Anaerobic treatment of industrial effluents in South Africa*

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Abstract

Biodegradable industrial effluents are generally best treated by anaerobic digestion. The main advantages of the anaerobic process are higher load rates and degree of purification, lower energy costs due to biogas production and lower surplus sludge production in comparison with aerobic treatment. This paper describes the successful operation of various full-scale plants in South Africa for the treatment of maize-processing, wine distillery, abattoir, brewery and apple-processing wastes.

Introduction

Concentrated organic industrial wastes such as distillery effluents and wastes resulting from the manufacture of various foodstuffs generally create serious treatment or disposal problems for the industry or local authority concerned because of their high organic load. These wastes are normally soluble or colloidal and have chemical oxygen demand (COD) concentrations varying from 2 to 200 g. ℓ^{-1} as compared to domestic sewage with a COD value of less than 1 g.ℓ^{-1}. Effluents of this type are thus reluctantly received into communal sewers by the controlling authority and the manufacturer is faced with heavy trade-effluent charges. Investigations by numerous researchers have shown that these effluents can seldom be treated satisfactorily by aerobic methods such as the activated sludge or biological filtration process because they require excessive dilution to render them amenable to aerobic breakdown. Moreover, rising energy costs make aerobic treatment increasingly expensive.

The feasibility of treating industrial waste waters by anaerobic digestion was recognised and extensive research into the fundamental aspects was undertaken by the Division of Water Technology (Toerien and Hattingh, 1969; Kotze *et al.*, 1969; Pretorius, 1969). In collaboration with various municipalities, a parallel programme of technological research with full-scale plants for the anaerobic digestion of effluents arising from glucose-starch manufacture (Hemens *et al.*, 1962) and wine distillery waste (Stander *et al.*, 1968) was successfully carried out. These full-scale plants were constructed in the early sixties and are still being operated by normal sewage works personnel.

This paper reviews the current situation in South Africa regarding the full-scale anaerobic digestion of industrial effluents, as summarised in Table 1 and Fig. 1.

Treatment of maize-processing waste at Bellville

Industrial waste arising from the manufacture of glucose and starch from maize is being treated in a full-scale upflow clarigester plant at the Bellville sewage works (Hemens *et al.*, 1962; Faber *et al.*, 1986). The plant was modified for this purpose in 1961 and comprises three identical clarigesters with a total capacity of 3 000 m^3. The average factory flow is 500 $m^3.d^{-1}$ with a mean unfiltered COD concentration of 7,2 $kg.m^{-3}$. A noteworthy feature of the plant is the good settling and thickening properties of the pelletised sludge. The nature and formation of this sludge have been studied and described by Ross (1984).

Waste-water characteristics

The factory (African Products) from which the waste water arises processes maize for the manufacture of corn flour and a wide range of starches, dextrins, glucose syrups and by-products such as maize gluten (20 to 60% protein content) and maize germ oil (54% oil mass). The composition of the effluent discharged to the clarigester plant varies according to processing conditions but in general consists of small quantities of soluble inorganic matter, protein, amino acids and other nitrogenous substances, lactic acid, carbohydrates and also finely divided solids such as starch, gluten, fibre and powdered activated carbon. The quality of the waste water is such that it can be anaerobically treated without additional supply of nutrients or buffer capacity.

An analysis of the waste water is presented in Table 2. About 80 per cent of the total chemical oxygen demand (COD) of the raw waste is soluble. However, some 50 per cent of the soluble COD cannot be identified by conventional liquid chromatography. Volatile fatty acids constitute a very low percentage of the COD in this instance.

The presence of heterogenous-polymeric material in the soluble raw feed was verified by precipitation with 2 volumes ethanol per 1 volume feed, according to the method of Forster (1971). Chemical analyses of the precipitated polymer revealed that the organic fraction (52%) was mainly composed of a carbohydrate and a protein. The molecular mass of the feed polymer was found to be as high as two million. The possible role that this polymer plays in the pelletisation process is being investigated.

Plant description

The present plant was originally designed for the treatment of raw sewage. In its original form each Dorr-Oliver clarigester consisted of a top compartment for settling of sewage with an inlet at the centre and a circumferential outlet weir. This settling compartment was separated from the bottom digester compartment by a diaphragm. The settled sludge was transferred from the top compartment to the bottom compartment by a scraper system.

The system was modified in 1960 by the removal of the original inlet and provision of a new bottom inlet into the bottom compartment, thus reversing the flow and creating an upflow anaerobic

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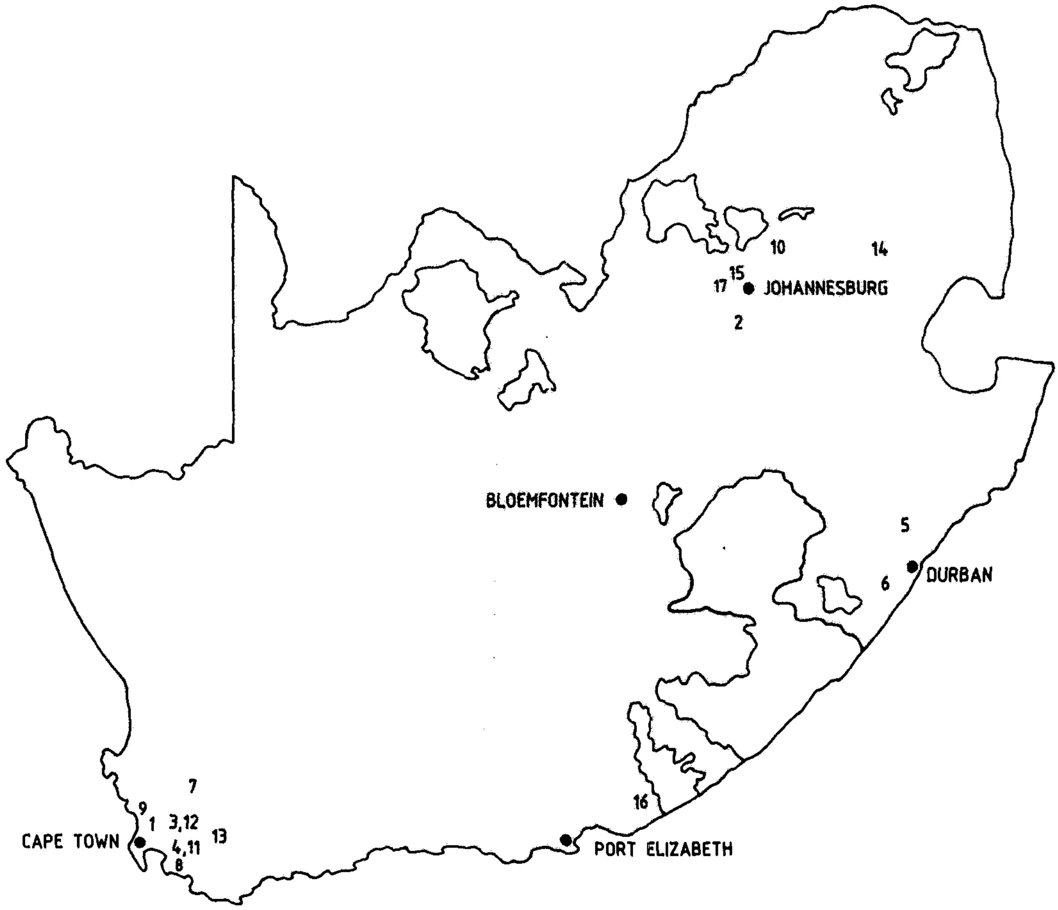
TABLE 1

FULL-SCALE ANAEROBIC DIGESTION PLANTS IN SOUTH AFRICA TREATING INDUSTRIAL WASTES (1988*)

