EVALUATION AND OPTIMIZATION OF DUAL DIGESTION OF SEWAGE SLUDGE

DIVISION OF WATER TECHNOLOGY
OF THE CSIR
MILNERTON MUNICIPALITY
UNIVERSITY OF CAPE TOWN
AFROX LTD

WRC REPORT 189/1/92

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EXECUTIVE SUMMARY

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THIS DOCUMENT FORMS THE EXECUTIVE SUMMARY OF A THREE PART RESEARCH REPORT CONSISTING OF THE FOLLOWING

EXECUTIVE SUMMARY	Report WRC 189/1/92
Part 1: Overall system performance	Report WRC 189/2/92
Part 2: Aerobic reactor performance	Report WRC 189/3/92
Part 3: Evaluation of the technology for practical implementation	Report WRC 189/4/92

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RESEARCH REPORT WRC 189/1/92

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GLOSSARY OF SYMBOLS AND ABBREVIATIONS

ATAD — Autothermal thermophilic aerobic digestion

COD — Chemical oxygen demand (g/L or kg/m^3)

CST — Capillary suction time test (seconds)

DD — Dual digestion

H_{bi} — Rate of biological heat generation (MJ/h)

H_{mi} — Rate of heat generation in the sludge due to mechanical action of pumps or stirrers (MJ/h)

H_{net} — the rate of aerobic reactor sludge enthalpy increase during the specific heat yield test (MJ/h)

H_{ve} — the rate of heat loss from the aerobic reactor in the latent heat of the reactor vent gas (MJ/h)

H_{we} — the rate of heat loss from the surfaces of the aerobic reactor and the Vitox oxygenation system (MJ/h)

O_c — Oxygen consumption rate (kgO/h)

O_{eff} — the fraction of oxygen supplied to the aerobic reactor which is consumed by the reactor sludge. This symbol is used in the specific heat yield test and is equivalent to OTE, the symbol preferred in design procedures.

OSR — Oxygen supply rate to the aerobic reactor [$kgO/(m^3.h)$]

OTE — Oxygen transfer efficiency i.e. the fraction of the oxygen supply which the oxygenation system is able to transfer to the mixed liquor. This symbol is used in design procedures and is equivalent to O_{eff}, the symbol preferred in the specific heat yield test.

OTR — the oxygen transfer rate i.e. the rate at which oxygen is transferred to the mixed liquor [$kgO/(m_3.h)$]

OUR — the biological oxygen utilization rate, i.e. the volume specific rate at which sludge consumes oxygen under oxygen sufficient conditions [$kgO/(m_3.h)$]

PSA	Pressure swing absorption
SRF	Specific resistance to filtration (m/kg)
STP	Standard Temperature and Pressure
TS	Total solids concentration (g/L or kg/m^3)
Vitox	Patented oxygenation system
VS	Volatile solids concentration (g/L or kg/m^3)
WRC	Water Research Commission
Y_{CO_2}	Respiration quotient, i.e. mole CO_2 generated per mole O_2 consumed.
Y_H	Specific heat yield i.e. the quantity of biological heat generated per unit of oxygen consumed (MJ/kgO)

EXECUTIVE SUMMARY

INTRODUCTION

The sludge produced by biological wastewater treatment processes is a putrefactive concentrated aqueous suspension of particulate organic material which is mainly biodegradable, but also has an inert fraction. The treatment and disposal of this sludge has become a problem of increasing magnitude. In most cases, nearly half of the cost of waste water treatment plant operation is incurred by the handling, treatment and disposal of sludge. Final disposal of sludge is usually by one of the four most common options, viz: landfill, ocean dumping, incineration, or by land application. All of these options could create health, environmental and economic problems if not judiciously managed, and consequently, prescribed codes of practice for sludge disposal exist in most countries.

Land application for agricultural purposes is the oldest and most common means of using sludge beneficially. Sludge used for this purpose should, however, be stabilized and disinfected to such a degree so as not to create nuisance conditions or be hazardous to health. It should also contain only limited amounts of heavy metals and chemical compounds which would accumulate in the soil if the sludge were to be applied over long periods.

Sludge stabilization by aerobic or anaerobic digestion is practised worldwide. The type of waste water treatment plant employed influences the choice of sludge stabilization process. Aerobic digestion is most commonly used at activated sludge plants, while anaerobic digestion is historically associated with trickling filter plants. Factors such as energy considerations, plant location, the type of community served, operator skill, and sometimes personal preferences may also affect the choice of stabilization process employed.

With the growing concern about the health risks associated with the use of sludge as a soil conditioner or for agricultural purposes, disinfection or pasteurization of sludge used for this purpose is now in many cases recommended or required. The degree of disinfection prescribed varies, but in general the sludge has to undergo treatment aimed specifically at improving its hygienic quality. To achieve this objective, a number of options are available. These include chemical treatment (lime, methyl bromide, ammonia, etc.), irradiation, and various forms of heat treatment, including pasteurization.

