /min)		
5	Cooled to room temperature		
6	The following were added:		
	Stock solution S7	18.0	
	Stock solution S5	1.8	
	Stock solution S6	1.8	
7	$NaHCO_3$ was added as powder		8.4
8	Flushed with OFN until pH stabiliseed around 7.1		
9	Autoclaved (30 min at 121 °C)		
10	Stored at 4 °C until use.		

Substrate

Wastewaters were either sampled from an industry or simulated in the laboratory. A range of concentrations was prepared by dilution in distilled water. A 10 % (v/v) dilution consisted of a solution in which 10 % was constituted by the wastewater, e.g., 10 mℓ substrate dissolved with 90 mℓ distilled water.

Sodium acetate-propionate stock solution

Sodium acetate-propionate solution was added to each reaction vessel in the anaerobic toxicity assay. A volume of 2 mℓ was added to each bottle to give an approximate concentration of 75 mg acetate and 25.6 mg propionate per 100 mℓ.

Inoculum

Inoculum, or seed biomass, for all assays was sampled from the primary anaerobic digesters at the Umbilo Sewage Purification Works. The biomass was stor short periods, at 4 °C. This sludge was chosen since there is a concentration of industry in close proximity to the works and many of these industries discharge effluent to sewer.

C.2 Experimental Procedure

The assay bottles were over-gassed with oxygen-free nitrogen (Fedgas) at a flow rate of 0.5 mℓ/min for 15 min according to Owen et al. (1979). The bottles were equilibrated at the incubation temperature. A 30 % (v/v) inoculum was used per serum bottle which was equivalent to 30 mℓ of digester sludge in a total working volume of 100 mℓ. The biomass was mixed with 30 mℓ of the defined nutrient medium (after equilibration of both to the assay temperature). A 40 mℓ sample of substrate (wastewater) was added. Acetate-propionate solution (2 mℓ) was added to the toxicity assay bottles by means of a hypodermic needle and 2 mℓ glass syringe. The headspace was over-gassed with OFN (0.5 mℓ/min for 15 min). The bottles were sealed with butyl rubber septa and aluminium crimp seals prior to incubation in a constant temperature room (37 °C). After equilibration for 1 h the gas volumes were zeroed, to ambient pressure, with a glass syringe. The assay bottles were shaken manually once a day to facilitate contact between the microorganisms and the substrate.

C.3 Analytical Procedures

Gas measurement

Gas volume sampling and removal during incubation were performed with a graduated glass syringe (20 ml) fitted with a 22-gauge disposable needle. The sample syringe was initially flushed with the OFN gas and lubricated with distilled water. The syringe needle was inserted through the rubber septum into the headspace. Readings were taken at the incubation temperature and the syringe was held vertical for measurement. Volume determinations were made by allowing the syringe plunger to move and equilibrate between the bottle and atmospheric pressure. Readings were verified by drawing the plunger past the equilibrium point and releasing to ensure that the plunger returned to the original equilibration volume (Owen et al., 1979). To continue the assay, gas was re-injected into the bottles without contamination or loss, or the syringe full of gas was removed for wasting. Gas was wasted when the difference between the internal and atmospheric pressures was >0.5 atm. This was equivalent to ca. 12 ml under the described experimental conditions. When gas production was lower than this, the measured gas was pushed back into the bottle.

Gas composition

The composition of the digester gas was analysed with a Chrompak CP9000 gas chromatograph equipped with a thermal conductivity detector (TCD) which could detect methane, carbon dioxide and nitrogen peaks. A stainless steel column (Poropak N, length :2 m , inner diameter: 3 mm, 80 to 100 mesh) was used for the separation with the the following conditions :

Conditions for the Chrompak CP9000 and TCD

Column oven	:	40 °C
Detector	:	200 °C
Filaments	:	250 °C
Injection port	:	100 °C

The carrier gas was helium at a flow rate of 10 mL/min The residence times of nitrogen, methane and carbon dioxide were approximately 0.96, 1.54 and 5.05 min, respectively. Samples of digester gas were withdrawn from each serum bottle (directly after the bottles had been equilibrated to atmospheric pressure) by inserting the needle of a gas-tight syringe (100 µl) through the butyl rubber septum and withdrawing 100 µl of headspace gas. The peak area was recorded with a Varian integrator with the attenuation set at 8 and the chart speed at 0.5 cm/min.

A biogas sample was drawn from the serum bottle, with a 100 µl precision syringe, just after wasting excess gas. The 100 µl sample was immediately injected into the gas chromatograph.

Standard Methods
Standard Methods were applied for the COD, total organic carbon, total solids, total suspended solids and volatile solids measurements (American Public Health Association, 1989).

C.4 *Material And Energy Balances*

Carbon and COD balances were made for serum bottle tests with a 5 g/ℓ glucose substrate to illustrate the method.

C.4.1 Carbon balance

The masses of carbon in the glucose solution, the biomass (or protoplasm), the nutrient medium and the biogas components were calculated.

TABLE C.3 : Process of calculation of the total mass of carbon in each component.

Component	Conc.	Amt added or produced	Mass/vol added (g)	Molec. weight (g/mol)	Carbon weight (g/mol)	C Mass (g)	C Mass (mg)
Glucose	5.0 g/ℓ	40 mℓ	0.2	180	72	0.08	80.0
Biomass	6.4 mg/ℓ	30 mℓ	0	113	60	1.02E−4	0.1019
Medium	651 mg/ℓ	30 mℓ	0	234	144	0.0012	1.2018
Carbon dioxide	-	84.4 mg	-	44	12	0.023	23.0
Methane	-	24.5 mg	-	16	12	0.018	18.375

The total organic carbon in the final solution (after incubation) was determined by total carbon analysis. These results are presented below:

TABLE C.4 : Results of the total carbon analyses on the final assay solution.

	mg/ℓ	mg/ 100 mℓ
Total carbon	745	74.5
Inorganic carbon	420	42
Total organic carbon		**32.5**

The ressultant carbon balance is given in **Table 5.1**.