Type of waste water	Location of plant	Type of plant and start-up	Waste-water flow ($m^3.d^{-1}$)	Waste-water COD ($kg.m^{-3}$)	Digestion capacity (m^3)	Clarifier capacity (m^3)	Total capacity of plant (m^3)	Digester space load rate (kg COD. $m^{-3}.d^{-1}$)	Sludge load rate (kg COD. kg $VSS^{-1}.d^{-1}$)	Digester temp. (°C)	Digester retention time (days)
Maize processing	Bellville sewage works	Clarigester (1961)	500	7,2	1 878	1 112	3 000	2,0	0,06	20	3,7
Maize processing	African Products, Meyerton	Clarigester (1968)	550	4,0	5 350	1 175	6 525	0,5	0,05	31	7,7
Wine distillery	Paarl sewage works	Clarigester (1962) Contact (1972)	180	30,5	1 745	800	2 545	3,2	0,30	35	9,7
Wine distillery	Stellenbosch sewage works	Contact (1974)	150	31,0	1 890	530	2 420	2,5	0,20	35	12,6
Abattoir	Cato Ridge abattoir	Contact (1979)	1 720	3,4	5 970	3 040	8 770	1,0	0,09	22	3,3
Beer brewery	S A Breweries, Prospecton	UASB (1985)	2 600	3,1	1 480	220	1 700	5,4	1,00	35	0,7
Apple processing	Ceres Fruit Growers, Ceres	UASB (1988)	430	5,0	-	-	525	4,1	-	35	1,2
Apple processing	Appletiser Pure Fruit Juices, Grabouw	Anaerobic pond (1987)	5 000	2,0	-	-	8 000	2,5	-	15	0,8

*Four further full-scale plants were under construction during 1988/1989 for the treatment of beer brewery, abattoir, petrochemical and egg processing wastes



FULL-SCALE PLANTS

NO.	TYPE OF WASTE	LOCATION
1	Maize processing	Bellville
2	Maize processing	Meyerton
3	Wine distillery	Paarl
4	Wine distillery	Stellenbosch
5	Abattoir	Cato Ridge
6	Beer brewery	Prospecton
7	Apple processing	Ceres
8	Apple processing	Grabouw

PILOT-SCALE PLANTS

NO.	TYPE OF WASTE	LOCATION
9	Paper processing	Milnerton
10	Paper processing	Rosslyn
11	Wine distillery	Stellenbosch
12	Wine distillery	Paarl
13	Fruit processing	Kraaifontein
14	Petrochemical	Secunda
15	Yeast	Johannesburg
16	Tannery	Grahamstown
17	Mine drainage	Krugersdorp

Figure 1
Location of full-scale and pilot-scale anaerobic digestion plants in South Africa treating industrial waste (1988)

digester incorporating a settling stage. The scraper system was retained to transfer the settled sludge back to the digester compartment.

A simplified section through the modified clarigester is shown in Fig. 2. The plant consists of three identical unheated and mechanically unmixed clarigesters, each with a digester and clarifier capacity of 623 m^3 and 374 m^3, respectively. The total capacity of the clarigester plant is thus some 3 000 m^3. A measure of insulation is obtained by the fact that the plant is underground. The operating temperature of the clarigesters is in the range 15 to 25°C and is determined mainly by the temperature of the incoming flow.

Flow from the clarigesters is diverted to two trickling filters for polishing prior to discharge to maturation ponds (Fig. 3).

TABLE 2
ANALYSIS OF MAIZE PROCESSING WASTE (1976-1984)

Parameter	Mean	Maximum	Minimum	Standard deviation
Daily flow (m^3/d)	454	1 253	41	215
pH	4,36	9,99	3,30	0,82
COD unfiltered (mg/ℓ)	6 690	98 960	1 100	5 812
COD filtered (mg/ℓ)	5 423	72 920	830	4 547
Dissolved solids (mg/ℓ)	4 793	69 220	570	4 218
Total solids (mg/ℓ)	5 723	72 550	800	4 496
Conductivity (μS/cm)	1 463	7 330	300	812

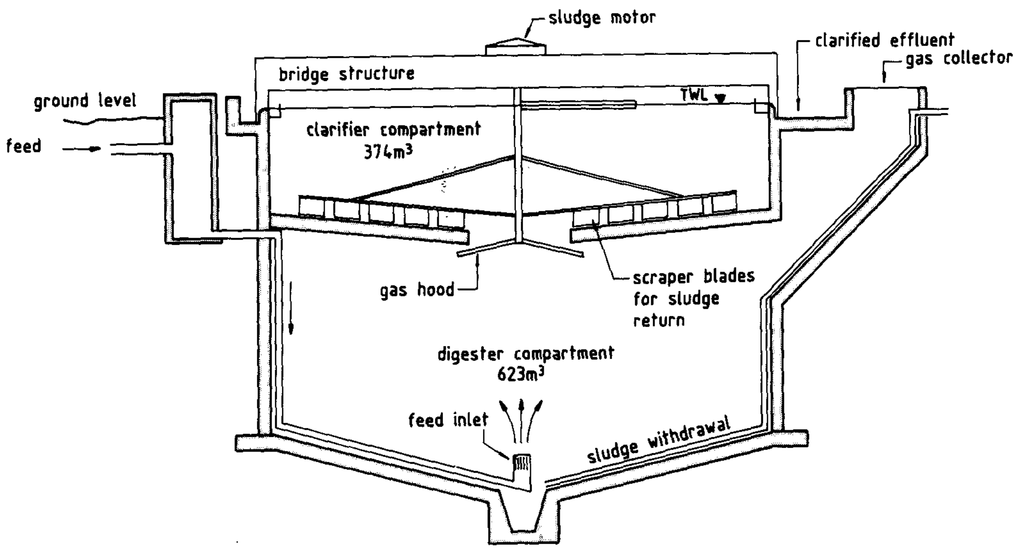


Figure 2
Reverse flow clarigester for treatment of maize processing waste at Bellville sewage works

