Evaluation of the dual digestion system:
Part 1: Overview of the Milnerton experience

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Abstract

A number of advantages are claimed for dual digestion as a system for sewage sludge pasteurisation and stabilisation. In this paper, the first of a series of 4, an overview of a 4-year full-scale (45 m^3 aerobic reactor and 500 m^3 anaerobic digester) dual digestion research project is presented. The project was undertaken at Milnerton (Cape, South Africa) and its principal objective was to evaluate the claims made for the dual digestion system. In this paper the claims are stated; the layout and operation of the dual digestion system described; the main results obtained briefly discussed; and the claims evaluated with the aid of the results. It is concluded that most of the claims are valid, *inter alia*, the mesophilic anaerobic digester performance is not adversely affected by the first stage autothermal thermophilic aerobic reactor compared to conventional digestion. The 3 sequel papers focus attention on the aerobic reactor; its operation, performance, control, design and simulation of the temperature profile for both air and pure oxygen systems.

Introduction

Generally the treatment of sewage sludge involves the controlled degradation of the biodegradable organic material, called stabilisation, and further concentrating the sludge, called dewatering. The stabilised and concentrated sludge then needs to be disposed of, and to do this in an economically and environmentally acceptable manner is one of our society's great challenges. Most municipal sludge is disposed of by land application, land filling, lagooning, ocean disposal or incineration. Land application, which is the controlled spreading of sewage sludge into the soil surface, is, due to its economy and nutrient value to the soil, by far the most popular means of sludge disposal (Ekama, 1992). With the growing concern about the health risks posed by human pathogens when using sludge as a soil conditioner for agricultural purposes, disinfection or pasteurisation of the sludge as part of sludge treatment are now also required for certain uses (Dept. of National Health, 1991).

Processes other than conventional pasteurisation (heating sludge and maintaining it at 70° C for 30 min) are also capable of disinfection. Thermophilic aerobic digestion, for example, a system popular in West Germany, allows simultaneous stabilisation and pasteurisation of sludge. In this process, sludge temperatures in excess of 60° C can be maintained autothermally at 6 to 8 d retention times, thereby obviating the need for external heating of the sludge; the heat is generated autothermally from the biological oxidation reactions and the organic material destroyed by these reactions results in stabilisation of the sludge. This process requires a substantial input of energy for oxygenation and mixing. In South Africa mesophilic anaerobic digestion of sludge for stabilisation is popular, but this system does not sufficiently disinfect the sludge. Consequently, to change to thermophilic aerobic digestion would change the anaerobic digesters from an energy producing (through methane generation) stabilisation system, to an energy consuming (through oxygenation) stabilisation-pasteurisation system. An alternative system known as dual digestion overcomes this problem. It combines the advantage of autothermal aerobic digestion by providing pasteurisation and the advantage of anaerobic digestion by providing energy efficient stabilisation.

The dual digestion system

The dual digestion system comprises an autothermal thermophilic aerobic reactor first stage and a mesophilic anaerobic digester second stage. The aerobic reactor is based on the principle that if the sludge mass is maintained under aerobic conditions by a supply of air or pure oxygen, and if heat losses from the reactor are minimised, then the waste heat from biological oxidation reactions in the sludge will cause the sludge temperature to rise into the thermophilic range (50 to 70°C). Due to the high rate of metabolism at the thermophilic temperatures, sufficient heat is generated biologically to sustain very short retention times. In combining a short retention time autothermal thermophilic aerobic reactor and a mesophilic anaerobic digester, a number of advantages are claimed to be obtained [Drnevich and Matsch, 1978; Appleton and Venosa, 1986; Water Research Commission (WRC), 1986], viz:

In the aerobic reactor:

(1) The thermophilic temperatures pasteurise the sludge making it safer for disposal
(2) The sludge is "pretreated" through partial solubilisation of particulate organic matter allowing short retention times (10 d) in the anaerobic digester
(3) Solubilisation produces alkalinity through ammonification of proteins lending greater pH stability to the anaerobic digester
(4) Very little sludge stabilisation takes place in the aerobic reactor - only to the degree that the heat generated biologically maintains thermophilic temperatures; final and