C.4.2 COD balance

The theoretical COD of a compound can be calculated:

$$Cr_2O_7^{2-} + 8\ H^+ \rightarrow 2\ Cr^{3+} + 4\ H_2O + 3\ O \qquad [C.1]$$

$$C_nH_aO_bN_c + dCr_2O_7^{2-} + (8d+c)H^+ \rightarrow nCO_2 + \frac{a+8d-3c}{2}\ H_2O + cNH_4^+ + 2dCr^{3+} \qquad [C.2]$$

$d = 2n/3 + a/6 - b/3 - c/2$

COD = 3/2 d *mole* O_2

This calculation was used to determine the theoretical COD of the mass balance components. An example of the calculation is given and the results are summarised in **Table C.5**.

<u>**Glucose**</u> **:**

$C_6H_{12}O_6$ $\quad n = 6$

$a = 12$

$b = 6$

$c = 0$

$$d = \frac{2n}{3} + \frac{a}{6} - \frac{b}{3} - \frac{c}{2} = 4$$

These values were substituted into Eq. E.2 to give:

$$1\ C_6H_{12}O_6 + 4\ Cr_2O_7^{2-} + 32\ H^+ \rightarrow 6\ CO_2 + 22\ H_2O + 8\ Cr^{3+}$$

The oxygen equivalent was then calculated.

1 mole $C_6H_{12}O_6 = \frac{3}{2}d$ moles O_2 = 6 moles O_2

1 mole $C_6H_{12}O_6$ = 180 g

1 mole O_2 = 32 g

Therefore, complete oxidation of 180 g $C_6H_{12}O_6$ requires 192 g O_2

So, 1 g $C_6H_{12}O_6$ requires 1.067 g O_2

Theoretical COD of 1 g $C_6H_{12}O_6$ is 1.067 g

TABLE C.5: Theoretical COD calculations.							
Compound	**Formula**	**n**	**a**	**b**	**c**	**d**	**g COD/ g compound**
Potassium hydrogen phthalate	$C_8H_5O_4K$	8	5	4	0	4.83	1.176
Glucose	$C_6H_{12}O_6$	6	12	6	0	4	1.067
Biomass	$C_5H_7O_2N$	5	7	2	1	3.33	10.00
Methane	CH_4	1	4	0	0	1.33	4
Carbon dioxide	CO_2	1	0	2	0	0	0

The COD was calculated for each component of the balance.

TABLE C.6 : Process of calculation of the total mass of COD in each component.			
Component	**Measured COD (mg/l)**	**Amt added or produced**	**Balance COD (mg/l)**
Glucose	11 089.5	40.0 ml	443.6
Biomass	2 677.043	30.0 ml	80.3
Medium	651.0	30.0 ml	19.53
Methane	-	24.5 mg	98.0
Final solution	4 225.0	100 ml	422.5

The resultant COD balance is given in **Table 5.2**.

Appendix D

Case Study

D.1 Residence Time Distribution Method

The 10 kg of LiCl (1.65 kg as Li) were dissolved in tap water by a person not involved in the sampling to avoid contamination of the samples during the test. This quantity should give a concentration of approximately 1.2 mg/ℓ Li in the design digester volume (1.34 Mℓ). Tests were carried out to determine the background concentration of lithium in the feed sludge and in the digester sludge prior to dosing. Dosing of the tracer to the digester took ca. 10 min.

When raw sludge was pumped into the digester, an equal volume of digested sludge automatically overflowed. This positive displacement of sludge meant that samples could only be taken when there was an overflow, i.e., when the digesters were being fed. A sample was taken 3 min after the tracer addition and every 5 min thereafter for the first hour. The interval between the samples was gradually increased until only one test sample was collected per day. The test ran for a total of 91 d, from 26 May 1997 to 28 August 1997. Samples were filtered (Whatman No. 4) and the filtrate analysed for lithium using an atomic adsorption (AA) spectrophotometer (GBC 906AA). Samples of the feed and digester sludge, prior to dosing, were used as blanks. The AA conditions were set as follows:

Instrument mode	: Flame emission
Wavelength	: 670.8 nm
Slit width	: 0.5 nm
Flame	: air-acetylene

The AA was calibrated with standards of Li of 0.1, 1.0 and 10 mg Li/ℓ.

A simulation was performed using the modelling program IMPULSE (Baddock et al., 1992). Details of the concentration of lithium in the overflow at the various feed times were entered. It was assumed that the digester
-ered. The volume of rating as an ideal CSTR and that all lithium dosed into the digester would b
the digester and the time during which the LiCl was added were entered as the constant inputs. The initial lithium concentration and the flow rate at the time of addition were entered as regressable parameters. From these data, a curve predicting the lithium output was obtained. The experimental data were entered and the output, or model, curve was then regressed against the reference curve.

D.2 Impulse Output

IMPULSE predicted the following parameters according to the output curve for the model:

Input

Concentration Scale: 0.998192071113171

-1	0
0	61.68
1	0
91	0

Split1

Mix1: 0.0194021152279701

Digester: 0.980597888477203

Digester

Vol: 1340000

num: 1

Mix1

Output: 1

Connectors

Split1 -> Mix1

Mix1 -> Output

Digester -> Mix1

Split1 -> Digester

Input -> Split1

D.3 Anaerobic Degradability of a Textile Size Effluent

The anaerobic degradability of a textile size solution was investigated (**Section 6.3**). These experiments were made with anaerobic sludge collected from the Umbilo Sewage Purification Works. The synthetic size solution was made as described in **Table D.1**

Table D.1 : Composition of the synthetic size effluent.