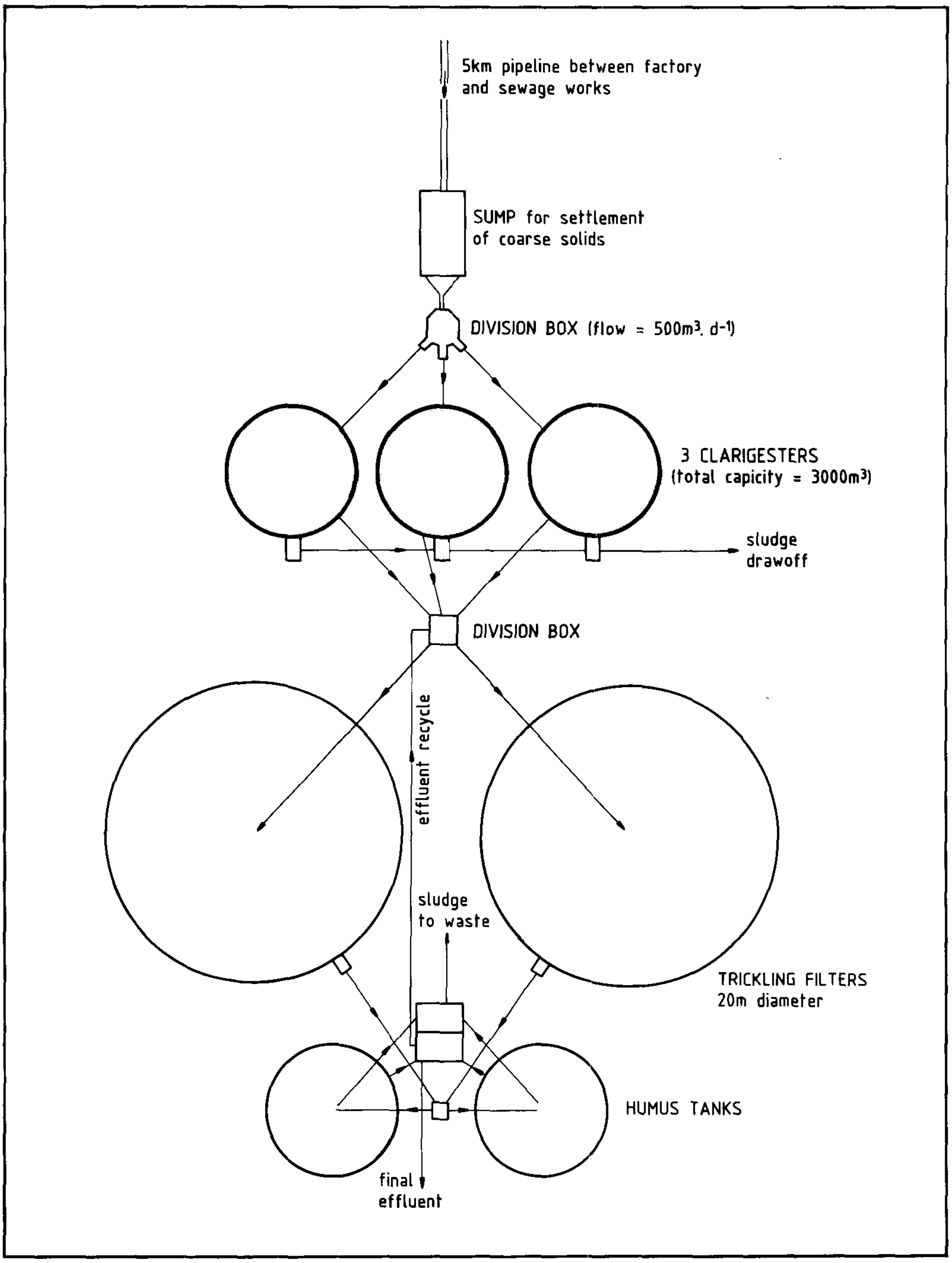


Figure 3
Layout of anaerobic digestion plant for treatment of maize processing waste at Bellville sewage works (Faber et al., 1986)

Plant performance

The operating conditions of the digester compartment are listed in Table 3. Due to production schedules the waste water discharged to the clarigesters is subject tot wide day-to-day fluctuation as regards both volume and organic strength. For example, the flow rate and COD concentration can vary in the range 400 to 1 300 $m^3.d^{-1}$ and 1 to 100 $kg.m^{-3}$, respectively. The digester compartment is operated at very low mean loading rates of some 2 kg COD. $m^{-3}.d^{-1}$. This, however, provides greatly increased capability to accommodate the high loading-rate variations encountered. Shock-loading problems are seldom experienced. It should also be realised that the feed is not well distributed with the result that the load rate in proximity to the feed inlet is significantly higher than in other parts of the reactor. The average COD reduction by the clarigesters is approximately 96 per cent. After trickling-filtration the final COD is 70 $mg.\ell^{-1}$ and lower.

TABLE 3
PERFORMANCE OF ANAEROBIC PLANT TREATING MAIZE PROCESSING WASTE AT BELLVILLE (1976-1984)

Parameter	Mean	Maximum	Minimum	Standard deviation
Space loading rate (kg COD.$m^{-3}.d^{-1}$)	1,92	15,99	0,41	1,45
Sludge loading rate (kg COD.kg $VSS^{-1}.d^{-1}$)	0,06	0,51	0,01	0,05
Hydraulic retention time (days)	4,12	45,59	1,42	1,33
Temperature (°C)	-	25	15	-
COD of digester effluent (kg.m^{-3})	0,24	0,98	0,04	0,22
SS of digester effluent (kg.m^{-3})	0,115	0,470	0,015	0,128
pH of digester effluent	6,8	7,6	6,3	0,22

A pilot-scale UASB type reactor of 4,3 m^3 total capacity was commissioned adjacent to the full-scale plant in order to study the sludge pelletisation process in more detail, and specifically at higher load rates. The major differences in the mode of operation of the two plants was that the feed to the pilot plant was better distributed and was preheated to 35°C. Satisfactory treatment efficiency was obtained at digester space load rates and hydraulic retention times of 10 to 20 kg COD. $m^{-3}.d^{-1}$ and 0,4 d respectively. This was significantly higher than that maintained on the full-scale plant, and was due to the improved design of the plant.

Pellet sludge characteristics

Of particular interest and significance is the pelletisation or granulation phenomenon which has been achieved in the clarigester plant (Ross, 1984). The suspended solids concentration in the digester compartment is approximately 45 kg. m^{-3} with some 90 per cent of this being volatile solids. The spherically shaped pellets obtained from the clarigesters vary in size from large granules (7 mm) to very fine particles. The periphery of the pellet surface is well defined and no filaments extend beyond the surface as is the case with most sludge flocs.

The solids flux method was used to determine the settling zone throughput capacity and the thickening characteristics of the maize processing pellet sludge. A typical solids flux curve (Fig. 4) for this sludge recorded a maximum solids flux value of 4 500 kg. $m^{-2}.d^{-1}$ suspended solids. The flux curve predicted a potential flux thickening to a concentration of some 90 kg. m^{-3} suspended solids. The stirred sludge volume index on the same sludge recorded a value of 11 $m\ell.g^{-1}$ at 60 $g.\ell^{-1}$ SS. The results of settling tests established that the rate of settling varied in the range 60 $m.h^{-1}$ for the fastest pellets to 6 $m.h^{-1}$ for the bulk of the slowest particles.

Various chemical analyses of the pellets are presented in Table 4. Crude protein was found to constitute the major fraction of the sludge (66 per cent) on a dry mass basis. Sludge extracellular polymers (ECP) were extracted from the washed pellets by boiling at a neutral pH for 1 h followed by centrifugation and precipitation with 2 volumes ethanol per 1 volume centrate. The yield of ECP by this method amounted to some 4 per cent of the suspended solids, dry mass. Of particular interest is the fact that a fraction of both the soluble polymer in the maize processing waste feed and the ECP which was bound to the pellet sludge surface have the same molecular mass, namely 2 million.

Based on microbiological and chemical data it would appear that the clumping of bacteria to form pellets is based on complex interactions of high molecular mass ECP. These polymers may be present in the feed substrate from the maize processing factory (feed polymers) but are normally synthesised by bacteria from simple precursor molecules during metabolism of the waste (biopolymers). The naturally produced insoluble polymers bond electrostatically or physically and subsequently bridge the bacterial cells and other particulate materials into a multicomponent matrix of sufficient magnitude (1 to 7mm) to settle as floc aggregates. Transmission and scanning electron micrographs show certain of the bacteria surrounded by very dense capsules while other cells are interwoven by a network of fibrous strands which appear to be extensions of the capsules and maintain cohesion of the pellet.

The slime and the capsular material constituting the ECP was shown by staining techniques and chemical analysis to consist of polysaccharides and proteins. Agglutination of bacteria is generally also due to the interaction between a polysaccharide and a protein, while these organics furthermore constitute the major fraction of the COD of the maize processing waste under study. The research identified the protein fraction (gluten) of the maize-processing waste as being an important precursor substance for accelleration of the pelletisation reaction.

Costs

Experience with this waste has shown that modified clarigesters operate very satisfactorily without requiring regular attention and without recourse to sophisticated equipment and highly skilled personnel. Other than periodic routine analysis of the influent and effluent by laboratory staff, no process control or monitoring is carried out.