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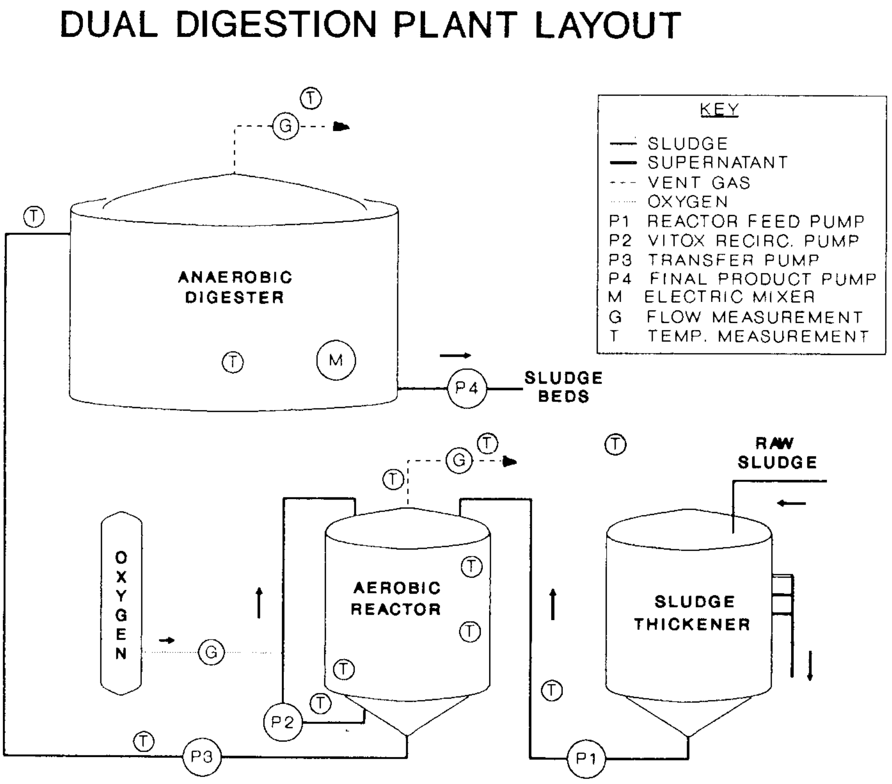

Figure 1
A schematic layout of the dual digestion plant at the Potsdam Waste-water Treatment Plant showing the sludge thickener, the aerobic reactor and the anaerobic digester, pumps, and positions of temperature and gas flow measurement

full stabilisation takes place in the anaerobic digester - methane generation is reduced only marginally by the aerobic pretreatment stage

(5) The major portion of the heat required to achieve thermophilic temperatures is biologically generated.

In the anaerobic digester:

(6) The heat required to maintain mesophilic temperatures is derived solely from the hot aerobic sludge feed with the result that the methane generated can be used for purposes other than digester heating.

From a practical point of view, claim (2) is of particular importance; if substantiated, then dual digestion would be a viable system for upgrading existing fully loaded anaerobic digesters. This single feature would justify implementation of dual digestion with sludge pasteurisation being an additional benefit. The dual digestion system, therefore, is particularly appropriate to South Africa where mesophilic anaerobic digestion is the preferred method for sludge stabilisation; where pasteurisation of sludge is required or where existing digesters are overloaded, dual digestion could be implemented to meet both pasteurisation and increased capacity requirements. Also, being a pre-(stabilisation)pasteurisation process, it is likely to overcome the problem of sludge recontamination by pathogen regrowth which the Swiss experienced with post- (stabilisation) pasteurisation during the 1970s (WRC, 1986).