Component	Formula	Measured COD (mg/ℓ)	Mass added (g)	g COD/g	Thoeretical COD/g
Polyvinyl alcohol	$(C_2H_4O)_n$	53 700	30.7	1.7	1.79
Starch	$(C_6H_{10}O_5)_n$	90 526	23.9	3.79	1.19
Plystran	$(C_5H_{14}O_6)_n$	19 200	16.1	1.19	1.32
Carboxymethyl cellulose	$(NaC_7H_{13}O_5)_n$	15 400	13.6	1.13	1.24
Oxidised modified starch	$(C_6H_{11}O_6Cl)_n$	4 900	2.9	1.69	0.86
Acrylic	$(NaC_3H_3O_2)_n$	1 900	0.73	2.6	0.94
Biocide	$C_5H_{12}ONCl$	13 300	0.05	2.66	1.94

Based on the quantities of each size component utilised by the mill, and an effluent production rate of ca. 10 m^3/d, it was calculated that the size effluent contained 88 g of size per litre. The COD of the synthetic size solution was measured at 138 500 mg/ℓ.

Standard assay conditions were followed as described in **Appendix C**. The controls were prepared in triplicate and each assay sample, in duplicate. Three concentrations were investigated for each compound, namely, the concentration of that compound in the typical size solution (112 g COD/ℓ), one half of the concentration, and 1.5 times the concentration. The three concentrations are referred to as normal, low and high, respectively. The anaerobic toxicity assay was made with the biocide (concentrations of 0.5, 5 and 50 mg/ℓ) and with the synthetic size effluent.

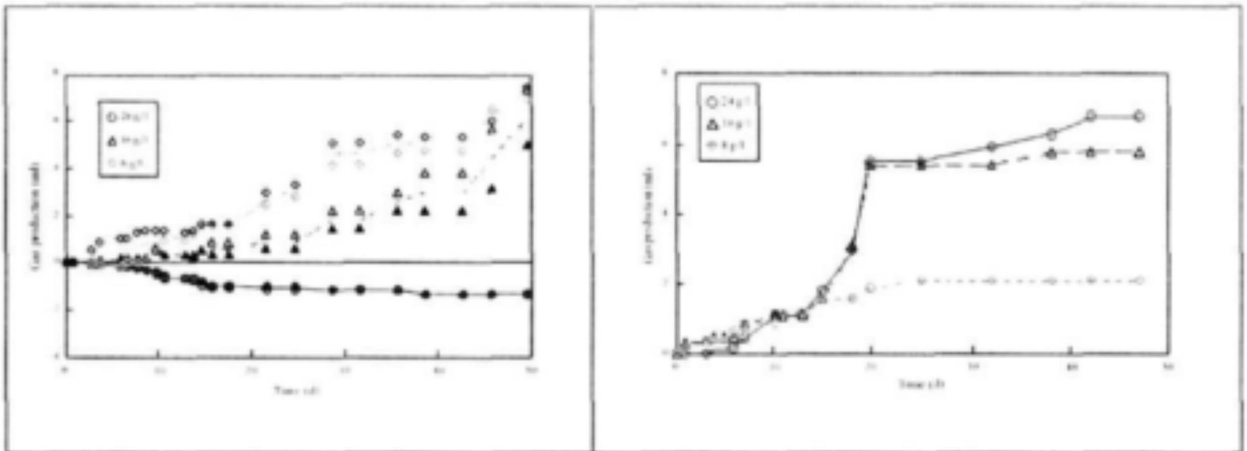
The bottles were incubated in a constant temperature room (37 °C) for 200 d. They were shaken manually once a day to facilitate contact between the microorganisms and the substrate. Gas production was measured daily for the first 2 weeks and periodically thereafter. Incubation in a constant temperature room ensured that the headspace was at the incubation temperature (37 °C). The gas volumes were corrected to STP. Gas composition was determined whenever biogas was wasted. COD and total suspended solids measurements were taken at the beginning and end of the incubation period.

D.4 Acclimation Experiments

The acclimated sludge was separated by settlement and the supernatant was decanted. A 30 ml sample of the acclimated sludge was added to each bottle, with 30 ml of the defined nutrient medium (**Appendix C**). To the Plystran-acclimated sludge, Plystran was added to give final concentrations of 24, 16 and 8 g/l. To the biocide-enriched sludge, solutions of 5 mg/l were added. The sludge in each bottle was exposed to the same conditions as in the previous assay.

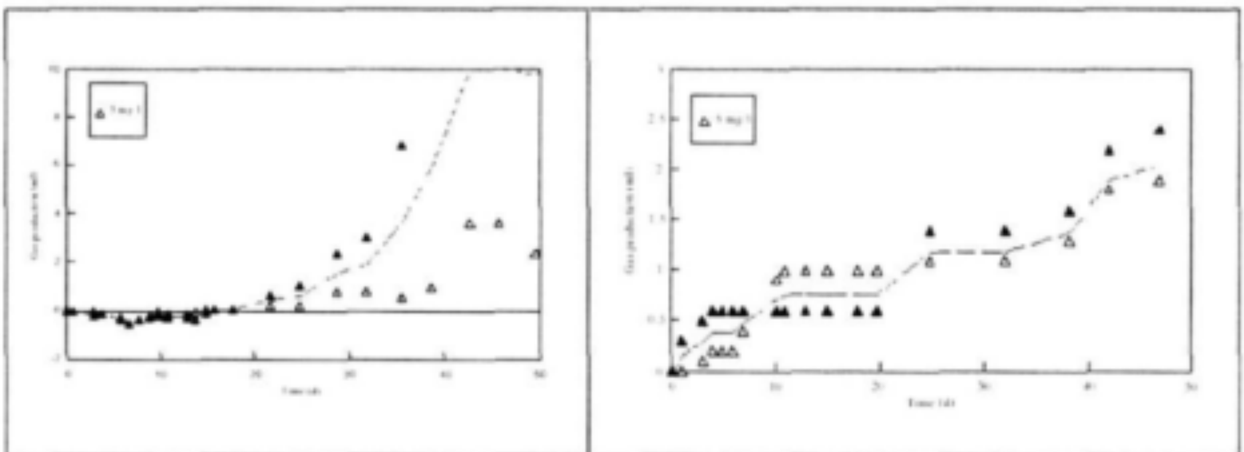
The bottles were incubated (37 °C) in a constant temperature room. The bottles were shaken manually once a day. Gas production was measured (Owen et al., 1979).