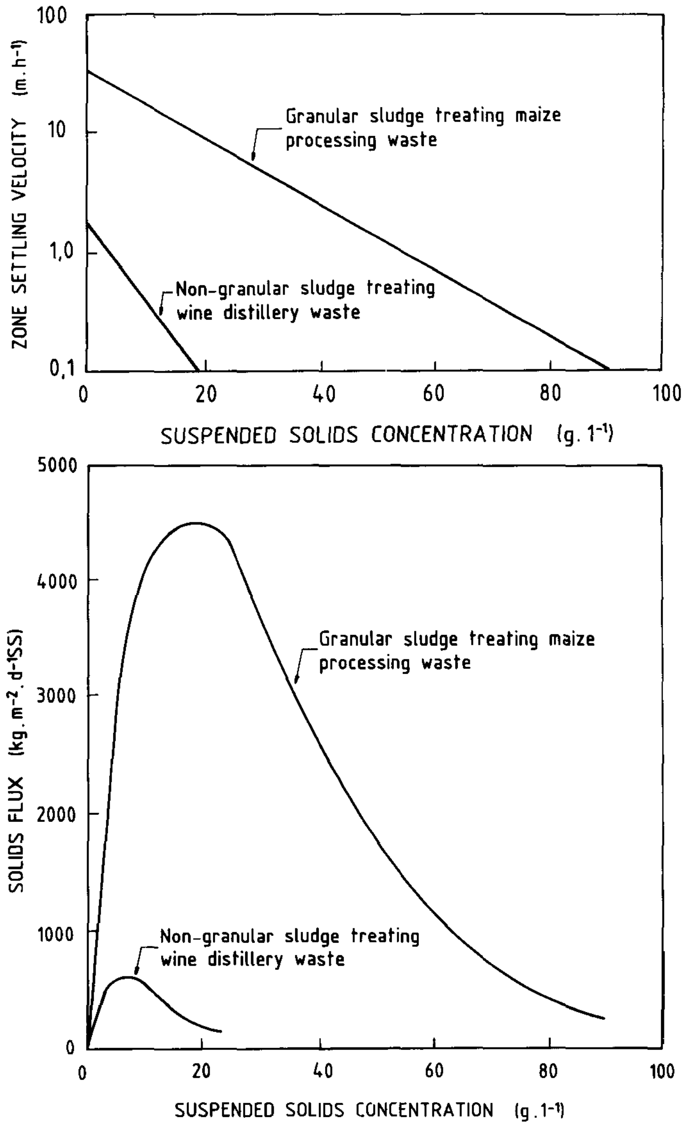


Figure 4
Comparison of settling characteristics and solids flux curves of anaerobic sludges treating different industrial wastes

The clarigesters are underground concrete structures and maintenance is limited to the painting of steelwork, e.g. handrails and the servicing of small electric motors, electrical equipment and gearboxes. Apart from routine inspections and maintenance done on the equipment, this plant is left unattended without detriment to its performance, making the process very attractive from the operational standpoint.

Since this plant is thirty-seven years old and has thus greatly exceeded its intended service life, capital operating costs may be said to be nil. In 1986 the cost of operating and maintaining the plant including the trickling filters was roughly R12 000 per annum. In terms of volume of effluent treated and amount of COD removed the unit costs are 7,24 cents per m^3 of effluent treated and 1,12 cents per kg of COD removed. By comparison, the industrial effluent tariff of this type of waste would amount to some 25 cents per m^3, confirming the advantageous cost-efficiency of the plant (Faber *et al.*, 1986).

Treatment of maize processing waste at Meyerton

The treatment of a maize processing waste is also being carried out at the Meyerton mill of Messrs. African Products. The plant consisting of 5 clarigesters with a total capacity of 6 525 m^3 (Table 1) was commissioned in 1968. The design is similar to that of the Bellville plant and each clarigester has a digestion and clarifier capacity of 1 070 m^3 and 235 m^3 respectively. On average the factory flow is 550 $m^3.d^{-1}$ with a COD value of 4 $kg.m^{-3}$. This results in a digester space load rate of 0,5 kg $COD.m^{-3}.d^{-1}$ and the plant is currently underloaded. The digesters are below ground level and no mechanical mixing or heating is applied. The anaerobically treated effluent is polished by means of biological filters and a maturation pond and then disposed of on-site by irrigation of lucerne.

Pellet sludges have not formed on this plant, as was the case in Bellville; the reasons for this are uncertain. A possible explanation could be certain differences in the chemical composition of the factory waste water. For example, the gluten fraction of the Meyerton waste has not been discharged to the anaerobic plant but has been

TABLE 4
CHEMICAL CHARACTERISTICS OF SLUDGE PELLETS TREATING A MAIZE PROCESSING WASTE

Parameters	Percentage concentration (dry mass basis)
Organic content	90
Inorganic content	10
Nitrogen content	11
Crude protein	66
Total carbohydrate	11
Yield of ECP material	4
Molecular mass of polymer	2 x 10^6

evaporated with the steep liquor. The Meyerton mill also produces more oxidised starches while the effluent has a higher salt loading due to regeneration chemicals from ion exchange processes used in the mill (Hugo, 1988).

Treatment of wine distillery waste at Paarl

Anaerobic digestion provides an effective and economical treatment of wine distillery waste which, having a pH of less than 4,5 and a COD value varying between 25 and 40 $kg.m^{-3}$, cannot be treated sensibly in an aerobic process. Wine distillery waste has been treated anaerobically at the Paarl sewage works since 1962 (Stander *et al.*, 1968). The present plant comprises one modified clarigester and two contact-type digester/clarifiers with a total capacity of 2 545 m^3. The treated through amounts to some 180 $m^3.d^{-1}$. During the six-month distillation season a total volume of 22 000 m^3 of waste is received at the sewage works, representing a total load of 770 t COD to be digested.

Waste-water characteristics

Wine distillery waste, the residue left from the distillation of wine, contains residual organic acids, soluble proteins and carbohydrates and various inorganic compounds. A typical analysis of the waste is given in Table 5. The macro-nutrients nitrogen and phosphorus are present in relative abundance and the trace elements required for metabolism should be sufficient. Digesters treating this waste (total cations of 160 $me.\ell^{-1}$) develop an alkalinity of 6 000 $mg.\ell^{-1}$

TABLE 5
TYPICAL ANALYSIS OF WINE DISTILLERY WASTE

Parameter (mg/ℓ)	Concentration
pH	4,0
COD	35 000
Total solids	18 000
Kjeldahl-N	350
Ammonia-N	10
Nitrate-N	1
Nitrite-N	1
Total-P	150
Ortho-P	130
K	3 000
Na	75
Ca	410
Mg	160
Fe	15
Cu	2
Al	3
Cl	160
SO_4	150
Co	0,6
Ni	0,4
Sr	0,1
Mn	2,3

TABLE 6
PERFORMANCE DATA FOR ANAEROBIC DIGESTION OF WINE DISTILLERY WASTE AT PAARL : 1986 SEASON

Parameters	Digester 1	Digester 2	Clarigester 3
Digester volume (m^3)	545	545	655
Clarifier volume (m^3)	200	200	400
Digester temperature (°C)	36,0	35,2	30,8
Feed rate ($m^3.d^{-1}$)	37,7	37,7	41,5
COD of feed ($kg.m^{-3}$)	33,7	33,7	33,7
Hydraulic retention time (days)	14,4	14,4	15,8
COD loading (kg $COD.d^{-1}$)	1 273	1 273	1 399
Suspended solids-composite ($kg.m^{-3}$)	21,3	18,9	22,4
Volatile suspended solids ($kg.m^{-3}$)	17,2	15,4	17,3
VSS as % of SS	80,5	81,2	77,4
Sludge mass (kg VSS)	9 352	8 371	11 358
Sludge load rate (kg COD.kg $VSS^{-1}.d^{-1}$)	0,136	0,152	0,123
Space load rate (kg $COD.m^{-3}.d^{-1}$)	2,34	2,34	2,14
Volatile acids ($mg.\ell^{-1}$ CH_3COOH)	90	85	84
Alkalinity ($mg.\ell^{-1}$ $CaCO_3$)	4 850	4 410	4 170
COD of final effluent ($kg.m^{-3}$)	0,86	0,83	0,69
COD removal (%)	97,5	97,6	97,6
SS of final effluent ($kg.m^{-3}$)	0,4	0,4	0,4
pH of feed	4,3	4,3	4,3
pH of final effluent	7,5	7,5	7,5

$CaCO_3$. This is due to the high potassium bitartrate concentration and consequent release of potassium ions, available for buffering during digestion.

Plant description

A layout of the Paarl anaerobic plant is illustrated in Fig. 5 (Heunis, 1986). The clarigester has digestion and clarifier capacities of 655 m^3 and 400 m^3 respectively. Two identical digesters (545 m^3 each), each with a 200 m^3 clarifier were modified to suit the requirements for wine distillery waste treatment. The waste from the distillery is stored in a 1 000 m^3 balancing tank which ensures an average COD concentration of about 30,5 $kg.m^{-3}$ to the digesters.

The twin digesters are equipped with mechanical stirrers and proper mixing of the contents is obtained by sludge recirculation at a rate of 300 $m^3.d^{-1}$, drawing from the top and injecting at the bottom of the digester. Efficient mixing of the wine distillery waste feed with the digester contents is likewise effected by injecting the feed into the sludge recirculation lines.