Dual digestion research requirements

Although the results of earlier research, which focused on the performance of the autothermal thermophilic aerobic reactor oxygenated with pure oxygen, were very encouraging (Trim, 1984a;b; Trim and McGlashan, 1985), before the dual digestion system could be adopted, a number of aspects needed careful study in order to ensure successful application in South Africa, viz.:

- Operation at a sufficiently large scale to develop design criteria and undertake an economic evaluation.
- Oxygen requirements and oxygen consumption efficiency with pure oxygen and air oxygenation and the influence of the foam layer resulting from air oxygenation.
- Minimum retention time of the aerobic reactor without compromising attainment of thermophilic temperatures.
- Temperature control of the aerobic reactor and anaerobic digester.
- Efficacy of pathogen inactivation in the aerobic reactor and mode of operation to prevent recontamination.
- Minimum retention time of the anaerobic digester without compromising digester performance and sludge stability.
- Performance of the anaerobic digester with respect to VS removal, gas production, sludge stability and sludge dewaterability.

In January 1987 under the sponsorship of the WRC and Milnerton Municipality, a full-scale (45 m^3 aerobic reactor and

500 m^3 anaerobic digester) dual digestion research project was initiated at the Potsdam Waste-water Treatment Plant (Milnerton, Western Cape), to investigate the aspects listed above.

The dual digestion research facility

Potsdam waste-water treatment plant (WWTP) layout

The Potsdam WWTP serves a population of about 80 000 and treats an average dry weather flow (ADWF) of 18 Mℓ/d. Treatment of sewage is currently achieved by screening, grit removal, primary sedimentation, biofiltration with humus tanks and maturation. The primary and humus sludge produced is accumulated in a central sludge collection sump, the contents of which are pumped to the sludge treatment facilities about 4 times daily. Currently sludge production is about 150 m^3/d at around 3,5% total settleable solids concentration.

When the Potsdam WWTP originally started, sludge was treated by cold anaerobic digestion in three 1 000 m^3 domed concrete digesters. In 1976 these digesters were decommissioned and a Zimpro treatment facility was installed which currently is still in operation. With the Zimpro process, sludge is pumped from the central collection sump to one of the decommissioned anaerobic digesters for sludge storage and thickening before discharge to the Zimpro process. The Zimpro process treated all the sludge produced until 1987, when the experimental dual digestion plant was put into operation. The experimental dual digestion plant treated about ¼ of the daily sludge production, i.e. about 36 m^3/d or 1 250 kg dry solids/d.

Dual digestion plant layout and operation

A schematic layout of the Milnerton dual digestion plant is shown in Fig. 1. The plant comprised 3 tanks in series, i.e. a sludge thickener, an aerobic reactor and an anaerobic digester. The thickener and reactor were identical 50 m^3 conical bottomed laminated fibreglass tanks which differed only in regard to their piping configurations. The thickener had 3 draw-off points for draining off supernatant during gravity thickening of the sludge. These were located at 2,1; 3,1 and 4,1 m from the bottom point of the thickener cone. Sludge feed for the thickener was pumped from the central collection sump. Supernatant from the thickener was returned to the head of works.

The resin used in the construction of the thickener and reactor is sensitive to temperature and the manufacturer's guarantee would be invalidated if sludge temperatures rose above 70°C. Accordingly 70°C was set as the maximum allowable reactor sludge temperature. To reduce heat losses, the reactor was lagged with 50 mm thick polyurethane foam. The operating volume of the reactor was set at 45 m^3. Reactor contents mixing and oxygenation were by means of a 150 m^3/h side stream pumped recirculation Vitox pure oxygen injection system (see Fig. 1).

The reactor was operated on a draw-and-fill basis to avoid contamination of the effluent pasteurised sludge with feed sludge. A centrifugal pump first transferred a fixed batch volume of hot, pasteurised sludge from the aerobic reactor to the anaerobic digester and then a macerator feed pump refilled the reactor to its operating volume with thickened (to $\approx$ 3,5%) feed sludge drawn from the base of the sludge thickener. The transfer and feeding operations were completed in about 3 and 4 min respectively. The draw-and-fill batch volume was fixed at $^1/_{12}$ of the reactor volume i.e. 3,75 m^3 and the time interval between feeding was varied between 2 and 6 h to achieve retention times varying from 1,0 to 3 d. The minimum batch cycle time interval of 2 h was set by the time constraints imposed by sludge disinfection, and this gave the minimum hydraulic retention time of 1,0 d. The batch operation also provided an accurate reading for the daily sludge volume treated.