The biogas production results were compared to those of unacclimated sludge, for the same time period .



(a) (b)

FIGURE D.1 : Comparison of the biogas production curves for the three Plystran concentrations seeded with the unacclimated (a) and acclimated (b) sludge.



(a) (b)

FIGURE D.2 : Comparison of the biogas production curves for the 5 mg/l biocide concentration seeded with the unacclimated (a) and acclimated (b) sludge.

Appendix E

Scale-Up

The set-up and operation of the 29.7 5ubmitted 6994 ile reactors are described.

E.1 Apparatus

Two reactors were set up with one as a control which was fed primary sludge only. The second reactor was the experimental reactor which was fed with sludge and textile effluent. The reactor was a 25 l aspirator bottle which was maintained in a waterbath at 37 °C.

Glass ports at the top and base of the vessel were used for feed addition and sludge overflow, respectively. There were valves at each point such that feeding or overflowing could be controlled. Sludge was withdrawn by gravity from the base of the digester through an outlet pipe that iswhich was sealed by a valve. An overhead stirrer (140 rpm) was used to mix the contents of the vessel. The gas evolved during digestion was collected in a 20 l bottle which contained acidified water (0.5 M HCl). Inoculum was obtained from the full-scale primary digester. The raw sludge was fed by a peristaltic pump, controlled by a timer. Small volumes of sludge were pumped at frequent intervals to give a residence time of approximately 25 d. The reactor was completely sealed except for a gas outlet pipe that was connected to the bottle of acidified water. The water was displaced for gas measurement. The sludge feed inlet pipe was sealed, by a valve, except during sludge feeding.

E.2 Operating Procedure

An experimental trial was run with digester sludge to develop an operating procedure:

The digetser was filled with 20 l of digested sludge, from the Umbilo primary digester, and fed with raw sludge from the plant. The overflow valve was closed during feeding. After feeding, the equivalent volume of sludge was removed from the reactor. The reactor was allowed to stabilise before the substrate under investigation was added with the feed. The acidified water displaced was equivalent to the gas production within the reactor. The gas tube was clamped when the gas was vented and also when the sludge was withdrawn to prevent the suction of the acidified water into the reactor. The decrease in pH would be detrimental to the biomass.

These reactors were run to simulate operation in the full-scale digester at the Umbilo Sewage Purification Works. The organic loading rate was calculated at 1.24 kg VS/m^3.d. The feed to the 20 l reactors should start off very low and only reach that of the full-scale digesters after ca. 14 d to prevent organic overload. An equivalent organic load, of 22.4 g VS/20l.d was calculated for the loading rate to the reactors. If the loading rate was increased to the optimal ca. 2 kg VS/m^3.d, the loading rate to the 20 l reactor would be 40g VS/d.

The total solids of the feed sludge was 3.6 %. This was concentrated, with sludge from the primary settling tank, to 5 %. At this concentration, 0.8 l was fed to the reactor per day to achieve the calculated loading rate. It was important to ensure that the feed tank did not run dry as this would have resulted in air being taken into the reactor and being represented as gas production. The timer was run on an 8 h cycle; 19 mℓ/min was pumped for 15 min then stopped for 465 min. This resulted in a pump rate of 285 mℓ / 480 min or 0,855 ℓ/d.

The expected gas production was calculated from the assumption that 1 m^3 biogas is produced per kg volatile solids destroyed. The displaced acidified solution was re-used. It was important that the bottom of the gas inleXas lower th
biogas was collected at a pressure
greater than atmospheric pressure and the incoming gas then displaced an equal volume of acidified water. A schematic diagram of the apparatus is given in **Figure E.1**.

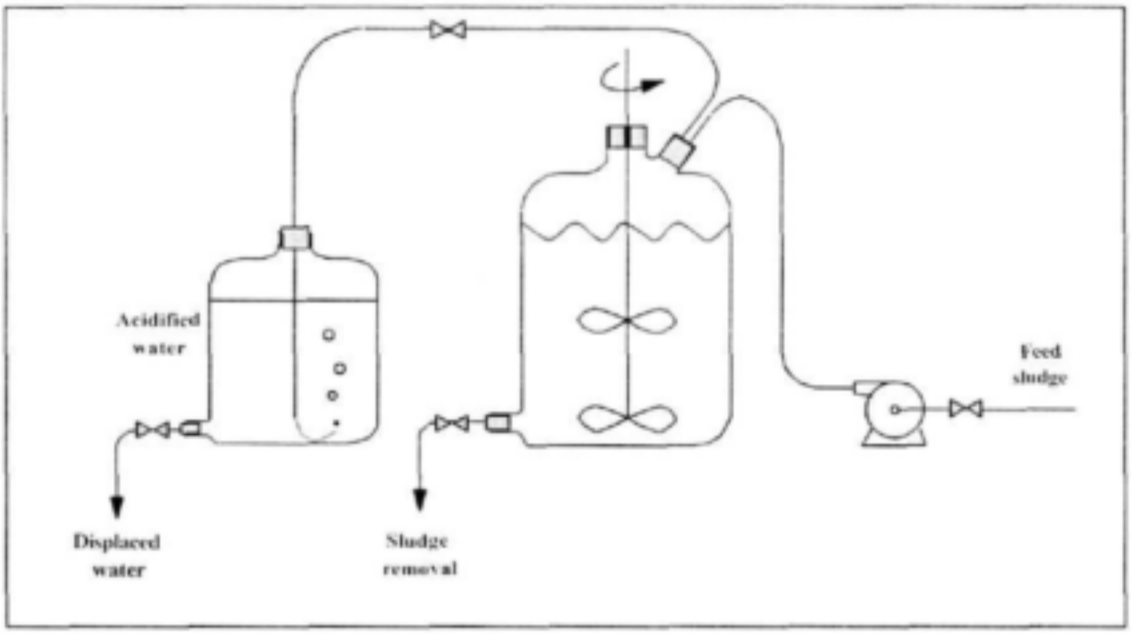


FIGURE E.1 : Schematic diagram of the 20 ℓ reactor set-up.