Heating of the digesters is done by hot water tubes spiralling on the inside of the digester walls, thus preventing local overheating of the mixed liquor. Biogas from the digesters is used as the main heat source of the hot water boilers. An average gas yield of 16 m^3 per m^3 waste fed, is obtained.

Plant performance

The performance of the twin digesters and the clarigester for 1986 is illustrated in Table 6 which indicates the type of routine monitoring carried out. Operation of the plant for 26 years has shown that once the domestic sewage sludge has been acclimatised no further additions are necessary. Indeed the plant is shut down completely at the end of each season and restored by gradually increasing the feed as the sludge is reactivated. Volatile fatty acids may initially be as high as 1 500 $mg.\ell^{-1}$, but decrease rapidly to below 200 $mg.\ell^{-1}$. A basic prerequisite is that the alkalinity should remain above 3 000 $mg.\ell^{-1}$. Under these conditions a pH of 7,0 to 7,4 is easily maintained in the digester.

It has further been found that when a digester temperature above 30°C is maintained (ideally 35°C), a digester space load rate of 3,2 kg $COD.m^{-3}.d^{-1}$ with a concomitant sludge load rate of 0,3 kg $COD.kg\ VSS^{-1}.d^{-1}$ can be obtained. The reduction in COD concentration of the waste averages 97,5 per cent. The effluent can further be treated by the conventional sewage purification works without deleterious effects. Operation and control of the anaerobic plant by normal treatment works personnel present no problems.

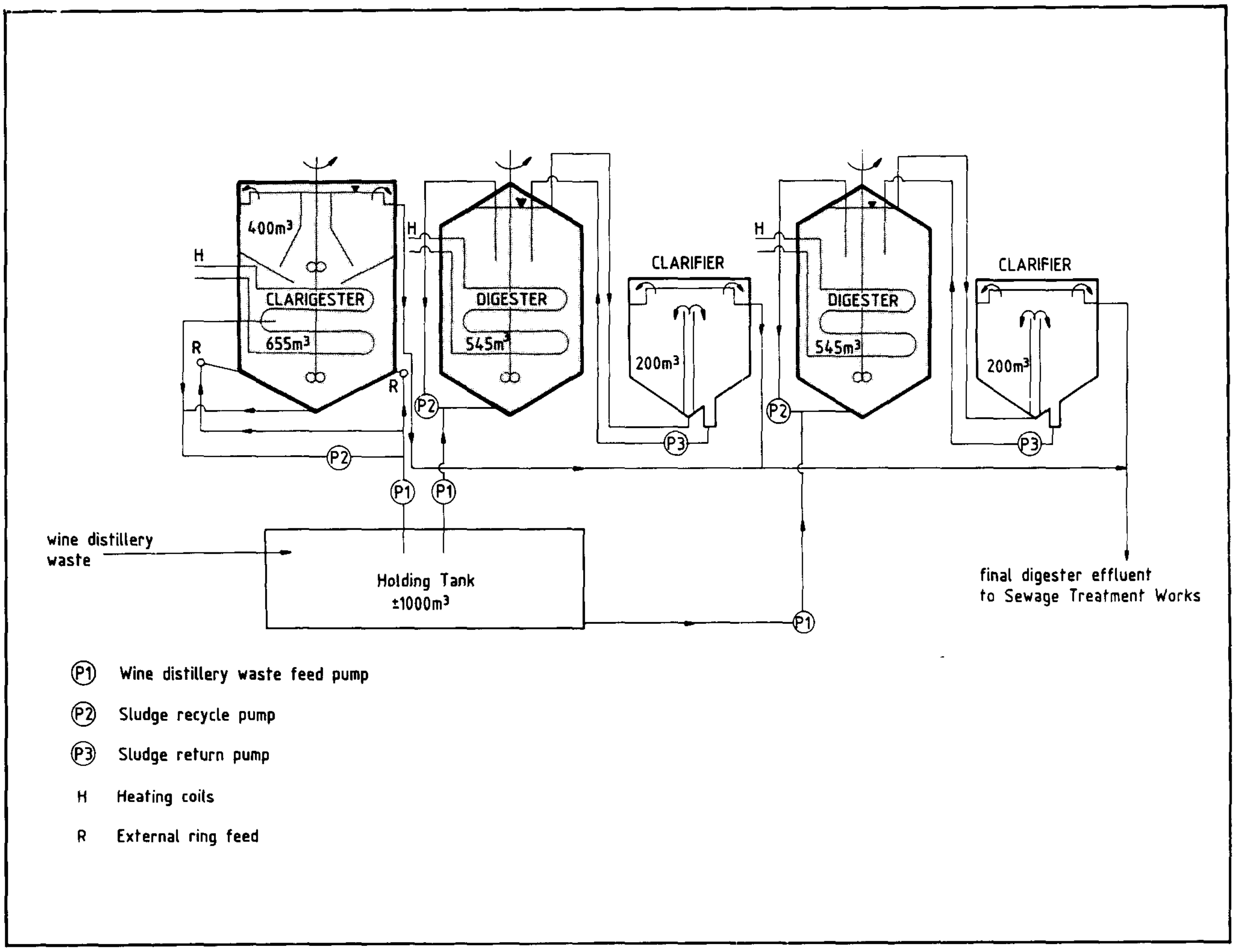


Figure 5
Layout of anaerobic digestion plant for treatment of wine distillery waste at Paarl sewage works (Heunis, 1986)

Wine distillery waste has poor settling properties owing to its diffuse (non-granular) and somewhat filamentous nature. A typical solids flux curve (Fig. 4) for this sludge recorded a maximum solids flux value of only 300 kg.m^{-3}.d^{-1} SS (Ross *et al.*, 1981). Experience has shown that settling and retention of this sludge become problematical at load rates above 4 kg COD. m^{-3}.d^{-1} as a result of residual gasification and consequent rise in the clarifier compartment. A digester : clarifier ratio of 1:0,37 is regarded as necessary for the load rates as applied at Paarl. The suspended solids in the digester outflow of 14 to 17 kg.m^{-3} are settled and thickened to 40 to 45 kg.m^{-3} before being returned to the digester (30 m^{-3}.d^{-1}). Very little sludge is lost in the treated effluent from the plant and no sludge is otherwise wasted.

Treatment costs

These are reflected in Table 7 for the year 1985 (Heunis, 1986). The anaerobic process renders a cost of R1.47 per m^3 treated or 4,85 cent per kg COD, confirming the economic viability of the system. It should also be stressed that the plant is less than 50 per cent utilised because of the seasonal nature of the waste.

TABLE 8
PERFORMANCE DATA FOR ANAEROBIC DIGESTION OF RUM DISTILLERY WASTE AT STELLENBOSCH

Parameters	Value
COD of feed (kg.m^{-3})	174
COD of digester effluent (kg.m^{-3})	4,8
Digester VSS concentration (kg.m^{-3})	13,8
Sludge load rate (kg COD.kg VSS^{-1}.d^{-1})	0,45
Space load rate (kg COD.m^{-3}.d^{-1})	6,6
Hydraulic retention time (days)	26
Gas volume/feed volume ratio	80
Volatile acids in digester (mg.ℓ$^{-1}$ CH_3COOH)	96

Treatment of wine distillery waste at Stellenbosch

The anaerobic digestion process for the treatment of wine distillery waste has also been applied at the Stellenbosch sewage works since 1974. The plant comprises two conventional digesters, each of 945 m^3 capacity, with phase separation of solids in one suction-lift clarifier of 530 m^3 capacity. Good mixing in the digesters is achieved by means of impeller draught tubes and gas recirculation using lances. Temperature control to 35°C is by steam heating of the incoming feed. The biogas is used as fuel for the boilers. The performance of the Stellenbosch plant has been similar to that of the Paarl plant (Refer Table 1) in terms of load rates and degree of purification. On average, the plant treats 150 m^3.d^{-1} over the five-month distilling season.