Vent gas temperature was measured as it emerged from the reactor, and specialised equipment was constructed to measure the vent gas composition, water vapour content and volumetric flow rate. This comprehensive monitoring of the vent gas allowed calculation of the sludge oxygen consumption rate (OCR_{sys}) or equivalently the mass oxygen transfer rate to the sludge (OTR), the oxygen transfer efficiency (OTE), the degree of vent gas water vapour saturation and the respiration quotient i.e. mol CO_2 produced per mol O_2 consumed.

The anaerobic digester was one of the decommissioned 1 000 m^3 domed concrete cold anaerobic digesters. The operating volume of the digester ranged between 400 and 600 m^3 depending on the anaerobic retention time required. Because of the batch operation of the reactor, the digester also was batch fed, receiving 3,75 m^3 of hot transfer sludge from the reactor every 2 to 6 h, depending on the reactor retention time. No external heating of the digester was provided and the hot feed sludge from the reactor was the only heat source available to maintain the digester at mesophilic temperatures.

To maintain the required digester retention time, sludge was discharged once daily from the digester in a single batch. The volume discharged was monitored via a 6 m high external sight-glass fitted to the digester for sludge liquid level control. As with the aerobic reactor, specialised equipment was fitted also to the digester to measure the gas composition and volumetric flow rate.

On 23 November 1990, almost 4 years after commencement of the project, the research was precipitously terminated due to the structural failure of the laminated fibreglass aerobic reactor. Fortunately by this time most of the aspects requiring research attention had been addressed at least in part. Some of the results achieved in the project have been presented from time to time as the research progressed (De Villiers and Messenger, 1988; Messenger, 1989; Messenger et al., 1989; 1990 and De Villiers et al., 1987; 1988; 1989; 1990; Messenger and Ekama, 1991) but all the results have been comprehensively documented in a 3-part final report viz. Part 1 by De Villiers et al. (1992); Part 2 by Messenger et al. (1992), and Part 3 by Laubscher et al. (1992).

In this first paper of a series of 4, an overview of the results obtained in the project is presented. The 3 sequel papers focus on the aerobic reactor viz. *Part 2: Operation and Performance of the Milnerton Pure Oxygen Aerobic Reactor* (Messenger et al., 1993); *Part 3: Considerations in the Process Design of the Aerobic Reactor* (Messenger and Ekama, 1993a) and *Part 4: Simulation of the Temperature Profile of the Batch Fed Aerobic Reactor* (Messenger and Ekama, 1993b).

Aerobic reactor investigation

Kinetics of biological heat generation

As part of the research project, a detailed investigation into the aerobic reactor perormance and behaviour was undertaken. In order to meet the objectives for the aerobic reactor it was necessary to examine the kinetics of biological heat generation. It was realised early in the investigation that the objectives of the thermophilic aerobic reactor in dual digestion and thermophilic aerobic digestion as a stand-alone process are different. In the latter, the principal objective is sludge stabilisation i.e. to reduce the sludge energy as measured by volatile solids (VS) removal; accordingly the kinetics are modelled in terms of a VS degradation rate, and from it is calculated the retention time to achieve a specified VS removal and the rates of biological heat generation and oxygen consumption (Andrews and Kambhu, 1969,1971; Vismara, 1985). For the kinetics to be controlled by the VS degradation rate, the process needs to be operated under oxygen **sufficient** conditions. This approach was found to be unproductive for modelling the aerobic reactor in dual digestion because sludge heating for pasteurisation is the principal objective and very little VS is removed in the reactor even though large quantities of biological heat are generated. Accordingly, because biological heat generation theoretically can be shown to be stoichiometrically related to oxygen consumption and the reactor is best operated under oxygen **limiting** conditions (Mason, 1986), the system oxygen consumption rate (OCR_{sys}), or equivalently the oxygen transfer rate of the oxygenation system (OTR), became the most useful parameters for operation, control, design and process simulation of the aerobic reactor. Consequently the principal objective of the aerobic reactor research devolved to verifying the direct proportionality between the rates of biological heat generation and oxygen consumption via the specific heat yield (Y_H, MJ/kgO) and demonstrating that with the oxygen supply rate (OSR), virtually instantaneous and complete control of the reactor sludge temperature could be obtained.