Stringent daily monitoring of the process was critical. The temperature of the waterbath was measured to ensure that the reactor contents were at the required temperature. The total and volatile solids of the feed sludge were determined according to the Standard Method (**Appendix C**). The 800 mℓ digester sludge was wasted and the pH was measured immediately to avoid inaccuracy by the loss of carbon dioxide to the atmosphere.

Determination of the volatile acids to alkalinity ratio of the sludge sample provided an indication of the acidity/alkalinity balance in the sludge. A simple titration procedure was used with two end points as described by Ripley et al. (1986). According to the Ripley method, alkalinity is approximated by titration with acid from the original sample pH to a pH value of 5.75. Volatile acids are approximated by further titration from the pH 5.75 to pH 4.3.

Biogas composition was analysed by gas chromatography.

Graphical representation of the results provided an indication of an upset in the digester. This allowed for precautions to be taken, such as reduction in the volume of substrate fed, to prevent complete failure of the digester.

The digesters were set up and fed primary sludge. This provided an opportunity for familiarisation with the operation and monitoring of the reactors and the establishment of the optimal strategy for efficient operation.

This technique could be applied prior to scale-up to a full-scale digester to give a more accurate prediction of treatment on a full-scale.

ANAEROBIC DIGESTION OF HIGH-STRENGTH OR TOXIC ORGANIC EFFLUENTS IN AVAILABLE DIGESTER CAPACITY

ANNEXURE I

MScEng Thesis

J SACKS

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Department of Chemical Engineering
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Durban

March 1998

Final report to the Water Research Commission on Project No. 762 entitled:

A Survey of Anaerobic Digesters in the KwaZulu-Natal Region in order to Assess their Availability for the Treatment of High-Strength or Toxic Organic Effluents.

Head of Pollution Research Group	:	Professor C A Buckley
Principle Researcher	:	Ms J Sacks

WRC Report No: ....

ISBN No: ....

ANAERORIC DIGESTION OF HIGH-STRENGTH OR TOXIC ORGANIC EFFLUENTS

A Survey of Anaerobic Digesters in the KwaZulu-Natal Region to Assess their Availability for the Treatment of High-Strength or Toxic Organic Effluents

Joanne Sacks

BSc (Hons)

Submitted in fulfilment of the academic requirements for the degree of

Master of Science in Engineering

in the

Department of Chemical Engineering,

University of Natal, Durban

December 1997

ABSTRACT

There is potential for the anaerobic baffled reactor (ABR) to be implemented on-site for pre-treatment of coloured wastewaters. The implementation of waste minimisation and cleaner production strategies in industry will result in the production of smaller volumes of concentrated wastewaters. With implementation of the ABR, the concentrated waste stream could be pre-treated, with an acclimated biomass, which should facilitate sufficient degradation such that the effluent could be discharged to sewer for further treatment.

The ABR is a high-rate compartmentalised anaerobic bioreactor, the design of which promotes the spatial separation of microorganisms. The use of molecular techniques to characterise the microbial populations and the dynamics of these populations with time and/or changing operating conditions will add to the current understanding of the process, which is based on the biochemical pathways and chemical analyses. This knowledge will allow for optimisation of the design of the ABR.

The hypothesis of the horizontal separation of acidogenesis and methanogenesis through the ABR was proven. Changes in the HRT affected the operation of the reactor, however, recovery from these upsets was almost immediate and operation of the reactor was stable.

Two synthetic dye waste streams, one food dye (tartrazine) and one textile dye (CI Reactive Red 141), and a real industrial dye wastewater, were treated in separate laboratory-scale ABRs. These investigations showed that successful treatment of a highly coloured wastewater is possible in the ABR. The design of the ABR facilitates efficient treatment of concentrated dye wastewaters by protecting the sensitive methanogens from the inhibitory dye molecules and promoting efficient colour and COD reduction.

The molecular-based method, fluorescent *in situ* hybridisation, allowed the direct identification and enumeration of microbial populations active in the ABR. In all of the reported investigations, there was a definite shift in the microbial populations through the ABR, with a predominance of eubacteria in the first compartments (acidogenesis) and archaea (methanogenesis) in the later compartments. The number of compartments involved in each depended on the strength of the substrate (organic loading rate - OLR). A combination of FISH probing, and the analysis of 98 archaeal 16S rDNA clone inserts provided useful descriptions of the methanogens actively involved within each compartment. These showed a predominance of the *Methanosaeta* spp., particularly in the last compartments of the reactor. Methanogens present in the first four compartments consisted of species of *Methanobacterium* and *Methanospirillum*, a relatively unstudied methanogen *Methanomethylovorans hollandica*, and an unidentified short filamentous species.

ANAEROBIC DIGESTION OF HIGH-STRENGTH OR TOXIC ORGANIC EFFLUENTS IN AVAILABLE DIGESTER CAPACITY

ANNEXURE 2

Publications

A. **J. SACKS, C.A. BUCKLEY, E. SENIOR AND H. KASAN**. (1997). The utilisation of available anaerobic digester capacity, in the KwaZulu Natal region, for the treatment of high strength or toxic organic efflfuents. *SAIChE '97*. Cape Town, South Africa.

B. **J. SACKS, C.A. BUCKLEY, E. SENIOR AND H. KASAN**. (1997). Anaerobic digestion of a high strength organic effluent. *Joint KwaZulu Natal Biochemistry and Microbiology Symposium*. Durban, South Africa.