Trials have also been carried out to determine the amenability of rum distillery effluent to treatment by sludge acclimatised to a feed of wine distillery waste (Ross *et al.*, 1981). The rum effluent was derived from molasses fermentation and was a soluble waste with a COD varying between 170 and 270 kg. m^{-3}. Digester operation with rum waste was carried out over a period of 13 weeks and the experiment proved a success. Various performance parameters over this period are summarised in Table 8. Unfortunately the production of rum has in the interim been discontinued and the waste is no longer available. The main advantages of such an integrated treatment scheme would be the maintenance of digester activity throughout the year and a reduction in overall treatment cost.

Treatment of abattoir waste at Cato Ridge

The South African Abattoir Corporation commissioned a regional abattoir at Cato Ridge in 1979. The effluent from the abattoir is required to comply with the General Standards for discharge into a river. Both anaerobic and aerobic biological treatment are being

TABLE 7
TREATMENT COST FOR ANAEROBIC DIGESTION OF WINE DISTILLERY WASTE AT PAARL : 1985

Parameter	Value
Annual flow (m^3)	22 274
Average COD (kg.m^{-3})	30,4
Annual COD load (kg per annum)	677 130
Annual cost (in Rand): Operating	4 569
Equipment	15 874
Structures	12 375
Total	32 818
Unit cost in : Cents per m^3 treated	147
Cents per kg COD removed	4,85

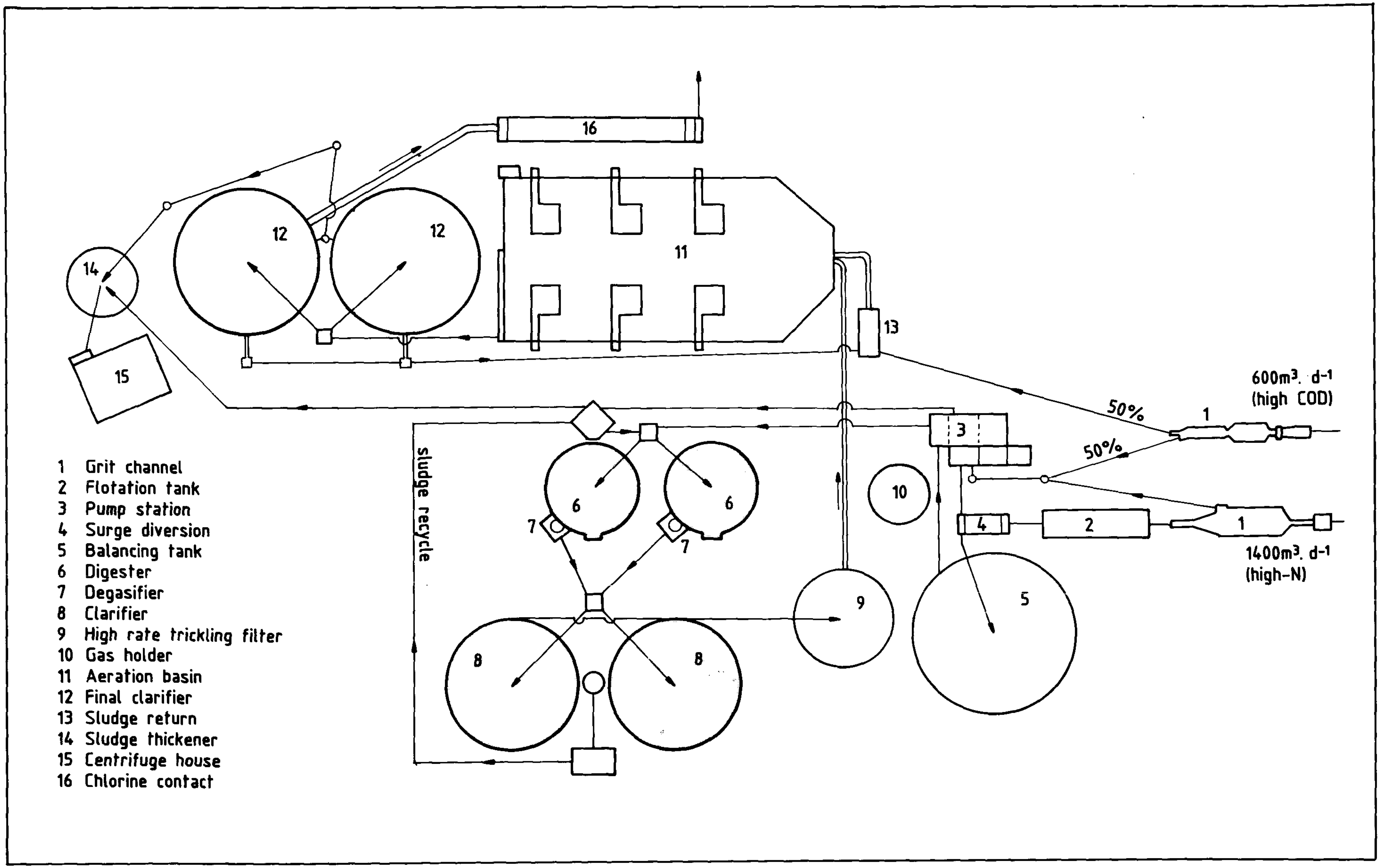


Figure 6
Layout of anaerobic digestion plant for treatment of abattoir waste at Cato Ridge (Barnard, 1986)

applied in order to achieve the required degree of purification. The anaerobic treatment plant is of the contact-type and comprises two digesters with a total capacity of 5 730 m^3 followed by sludge separation in two clarifiers with a total capacity of 3 040 m^3. Current average abattoir flow is 1 720 $m^3.d^{-1}$ with a mean COD concentration of 3,4 $kg.m^{-3}$. A noteworthy feature of the plant is vacuum degasification of the digester sludge to improve settlability thereof in the clarifiers (Barnard, 1986).

Waste-water characteristics

The waste-water treatment plant was designed to process the abattoir effluent arising from the slaughtering of 1 450 head of cattle, 7 250 sheep and 800 pigs per day. The abattoir is operated 5 d per week and produces a high nitrogen waste flow of some 1 120 $m^3.d^{-1}$ together with a high carbon waste flow of some 600 $m^3.d^{-1}$. Half of the high-carbon flow is diverted directly to the activated sludge plant to maintain the correct F/M ratio for foam control. The total influent nitrogen to the anaerobic plant is of the order of 150 $kg.m^{-3}$ and there is sufficient phosphorus to sustain biological growth in the treatment plant.

Plant description

A pre-effluent plant removes most of the coarse solids and fats from the flows. Vibrating screens allow a minimum of solid paunch contents to reach the main plant. Paunch contents are treated separately from the liquid fraction and are composted by the forced aeration static pile process.

The general layout of the Cato Ridge abattoir waste-water treatment plant is shown in Fig. 6 (Barnard, 1986). The two inflow streams are lead to a balancing tank of 4 800 m^3 capacity which facilitates a more continuous and homogenous feed to the digesters. The two digesters, each 2 866 m^3 capacity, are unheated and operate at an average temperature of 22°C. Suspended solids in the digester mixed liquor are maintained in the 12 to 18 kg $SS.m^{-3}$ range and mixing is by draught-tube mixers. Each digester is equipped with a vacuum degasifier operating at a vacuum of 60 kPa to strip dissolved and entrapped gases from the liquor and improve sludge settlement in the clarifiers (each of 1 519 m^3 capacity). The recycle rate of the sludge underflow from the clarifiers back to the digesters is 3,5:1 based on the feed rate.

An ultra high-rate plastic-medium trickling filter (20 $m^3.m^{-3}.d^{-1}$) was installed for aeration of the digester liquor and oxidation of sulphides to minimise bulking of the activated sludge. The effluent from the trickling filter is discharged into an activated sludge plant consisting of an open basin having a volume of 3 330 m^3 and provided with 6 aerators each 45 kW.