Aerobic reactor results

Over a period of 8 months, 116 heat and oxygen mass balances were done on the aerobic reactor. During this time the operating conditions differed widely viz. reactor sludge temperature 54 to 69°C, retention time 1,2 to 3 d, average ambient temperature 8 to 30°C and oxygen supply rates (OSR) from 0,13 to 0,54 kgO/(m^3·h) giving oxygen transfer rates (OTR), or equivalently system oxygen consumption rates, (OCR_{sys}) from 0,13 to 0,44 kgO/(m^3·h) and oxygen transfer efficiencies (OTE, equal to OTR/OSR) from 1,00 to 0,75 respectively. From these tests the following results were obtained (see Messenger et al., 1990; 1992; 1993 for details):

- Biological heat generation rate (H_{bi}) was directly proportional to the oxygen transfer rate (OTR), or equivalently the system oxygen consumption rate (OCR_{sys}). The constant of proportionality is the specific heat yield (Y_H) and was measured to be about 13,1 MJ/kgO. This value conforms closely to thermodynamically and bioenergetically calculated values (McCarty, 1972).
- Reactor sludge temperature increases could be completely and virtually instantaneously controlled by means of the oxygen supply rate (OSR) for as long as the reactor was oxygen limited [i.e. oxygen transfer rate (OTR) less than the biological oxygen consumption rate (OCR_{bio})].
- Respiration quotient (Y_{CO2}) i.e. mol CO_2 generated per mol O_2 consumed, was measured to be around 0,66 instead of 1,0 often assumed. In hindsight the accuracy of the specific heat yield data rested on the decision not to accept 1,0 for Y_{CO2} (which is often done in the literature) but to measure the total dry vent gas low rates.
- Vent gas was saturated with water vapour at all vent gas low rates.
- COD and/or VS removal rates were poor parameters for quantifying the biological heat generation rate and controlling the reactor sludge temperature because the tests are prone to such high variability when dealing with sewage sludges that it is virtually impossible to establish reliably the mean difference between the influent and effluent values. In contrast, the close correlation, and rapidity of response, between the biological heat generation rate and the oxygen transfer rate (OTR) make the OTR a pivotal parameter in design and process simulation of autothermal thermophilic aerobic reactors in dual digestion.

Evaluation of aerobic reactor investigation

With the Milnerton pure oxygen oxygenated aerobic reactor, the objectives set for the aerobic reactor investigation (listed above) were met.

With regard to air oxygenation, this was not done at Milnerton, but the work of Pitt (1990) and Pitt and Ekama (1993) at the Athlone (Cape) air oxygenated aerobic reactor complemented the Milnerton research and provided the required additional information. A design procedure was developed based on a steady state heat balance allowing *inter alia* the retention time in the reactor for specified influent and effluent sludge temperatures to be determined in terms of the OTR and the OTE of the oxygenation system (Messenger and Ekama, 1991; 1993a). Also for the purposes of simulating the saw-tooth reactor sludge temperature profile under the batch feed draw-and-fill conditions an algorithm and simulation computer program was developed which solves the unsteady heat balance under specified operating conditions and gives the moment-by-moment temperature profile (Messenger and Ekama, 1993b).

With these design and simulation procedures the responsibility of the design engineer is to correctly estimate the relationship between oxygen transfer rate (OTR) and efficiency (OTE) of the pure oxygen or air oxygenation system. To define the maximum OTR required of the oxygenation system, knowledge of the sludge's unlimited oxygen consumption rate (OCR_{bio}) is important to estimate the degree of oxygen limitation and the minimum retention time. No ancillary method for determining the sludge's OCR_{bio} was developed in this research, and for the present, laboratory- or pilot-scale tests have to be employed to determine this value for a particular sludge. If heat sources other than biological and mechanical are exploited it is possible to avoid requiring an accurate knowledge of the sludge's OCR_{bio}. This aspect is discussed under supplementary heat sources below.