C. **J. SACKS, C.A. BUCKLEY, E. SENIOR AND H. KASAN**. (1997). Availability of anaerobic digesters in the KwaZulu Natal region for the treatment of high strength organic effluents. *Biotech SA '97*. Grahamstown, South Africa.

D. **J SACKS, CA BUCKLEY, E Senior and H Kasan**. (1997). Treatment of textile size effluent by anaerobic digestion: laboratory-scale trails. *Biotech SA '97*. Grahamstown, South Africa.

E. **J. SACKS, C.A. BUCKLEY, E. SENIOR AND H. KASAN**. (1997). An assessment of the feasability of anaerobic digestion as a treatment method for high strength or toxic organic effluents. *IAWQ Specialised Conference on Chemical Process Industries and Environmental Management*. Cape Town, South Africa.

F. **J. SACKS and C.A. BUCKLEY**. (1998). Anaerobic digestion of a textile size effluent. *WISA '98* Cape Town, South Africa.

G. **J. SACKS ,C.A. BUCKLEY AND D.C. STUCKEY**. (1998). Treatment of high-strength or toxic organic effluents in the anaerobic baffled reactor (ABR). *WISA '98* Cape Town, South Africa.

H. **J. SACKS and C.A. BUCKLEY**. (1998). Anaerobic digestion of a textile size effluent *IAWQ Fourth International Symposium on Waste Management Problems in Agro-industries*. Istanbul, Turkey.

FINAL REPORT

ABSTRACT

The Utilisation of Available Anaerobic Digester Capacity in the KwaZulu Natal Region for the Treatment of High Strength or Toxic Organic Effluents

South African Institute of Chemical Engineers (1997), Cape Town, South Africa

Annexure 2A

Compiled by

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Department of Chemical Engineering
University of Natal
Durban

February 1998

Report to the Water Research Commission on Project No. 762.

Head of Pollution Research Group	:	Professor C A Buckley
Principle Researcher	:	Ms J sacks

THE UTILISATION OF AVAILABLE ANAEROBIC DIGESTER CAPACITY, IN THE KWAZULU NATAL REGION, FOR THE TREATMENT OF HIGH STRENGTH OR TOXIC ORGANIC EFFLUENTS

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Anaerobic digestion is a process by which a wide variety of organic materials can be bioconverted into a gas rich in methane. The anaerobic degradation process has several advantages over aerobic processes for waste treatment of high strength organic effluents. The KwaZulu Natal region has the potential to attract a significant amount of industry many with high strength organic effluents, and a number of under-utilised anaerobic digesters have been identified. A strategy has been developed to evaluate the degradability and toxicity of effluents and, ultimately, predict the efficiency of treatment in a full-scale digester. This paper details the strategy and investigates the degradation potential of a textile size effluent.

FINAL REPORT

ABSTRACT

Anaerobic Digestion of a High Strength Organic Effluent

Joint KwaZulu Natal Biochemistry and Microbiology Symposium (1887), Durban, South Africa

Annexure 2B

Compiled by

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February 1998

Report to the Water Research Commission on Project No. 762.

Head of Pollution Research Group	:	Professor C A Buckley
Principle Researcher	:	Ms J sacks

ANAEROBIC DIGESTION OF A HIGH STRENGTH ORGANIC EFFLUENT

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Anaerobic digestion has the potential to treat high strength or toxic organic effluents. The objectives of this research have been to identify available anaerobic digester capacity, in the KwaZulu Natal region; and to assess the feasibility of treating effluents, which are usually difficult to dispose of, in this spare capacity. A laboratory-scale protocol has been developed to evaluate the efficacy of the anaerobic process for the degradation of an effluent.

Textile size effluent is a high strength organic effluent with a COD of ca. 100 000 mg/*l*. The laboratory-scale batch tests showed that the textile size effluent was degradable. The batch tests were scaled-up to 20 *l* reactors. A control reactor was fed only primary feed sludge; a second test reactor was fed feed sludge and the textile size effluent. Parameters were monitored to assess the performance of the reactors. This paper will discuss the results of these trials and the application of the results for scale-up to treatment in a full-scale digester.

FINAL REPORT

ABSTRACT

Availability of anaerobic digesters in the KwaZulu Natal region for the treatment of high strength organic effluents.

Second South African Biotechnology Conference, Grahamstown, South Africa. 21 to 24 January 1997.

ANNEXURE 2C

Compiled by

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Department of Chemical Engineering
University of Natal
Durban

February 1998

Report to the Water Research Commission on Project No. 762.

Head of Pollution Research Group	:	Professor C A Buckley
Principle Researcher	:	Ms J sacks

AVAILABILITY OF ANAEROBIC DIGESTERS IN THE KWAZULU NATAL REGION FOR THE TREATMENT OF HIGH STRENGTH ORGANIC EFFLUENTS

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The KwaZulu Natal region has the potential to attract a significant amount of agro-industrial development due to its abundance of water relative to the rest of the country. These industries usually discharge high strength organic effluents. It has been found that there are a number of sewage works, in the KwaZulu Natal region, with under-utilised anaerobic digestion facilities. The objective of this research was to identify available capacity in existing anaerobic digesters, as well as high strength or toxic organic industrial effluents which can be efficiently treated via anaerobic digestion in these reactors. The increased use (and income) of this existing anaerobic digester capacity could assist in financing additional infrastructure, such as the provision of sanitation in rural or peri-urban areas.

The regional authorities were approached and individual digesters were visited. Physical details and operating data were obtained. From this information, performance criteria and operating efficiencies were calculated. This highlighted those digesters with available capacity, and also indicated possible operational difficulties or inefficiencies.

Regional pollution control officers were interviewed to identify industries producing high strength or toxic organic effluents. Many of these companies have been visited and detailed data of the trade effluents obtained. These visits provided the opportunity to discuss possibilities for pollution prevention and waste minimisation, as well as the possibility of on-site concentration and trucking , of trade effluent, to an existing anaerobic digester.