Plant performance

About 70 per cent COD removal takes place in the anaerobic digesters. Mechanical breakdown in the abattoir has led to discharges of batches of semi-processed blood or other by-products. The anaerobic system was able to handle these heavy loads very adequately, thus protecting the activated sludge process and allowing it to polish the effluent such that more than 96 per cent overall COD removal is achieved. High volatile fatty acids concentrations in the digester effluent are beneficially used in the subsequent aerobic process for denitrification of nitrates. The mean space load rate of the digester compartment amounts to 1 to 2 kg $COD.m^{-3}.d^{-1}$ at 22°C (Table 1).

Treatment of brewery waste at Prospecton

A high-rate anaerobic treatment plant was commissioned at the South African Breweries Prospecton brewery near Durban in 1985 (Hoffmann, 1985). The purpose of the plant is to pretreat the brewery effluent to conform to the standards (limit of 250 $mg.\ell^{-1}$ OA) imposed by the local authority as a precondition for acceptance of the effluent for further aerobic treatment. The daily flow amounts to some 2 600 $m^3.d^{-1}$ with a mean COD value of 3,1 $kg.m^{-3}$. The digester is of the UASB-type (upflow anaerobic sludge blanket) and patented as the Biothane Process and has a total capacity of 1 700 m^3.

A decision was taken to import the quantity of biomass required, namely 120 t of wet sludge (equivalent to 7 200 kg volatile suspended solids) from Holland. The reason was that this sludge would already be in a pelletised form and it was conditioned to a carbohydrate substrate. It was anticipated that the cost would be justified by the reduction in the biological commissioning time.

Waste-water characteristics

The waste water from the packaging hall is equivalent to two-thirds of the total flow volume but has a low COD of 50 $mg.\ell^{-1}$. This flow is segragated and discharged directly to the sewer. Process waste water from the other sections of the brewery (brewhouse, fermenting cellars, filter room and engine room) are combined into a single stream which flows to two circular clarifier/balancing tanks (each 250 m^3 capacity) in series for balancing irregular flows and removing suspended solids. Suspended matter (such as yeast cells and husks) in the process waste water has caused problems in the digester as the hydraulic retention time is too short (18 h) for complete hydrolysis and this suspended material is then present in the final effluent. Extra precautions have been taken to remove solids by flocculation with a cationic polyelectrolyte. The underflow from the clarifiers is wasted to tankers for off-site disposal.

The brewery waste water has a high carbohydrate content but is badly buffered and NaOH and $NaHCO_3$ has to be added for pH control. The major nutrients result in a COD:N:P ratio of 500:8:1 and it has not been found necessary to supplement the feed with nitrogen and phosphorus.

Plant description

A simplified process flow diagram of the anaerobic plant is shown in Fig. 7. The flow-balanced effluent passes through self-cleaning static screens to remove solids larger than 0,75 mm. The screened effluent flows into a conditioning tank (fitted with a submersible mixing unit) where provision is made to dose sodium bicarbonate or phosphoric acid for pH control.

From the conditioning tank the waste water is pumped to the digester via a biogas-fired hot water plate heat exchanger to maintain the digester temperature in the range 32 to 35°C. For optimum biological activity the pH inside the digester is maintained within the range of 6,7 to 7,3 by dosing a caustic soda solution into the waste water entering the digester.

The UASB digester, a rectangular concrete tank of 1 700 m^3 total capacity, is provided with specially designed internal settlers for phase separation of biomass, biogas and treated effluent. The baffle-plate arrangement is designed to allow for degasification of the biomass and to promote the development of highly settlable granular sludge particles.

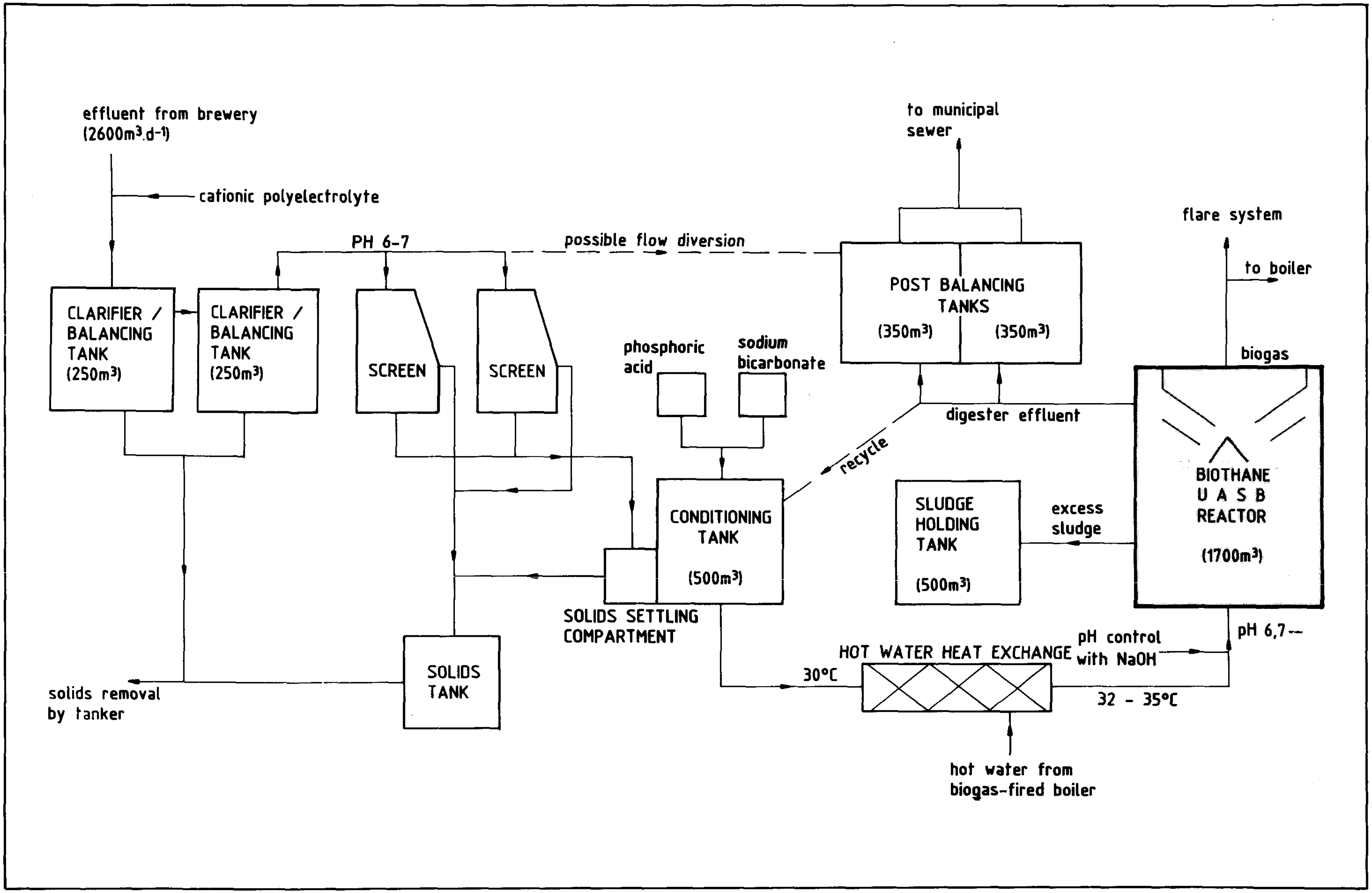


Figure 7
Layout of anaerobic digestion plant for treatment of beer brewery waste at Prospecton (Hoffmann, 1985)

The heated waste water enters the bottom of the digester through two sparge piping systems and a pulsed system is used to vary flow portions through each set of pipes. An adjustable timing system is used to alter the sparging period. This constantly repeated cycle redistributes the biomass to ensure that no channeling will take place and that the maximum surface area of the biomass is utilised.

Excess sludge generated in the digester is stored in a 500 m^3 sludge tank. The treated effluent flows into two post balancing tanks from where it gravitates to the municipal pump station. Whenever extreme changes are detected in the process waste water from the brewery, the flow is diverted directly to the post balancing tanks and the recycle flow system between the digester and the conditioning tank is put into operation.

The digester biogas is piped from the settlers through a water seal tank and a defoaming tank. Excess biogas not used to fire the water heaters is flared. The methane quality of the biogas is continually monitored by means of an in-line methane analyser.