The Milnerton aerobic reactor, oxygenated with pure oxygen could be operated at 1 d retention time during hot summer months when feed sludge (26°C) and ambient temperatures (30°C) were high. In winter, when the feed sludge was cold (17°C) and ambient temperatures low (10°C), a retention time of 1,25 d was required to maintain reactor temperatures above 60°C. At 1,25 d retention time, the biological heat generation rate was 75% of the total heat required (81 kW).

In operation, the aerobic reactor was stable, reliable and easy to operate. For 8 h/d (24:00 to 08:00), it was left unattended by operating staff, who, when on duty during the 16 h working day, had little more to do than take sludge samples and check that feed sludge was available in the feed sludge thickener. Technical failure seldom occurred; the major maintenance problem arose from erosion/abrasion of the Vitox oxygenation recirculation pump which continuously pumped sludge through the oxygen injection system and provided mixing of the reactor sludge. Special precautions needed to be taken to minimise shaft wear and the casing of this pump needed to be rebuilt at about 5-month intervals (For details see Laubscher et al., 1992).

Evaluation of anaerobic digester performance

Detailed behaviour of the anaerobic digester receiving the effluent from the aerobic digester is not presented in this paper (for details see De Villiers et al., 1992). However, the aerobic reactor has been claimed to have a significant influence on the anaerobic digester performance; it is therefore of interest to evaluate these claims from the observed performance of the dual digestion plant at Milnerton. In general, the operation and performance of the digester was not found significantly different from that of a conventional mesophilic digester except in start-up and temperature control. With regard to start-up, this needed to be done without a sludge seed to avoid sludge pathogen contamination. As a result start-up took 2 to 3 months during which, the $H_2CO_3^*$ alk,[1] *in situ* pH, short-chain fatty acids (SCFA) and temperature needed to be carefully monitored and pH and temperature controlled. Controlling the pH to above 6,8 was necessary to allow methanogenesis to develop; this required dosing the digester with large quantities of $H_2CO_3^*$ alk in the form of carbonate, bicarbonate and lime. Once methanogenesis commenced, the SCFAs decreased from several thousands to below 200 mg/ℓ in a few days, gas production increased dramatically, and $H_2CO_3^*$ alk dosing was no longer required. With regard to temperature control, in the winter the heat loss from the digester was sufficient to prevent the digester from overheating but during the hot summer months, the digester heat loss was insufficient and overheating (44°C) occurred under normal operation. Because no digester feed sludge cooler or heat exchanger was available, the digester temperature had to be controlled to 37°C by diverting batches of hot sludge from the reactor to the Zimpro feed sludge storage tank. This affected the retention time of the anaerobic digester and because effective mixing could not be achieved in the digester with less than 400 m^3 of sludge in it, difficulties were encountered in determining the minimum anaerobic retention time, particularly in summer. In properly designed dual digestion systems, this problem is unlikely to arise because digester lagging and a heat exchanger are likely to be included in the design to make it more economical (see **Exploitation of supplementary heat sources** below).

Evaluation of dual digestion system results

In the context of the claimed advantages of the dual digestion system set out earlier, experience with the plant at Milnerton indicates the following (for details see De Villiers et al., 1992):

- ***Pasteurisation***. On the basis of the indicator organisms selected, pasteurisation was satisfactory, with zero viable *Ascaris* ova in the final (anaerobic effluent) sludge; faecal coliforms reduced by about 9 orders of magnitude, and *Salmonellae* were not detected in the final sludge. Interestingly, *Salmonellae* also were not detected in the feed to aerobic reactor sludge; apparently this is due to rapid *Salmonellae* die-off at the low pH conditions (5,2) in the feed sludge thickener.