A matrix is under construction to detail the current capacity, the spare capacity, and the potential spare capacity of the existing systems; and the sources and potential sources of high strength or toxic organic effluents

FINAL REPORT

ABSTRACT

Treatment of Textile Size Effluent By Anaerobic Digestion : Laboratory-Scale Trials.

Second South African Biotechnology Conference, Grahamstown, South Africa. 21 to 24 January 1997.

ANNEXURE 2D

Compiled by

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Department of Chemical Engineering
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February 1998

Report to the Water Research Commission on Project No. 762.

Head of Pollution Research Group	:	Professor C A Buckley
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TREATMENT OF TEXTILE SIZE EFFLUENT BY ANAEROBIC DIGESTION : LABORATORY-SCALE TRIALS

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In view of the current problems, both in the protection of the environment and the search for sources of renewable energy, anaerobic digestion appears to be a favourable biotechnological process to dispose of organic wastes through bioconversion to energy. The objective of this research was to assess the efficiency of anaerobic digestion to biodegrade a textile size effluent.

Textile size is a coating which is applied to yarn to improve its weaving efficiency. Since the size is composed mainly of starch, the effluent from the size baths is of a very high organic strength (COD of approximately 125 000 mg l^{-1}).

Batch tests were conducted, in serum bottles, to assess the anaerobic biodegradability of different concentrations of each of the size components, and a synthetic size solution.

Gas production was monitored to determine the rate and extent of biodegradation. The methane content of the biogas was determined. The efficiency of the digestion was assessed by COD reduction, which was 85 % in some of the bottles. Two of the size components (plystran and the anti-mildew agent) were found to be slightly inhibitory to the anaerobic biomass and resulted in a 2 d lag period in the degradation of the synthetic size effluent. Thus, the concentrations of these constituents, in the effluent stream, must be controlled to optimise anaerobic digestion.

Current work involves a continuous culture system, with the acclimated biomass from the batch trials, and this will be consolidated by full-scale trials in a digester, with spare capacity, at a municipal sewage works.

FINAL REPORT

ABSTRACT

An Assessment of the Feasibility of Anaerobic Digestion as a Treatment Method for High Strength or Toxic Organic Effluents.

IAWQ Specialised Conference on Chemical Process Industries and Environmental Management. Cape Town, South Africa, 8-10 September 1997.

ANNEXURE 2E

Compiled by

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Department of Chemical Engineering
University of Natal
Durban

February 1998

Report to the Water Research Commission on Project No. 762.

Head of Pollution Research Group	:	Professor C A Buckley
Principle Researcher	:	Ms J sacks

AN ASSESSMENT OF THE FEASIBILITY OF ANAEROBIC DIGESTION AS A TREATMENT METHOD FOR HIGH STRENGTH OR TOXIC ORGANIC EFFLUENTS

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ABSTRACT

The anaerobic digestion process converts organic materials into a methane-rich biogas. The KwaZulu Natal region has the potential to attract a significant amount of industry, many with high strength organic effluents. The objective of this research was to assess the feasibility of using anaerobic digestion as a treatment method for these types of effluent. A strategy was developed to evaluate the degradability and toxicity of effluents and, ultimately, predict the efficiency of treatment in a full-scale digester. This paper details the strategy and investigates the degradation potential of a textile size effluent (COD ca. 140 000 mg/l). The ultimate degradability of the effluent was determined as well as the concentrations and volumes which could be treated effectively. The inhibitory components of the size effluent were found to be Plystran (10 mg/l) and the biocide (5 mg/l). Anaerobic digestion was found to be feasible, on a laboratory-scale. These results are being applied for scale-up, to full-scale implementation in an existing anaerobic digester.

FINAL REPORT

ABSTRACT

Anaerobic Digestion of Textile Size Effluent : Laboratory and Full-Scale Trials

The Water Institute of Southern Africa (WISA) Biennial Conference, Cape Town, South Africs, 4 to 7 May 1998.

ANNEXURE 2F

Compiled by

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Department of Chemical Engineering
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February 1998

Report to the Water Research Commission on Project No. 762.

Head of Pollution Research Group : Professor C A Buckley
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ANAEROBIC DIGESTION OF TEXTILE SIZE EFFLUENT : LABORATORY AND FULL-SCALE TRIALS

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Anaerobic digestion has the potential to treat high strength or toxic organic effluents. The objectives of this research have been to identify available anaerobic digester capacity, in the KwaZulu Natal region; and to assess the feasibility of treating effluents, which are usually difficult to dispose of, in this available capacity . A laboratory-scale protocol has been developed to evaluate the efficacy of the anaerobic process for the degradation of an effluent.

Textile size effluent is a high strength organic effluent with a COD of ca. 100 000 mg/*l*. The mill producing the effluent under investigation currently tankers the effluent 40 km for marine discharge. The laboratory-scale batch tests showed that the textile size effluent was degradable. The degradability and inherent toxicity of each component of the size solution was investigated. Three concentrations of each compound were evaluated to determine the concentrations at which a component may become toxic to the anaerobic biomass. The batch tests were scaled-up to 20 *l* reactors. A control reactor was fed only primary feed sludge; a second test reactor was fed feed sludge and the textile size effluent.

Parameters were monitored to assess the performance of the reactors. Comparison between the control and test reactor indicated whether the loading of the effluent had an adverse effect on the operation of the digester and, therefore, assessed the feasibility of this treatment. This paper will discuss the results of these trials.

The laboratory digesters gave information on volumes and concentrations of the size effluent which could be treated effectively by anaerobic digestion. This information could be applied to scale-up for the ultimate treatment of the effluent in a full-scale digester. The final objective would be for the mill to implement waste minimisation and effluent segregation techniques to provide a low volume, concentrated organic effluent which would then be tankered to the nearby waste water treatment works for treatment in the available anaerobic digester capacity.