An automatic control system monitors and records various readings such as pH, temperature, tank levels, liquid and gas flow rates and gas purity. The system is designed so that simultaneous readout information is available in the plant control room as well as in the utilities control room at the brewery. Changes within normal operating limits can be adjusted automatically but changes outside these limits constitute an alarm condition requiring operator response. During a normal eight hour shift one technician can operate the plant with the majority of his time being spent on control analyses. During the remaining sixteen hours of operation the plant is controlled from the utilities control room.

Plant performance

Three weeks after commissioning the design flow of 3 000 $m^3.d^{-1}$ of waste water was fed into the digester (Hoffmann and Heilbron, 1986). Soluble COD removals in excess of 80 per cent can be achieved on brewery waste water (refer Table 9). In terms of the municipal requirement that the OA value not exceed 250 $mg.\ell^{-1}$, the plant has performed exceptionally well by producing a treated effluent with OA values consistently well below this value. The digester has performed well even at high sludge load rates of 1 kg COD. kg $VSS^{-1}.d^{-1}$, equivalent to a digester space load rate of 5,4 kg $COD.m^{-3}.d^{-1}$ at 35°C. The suspended solids concentration in the digester varies from 90 $kg.m^{-3}$ at the bottom of the sludge bed to some 10 $kg.m^{-3}$ below the settler compartment. The existence of a highly settlable pelletised sludge in this plant is of particular significance as it permits short hydraulic retention times of 17 h.

Process economics

The 1986 annual effluent cost was 210c per m^3 or approximately R3,2 million per annum for a flow of 4 200 $m^3.d^{-1}$. By reducing the OA value from 570 to 200 $mg.\ell^{-1}$, the charge is reduced to 93c per m^3 or approximately R1,4 million per annum. There was thus a considerable incentive to reduce the OA value. If a market value of R2 per GJ biogas is assumed the value of the biogas generated will be approximately R103 000 per annum or 7c per m^3 effluent treated.

Treatment of apple processing wastes

Appletiser Pure Fruit Juices, Grabouw

The use of anaerobic activity in ponds has been recently applied in Grabouw for the treatment of apple processing waste water. The design of this system was based on research by Dold *et al.*, 1987. The system comprises two anaerobic ponds in series (each 4 000 m^3 capacity) followed by aerated ponds for polishing the effluent. During the peak season (summer months - February to May) the flow from the factory amounts to 5 000 $m^3.d^{-1}$ with a mean COD concentration of 2 $kg.m^{-3}$. The anaerobic ponds are six metres deep and the first pond has a design loading of 2,5 kg $COD.m^{-3}.d^{-1}$.

In order to maximise the effectiveness of the ponds, these have been designed to operate in an upflow mode with flow entering the pond at the bottom via a distribution manifold and passing up-

TABLE 9
PURIFICATION EFFICIENCY OF ANAEROBIC DIGESTER TREATING BREWERY WASTE

Parameters	Digester inflow	Digester outflow
pH	7,6	7,2
Bicarbonate alkalinity ($mg.\ell^{-1}$)	550	700
Volatile fatty acids ($mg.\ell^{-1}$)	308	206
COD (soluble) ($mg.\ell^{-1}$)	3 117	545
OA ($mg.\ell^{-1}$)	500	140
Total suspended solids ($mg.\ell^{-1}$)	579	559
Volatile suspended solids ($mg.\ell^{-1}$)	500	425
Total solids ($mg.\ell^{-1}$)	2 521	1 993
Volatile solids ($mg.\ell^{-1}$)	1 681	732
Settleable solids ($mg.\ell^{-1}$)	16	12
Kjeldahl-nitrogen ($mg.\ell^{-1}$)	21	-
Total-P ($mg.\ell^{-1}$)	8	-
COD:N:P ratio	500:8:1	-

wards through the sludge to launders at the surface. Although newly commissioned, the anaerobic ponds are performing satisfactorily and remove some 50 per cent of the incoming COD load. No supplementation of the feed with nitrogen and phosphorus or additional buffer has been found necessary (Palmer, 1988)

Ceres Fruit Growers, Ceres

A UASB plant was commissioned at Ceres during 1988 for the treatment of apple processing waste. For six months of the year the factory flow amounts to 430 $m^3.d^{-1}$, reducing to 120 $m^3.d^{-1}$ for the remainder of the year. The COD has a mean value of 5 $kg.m^{-3}$. The plant comprises a balancing pond of 30 000 m^3 followed by three UASB-type stainless steel digesters, each of 175 m^3 capacity. Provision has been made for heating to 35°C and for digester pH control (Visser, 1988). No data are as yet available on the performance of the plant.

General discussion of plant performance

Treatability of waste waters

The anaerobic digestion process has been shown to be ideal for the treatment of a wide spectrum of organic industrial effluents. These wastes are essentially biodegradable and the degree of purification attained is 80 to 97 per cent. Effluents deficient in the major nutrients nitrogen and phosphorus and in buffer requirements can be supplemented by chemical addition. The concentration and pH of the waste may vary substantially over a short period and it has been found expedient to provide balancing capability.

Design considerations

Successful anaerobic digestion of soluble organic wastes is conditional upon proper biological treatment followed by effective phase separation of the biogas, treated liquor and the sludge. The most important factor for operation of a high-rate anaerobic process is biomass concentration and retention. Various process configurations aimed at prolonging active biomass retention are currently under study.

In South Africa both upflow sludge blanket and contract-type plants have been in general use. These plants rely on clarifiers to concentrate and recycle the biomass to the digestion compartment. With non-granular sludges gravity separation limits the suspended solids concentration of the digester mixed-liquor to 20 $kg.m^{-3}$ and clarifier upflow velocities to 0,1 $m.h^{-1}$. By comparison, granular sludge of 60 $kg.m^{-3}$ permits higher space load rates with hydraulic retention times of less than one day.

Process control

Fundamental concepts have been established for the anaerobic treatment of industrial wastes which provide a basis for digester control (Ross and Louw, 1987). High-rate systems operating at space load rates above 5 kg $COD.m^{-3}.d^{-1}$ generally require a greater degree of monitoring and automatic control. Plants operating at lower space load rates require less control and are better able to withstand shock loads.

Experience indicates that no single parameter is sufficiently sensitive to permit reliable forecasting of incipient overload or digester failure, particularly at high load rates. Effective monitoring requires a combination of physical, chemical and biological indices. The most useful control parameters to ensure process stability and reliability are:

- digester pH should be maintained within the range 6,8 to 7,2 with an excess bicarbonate alkalinity in excess of 1 500 $mg.\ell^{-1}$ $CaCO_3$
- the sludge load rate should be maintained below 0,5 kg COD. kg $VSS^{-1}.d^{-1}$ at 35°C. A temperature drop of 10°C results in a 50 per cent reduction of biological activity and hence in permissible load rate over the mesophilic temperature range of 35 to 15°C; and
- healthy digestion should generate some 0,5 m^3 biogas per kg COD utilised and the feed rate should be controlled accordingly.

Future prospects for industrial application

There is a reawakening of interest in anaerobic digestion in South African universities and other research organisations. The first symposium specifically on this subject was held in Bloemfontein in 1986, to be followed by the second symposium in September 1989. Current pilot-scale research and development programmes in South Africa concern the treatment of paper processing, pulp bleaching, malting, egg processing, wine distillery, petrochemical, fruit processing, tannery, yeast and mine drainage wastes (Fig. 1). It is anticipated that successful completion of these studies will lead to further full-scale industrial applications.

More research is however required to improve the design of digester systems so as to utilise the microbiological potential of the anaerobic organisms. For example, a promising local development is the success achieved with polyethersulphone ultrafiltration membranes for solids-liquid separation in anaerobic digestion systems treating organic industrial effluents (Ross *et al.*, 1988). This has come to be known as the ADUF process (anaerobic digestion ultrafiltration) (Ross *et al.*, 1989). The main advantages of this system are the production of a clear effluent and maintenance of high biomass concentration in the digester.

It is recognised that ongoing research will lead to the development of rational criteria, improved economics and greater reliability.

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