- ***Effect of aerobic pretreatment***. The lowest stable anaerobic retention time was 15 d; at 12 d retention time the gas production declined and SCFA increased sharply, but reverted to normal upon increasing the retention time again to 15 d. It was difficult to establish the minimum anaerobic retention time because of the problems encountered with digester overheating and as a consequence no firm conclusions regarding the effect of aerobic pretreatment on digester retention time could be made.

- ***Anaerobic digester stability***. In the aerobic reactor, the ammonium and $H_2CO_3^*$ alk increased to about 150 mg N/ℓ and 540 mg/ℓ as $CaCO_3$ respectively. The increase in $H_2CO_3^*$ alk and the higher CO_2 partial pressure in the aerobic reactor (>80% of the total pressure) increased the carbonic species concentration C_T from less than 200 to over 1 200 mg/ℓ as $CaCO_3$. The higher C_T increased the buffer capacity of the anaerobic digester feed which, when the digester retention time and temperature were adequately controlled, provided good pH stability to the digester. The pH of the aerobic reactor feed sludge was about 5,2, the *in situ* aerobic reactor pH was calculated (from the measured $H_2CO_3^*$ alk and reactor partial pressure of CO_2 values) to be around 6,3 and the measured pH of a cooled reactor sample (from which considerable CO_2 has been lost) was 6,7. The anaerobic digester NH_4^+, pH, HAc + $H_2CO_3^*$ alk and SCFA concentrations averaged around 650 mg N/ℓ; 7,6; 2 300 mg/ℓ as $CaCO_3$ and 300 mg Ac/ℓ respectively.

- ***Sludge stabilisation***. The claim that very little sludge stabilisation takes place in the aerobic reactor, and that stabilisation takes place principally in the anaerobic digester was verified - during the investigation the average VS and COD removals in the aerobic reactor were 1,5% and 12% respectively, whereas in the anaerobic digester the removals of VS and COD were about 50% and 44% respectively at 20 d retention time. Gas production in the anaerobic digester did not appear to be influenced by the pretreatment in the aerobic reactor; a specific gas production of 1,2 m^3 (30°C and 1 atm)/kg VS removed at 67% methane content was greater than the 0,75 to 1,1 m^3/kgVS removed range normally observed in conventional anaerobic digesters.

  The sludge from the aerobic reactor was very difficult to dewater (as found by Trim, 1984a;b). Even with centrifugation, a large mass of fine material remained suspended which necessitated drying the complete sludge sample, without prior centrifugation, in order to obtain accurate results in the solids analysis (VS, TS).

  The final (anaerobic effluent) sludge was stable and odourless. It settled well but, due to the presence of some fine material (but much less than in the aerobic sludge), it tended to blind the sludge drying beds. Its dewatering characteristics in terms of capillary suction time (CST) and specific

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[1] Commonly, but incorrectly and confusingly, known as the Total Alkalinity. In a mixed weak acid/base system like anaerobic digestor supernatant not only the carbonate system but also the SCFA system, influences the pH titration curve so that the titration down to pH 4,3 does not reflect the total alkalinity of the carbonate system only, but includes that of the SCFA system. $H_2CO_3^*$ alk is specifically only the alkalinity of the carbonate system with respect to the $H_2CO_3^*$ carbonate system reference species i.e. equivalent carbonic acid solution (see Loewenthal et al., 1989). A simple 5-point pH titration method for determining the $H_2CO_3^*$ alk, as well as the SCFA concentration and its alkalinity contribution in digestor supernatants, has been developed by Moosbrugger et al. (1992; 1993) and was used in the latter half of this investigation.

resistance to filtration were approximately 350 s and 600 x 10^{12} m/kg respectively which indicate a poorly dewaterable sludge; however these dewaterability indicators were no worse than those for a conventional mesophilic anaerobically digested primary and activated sludge mixture (Smollen, 1986).