FINAL REPORT

ABSTRACT

Treatment of High Strength or Toxic Organic Effluents in the Anaerobic Baffled Reactor (ABR)

The Water Institute of Southern Africa (WISA) Biennial Conference, Cape Town, South Africs. 4 to 7 May 1998.

ANNEXURE 2G

Compiled by

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Department of Chemical Engineering
University of Natal
Durban

February 1998

Report to the Water Research Commission on Project No. 762.

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TREATMENT OF HIGH STRENGTH OR TOXIC ORGANIC EFFLUENTS IN THE ANAEROBIC BAFFLED REACTOR (ABR)

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The predicted high industrial growth rate in South Africa, coupled with the limited water resources will necessitate the implementation of advanced and sophisticated effluent treatment systems. One of the classes of effluents that will be particularly problematic are the organic effluents arising from the agro-industrial, food and beverage, textile and fine chemical sectors. Some of the effluents may contain xenobiotics, which could be toxic. The objective of this research is to investigate the applicability of anaerobic digestion, in the anaerobic baffled reactor (ABR), for the treatment of very high strength organic industrial liquid effluents, or toxic organic liquid effluents. The ABR is well suited to intermittent high organic or hydraulic loads as it separates the hydraulic retention time from the solids retention time.

Laboratory-scale investigations have determined the efficiency of the ABR for treatment of these waste streams. Fundamental research will be done such as the investigation of the composition and dynamics of the microbial population based on molecular probes and sequencing. Methods for optimal degradation will be evaluated by investigating the production and degradability of soluble microbial product produced in the ABR. Design criteria will be optimised depending on effluent characteristics and subsequent population dynamics. Scale-up of the digester will be investigated.

The contribution that this research will make is significant as it will promote the development of new industries in South Africa with an emphasis on waste minimisation and pollution prevention.

FINAL REPORT

ABSTRACT

ANAEROBIC DIGESTION OF A TEXTILE SIZE EFFLUENT

IAWQ Fourth International Symposium on Waste Management Problems in Agro-Industries. Istanbul, Turkey. 23 to 25 September 1998.

ANNEXURE 2H

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February 1998

Report to the Water Research Commission on Project No. 762.

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ANAEROBIC DIGESTION OF A TEXTILE SIZE EFFLUENT

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Anaerobic digestion has the potential to treat high-strength or toxic organic effluents. The objective of this research was to identify available anaerobic digester capacity, in the KwaZulu-Natal region and to assess the feasibility of treating effluents, which are usually difficult to dispose of, in the available capacity. A laboratory-scale protocol was developed to evaluate the efficacy of the anaerobic process for the degradation of a textile size effluent.

Textile size is a high-strength organic solution with a COD of ca. 100 000 mg/l. The effluent produced by the textile mill under investigation was tankered approximately 40 km for marine discharge. Laboratory-scale serum bottle tests were performed to assess the anaerobic degradability and potential toxicity of the size solution. Investigation of the individual components of the size solution identified those that were potentially inhibitory and the concentrations at which they would inhibit the anaerobic biomass. These included: PVA, which became inhibitory at concentrations > 30 g/l; Plystran, at concentrations > 10 g/l; acrylic, at concentrations > 4 g/l; and biocide which became inhibitory at concentrations > 0.5 mg/l and toxic at a concentration of 50 mg/l. Investigation of the synthetic size solution showed that it was degraded by the anaerobic digester biomass although the tests suggested that the system could become overloaded at high size concentrations. This verified the importance of the screening tests prior to loading into a digester to prevent digester failure. The ability of anaerobic microorganisms to acclimate to inhibitory substrates was demonstrated by the enrichment tests. The biomass was acclimated to the inhibitory components of the size solution. The acclimated biomass was able to degrade the substrate at a concentration that had previously been inhibitory, the lag period was reduced and the degradation rate increased.

Available anaerobic digester capacity was identified at the Umbilo Sewage Purification Works (located 10 km from the textile mill). The flow-rates to the anaerobic digesters were low which indicated available hydraulic capacity. The organic load to the digesters was low. They were well mixed and heated, therefore they had the ability to accept an organic load of ca. 3 kg VS/m^3.d. The digesters were only fed an average of 1.12 kg VS/m^3.d; there was available organic capacity. The mixing efficiency and flow distribution within the digesters was assessed by a tracer test.

The results of these tests allowed for the prediction of the efficacy of treatment in a full-scale digester. This investigation identified and verified the potential for treatment of the textile size solution in available anaerobic digester capacity.

Other related WRC reports available:

Waste minimisation guide for the textile industry: A step towards cleaner production. Vol I

Barclay SJ; Buckley CA

In its development during the project, the Guide was drafted (in a somewhat different format compared to the final version), peer-reviewed by a range of parties actively involved with the environmental performance of the textile industry in the RSA, field-tested by students carrying out water and effluent surveys in the industry, and has thus undergone thorough evaluation during its development.

The Guide has been found to be a useful tool for assisting the RSA textile industry to improve its environmental performance in the following areas of application:

- The textile industry can use the Guide to self-assess and improve its implementation of waste minimisation practices and, hence, its aquatic environmental performance
- Similarly, use of the Guide will assist factories in achieving compliance with environmental management standards e.g. 1S0 14000, and, thereby, improving their international competitiveness
- Local regulatory authorities can use the Guide both as a training tool and as a management tool for monitoring and assessing the performance of textile manufacturers in their area of jurisdiction.

A key feature of the Guide is the comprehensive set of work-sheets, which provide a structured basis for establishing essential information regarding water use, effluent generation and process-related data such as chemicals and energy use. In achieving the final Guide format, the assistance of the Danish Technical Institute, and particularly Prof H Wenzel who voluntarily contributed many days of editorial and re-drafting input, is gratefully acknowledged. Follow-up activities stimulated by the project include the DANCED project to promote cleaner production in the RSA textile industry commencing in 2000, in which the guide will be used for technology transfer and training.

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