- ***Aerobic reactor heating requirements.*** At 1,25 d retention time, the retention time at which the reactor maintained temperatures above 60°C during summer and winter, about 75% of the total heating requirements (81 kW) was supplied by biological means with the remainder being mechanical heat input via the recirculation pump. This substantiates the claim that most of the heat for the aerobic reactor is biologically generated. Although the Milnerton reactor was not operated at temperatures above 69°C because the laminated fibreglass reactor was guaranteed only to 70°C, temperatures in excess of 70°C could have been achieved readily by increasing the retention time to 1,5 d and increasing the oxygen supply rate to increase the biological heat generation rate. At temperatures above 70°C for more than 30 min undisturbed detention time, the reactor would comply with conventional pasteurisation specifications and in terms of the USEPA regulations qualify as a "Process to Further Reduce Pathogens" (PFRP) rather than only as a "Process to Significantly Reduce Pathogens" (PSRP) (Heidman, 1989).

- ***Digester heating requirements.*** In the winter months, all the heat of the hot effluent sludge from the aerobic reactor at 1,25 d retention time was required to maintain 37°C in the digester at 15 d retention time. In the summer, this was too much with the result that the digester overheated unless the aerobic reactor retention time was reduced or the hot aerobic reactor sludge was diverted, to reduce the heat flow to the digester. Considering that the digester was built for ambient digestion, so that heat retention probably was not seriously considered in its design, this substantiates the claim that the heat from the hot aerobic reactor sludge is sufficient to maintain mesophilic temperatures in the digester, with the result that the methane generated can be used for purposes other than digester heating. Indeed in a properly designed dual digestion system the anaerobic digester would include heat retention measures such as lagging with the result that a heat exchanger would be required to avoid overheating of the digester even in winter.

Exploitation of supplementary heat sources

When supplementary heat sources are exploited then, irrespective of pure oxygen or air oxygenation, a number of advantages are obtained for the aerobic reactor. Two readily exploitable supplementary heat sources available for dual digestion systems are heat exchange between reactor effluent and influent sludge and combustion of anaerobic digester gas. These aspects were not investigated experimentally at Milnerton, but their implications on design were evaluated with the aid of the steady heat balance (see Messenger et al., 1992; Messenger and Ekama, 1993a). Advantages of these supplementary heat sources on the steady state heat balance are most easily appreciated by considering that its effect is to increase the reactor sludge feed temperature (T_{si}). If the retention time remains unchanged, then the increased T_{si} reduces the heat required to heat the sludge to the reactor temperature which has the same effect as increasing the mechanical heat input H_{mi}, i.e. it adds heat without contributing to the heat losses. The additional heat allows the biological heat generation rate (H_{bi}) and hence oxygen transfer rate (OTR) to be reduced by reducing oxygen supply rate (OSR) which *inter alia* reduces oxygenation costs, increases oxygen limitation and reduces vent gas heat loss. On the other hand, if H_{bi} is kept constant (by keeping OSR and OTE constant) then the high feed sludge temperature allows a greater throughput of sludge liquid, thereby allowing a reduced retention time.

With regard to the heat exchange, the amount of heat that can be extracted from effluent sludge via a heat exchanger for preheating the influent to the aerobic reactor, will depend on the anaerobic digester heat losses via hot effluent sludge (i.e. retention time), the walls and vent gas water vapour and sensible heats. Because the only heat source for the digester is the hot effluent sludge from the reactor, this hot sludge must not be cooled too much otherwise mesophilic temperatures (37°C) cannot be maintained in the digester. At Milnerton, a heat exchanger would only have been useful during the hot summer months (see **Evaluation of dual digestion system results** above).

Additional heat could be derived from an alternative heat source such as the combustion of all, or part of, the methane produced in the anaerobic stage of the system. This source alone might be sufficient to produce all of the heat required, giving rise to a situation where biological heat generation could be completely dispensed with. In such a situation, the 2-stage system would no longer be a dual digestion system but would become the combination of a sludge pre-pasteuriser and an anaerobic digester as currently practiced at Cape Flats WWTP (Morrison, 1990). However, dispensing altogether with biological heat generation, and therefore sludge oxygenation, might have an impact on the claimed favourable sludge pretreatment effect in the reactor. While sludge pasteurisation could still be accomplished, the claimed potential of the reactor to significantly enhance the performance of the subsequent anaerobic digester might be lost, a claim which could not be conclusively verified at Milnerton.

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