The heat treatment option is the one that is the most commonly used. High temperature processes such as the Porteous, Zimpro, flash drying or rotary kiln drying are very effective in inactivating pathogens and parasites, but are usually very costly. Pasteurization, both pre- and post-stabilization, has frequently been used, but the latter was plagued by rapid reinfection and regrowth of pathogenic organisms. Pre-pasteurization is now commonly used, but it is an expensive process if waste energy is not available.

The heat treatment processes mentioned all require external energy input, which, with rapidly increasing energy prices, make them less attractive.

Alternative processes have been developed which utilize the heat liberated by the biological degradation of the organic fraction of the sludge to effect both stabilization and disinfection under the right conditions. These processes require a much reduced external energy input, which makes them attractive in the energy conscious world of today. Processes in this category include forced aeration composting, autothermal thermophilic aerobic digestion (ATAD), and dual digestion (DD). The latter process was developed by the Union Carbide Corporation in 1975 and the present patent holders are Linde Aktiengesellschaft, Germany. Engineering Management Services (Transvaal) (Pty) Ltd, Bedfordview 2008 (phone (011) 4561000) are the licence holders for the dual digestion process in South Africa. The evaluation of latter process is the subject of this report.

THE DUAL DIGESTION PROCESS

The dual digestion system comprises an autothermal thermophilic aerobic reactor first stage and a mesophilic anaerobic digester second stage. The aerobic reactor stage is based on the principle that if the sludge mass is maintained in the thermophilic temperature range (50-70 °C) under aerobic conditions by supply of air or pure oxygen, a population of thermophilic organisms develop which oxidize some of the sludge organic material. Due to the high rate of metabolism at the thermophilic temperatures, sufficient heat is generated biologically to sustain very high sludge loading rates and typically retention times of 1-2 days are possible. At this low retention time only a small portion of the organic matter in the sludge is oxidized so that only partial stabilization is achieved. In the anaerobic stage the stabilization of the sludge is completed and, because very little sludge stabilization takes place in the aerobic reactor, the gas production is not significantly reduced. In combining a short retention time autothermal thermophilic aerobic reactor and a mesophilic anaerobic digester the dual digestion process is claimed to have the following advantages:

1. Disinfection and stabilization of the sludge occurs in one process. The thermophilic temperatures in the first stage disinfect the sludge while full stabilization occurs in the second stage.

2. The use of energy for the supply and dissolution of oxygen is low since the degree of oxidation of the sludge limited, the only requirement being the maintenance of the chosen temperature to effect disinfection. Stabilization is completed in the anaerobic stage, which uses no oxygen.

3. No external heating of the anaerobic digester is required as all the heat required is provided by the hot sludge fed from the first stage.

4. The process is an overall net producer of energy since all the biogas, which contains approximately 65 % methane, is available for use external to the digestion plant. By way of comparison, a conventional anaerobic digestion process consumes 40 to 100 % of the methane produced to maintain the optimum operating temperature.

5. The process may be started up much more quickly than an anaerobic plant, eight to ten days being required instead of thirty to forty days to reach full operating capacity.

6. The stability of the anaerobic stage is considerably improved by the partial solubilization of particulate organic matter in the aerobic stage, allowing more rapid digestion (8 to 10 days retention). Alkalinity is produced through ammonification of proteins lending greater pH stability to the anaerobic digester.

7. Although the system requires two separate digestion tanks, the overall capital cost of the process is lower than that of conventional anaerobic digestion. This is a consequence of the reduced tank volumes required (60 % less volume for the anaerobic stage due to increased digestion rate) and the fact that no heating equipment is necessary.

8. The dual digestion process is particularly suited to cases where the existing anaerobic digestion plant has to be upgraded. By installing an aerobic reactor ahead of the existing anaerobic digester, the capacity of the plant may be increased by a factor of 2 to 3.

Recognizing the potential of the dual digestion process while it was still under development in the USA, the Water Research Commission (WRC) sponsored research by the Johannesburg Municipality into autothermal thermophilic aerobic digestion, i.e. the first stage of dual digestion, on a pilot scale. The promising results obtained prompted further research and accordingly, a tripartite agreement was finalized between the WRC, the Division of Water Technology of the CSIR, and Milnerton Municipality to evaluate a full-scale dual digestion process at Milnerton's Potsdam wastewater treatment works.

The research carried out under the joint agreement as well as detailed research into the ATAD process, specifically as it is applied in the first stage of the dual digestion process, have been comprehensively documented in a three part Final Report, viz. "Evaluation and optimization of dual digestion of sewage sludge".

Part 1 : **Overall system performance** by H A de Villiers, J R Messenger, K Kenmuir, S J A Laubscher and G A Ekama.
Part 2 : **Aerobic reactor performance** by J R Messenger, G A Ekama, H A de Villiers, K Kenmuir and S J A Laubscher.
Part 3 : **Evaluation of the technology for practical implementation** by S J A Laubscher, K Kenmuir, H A de Villiers, J R Messenger and G A Ekama.

RESEARCH AND DEVELOPMENT PROGRAMME

A large-scale dual digestion facility was to be established at Milnerton to treat about 50 m^3 sludge per day, using some of the existing infrastructure. The plant was to be commissioned and evaluated to determine whether the process would be technically and economically viable. Design criteria would also be established.

Specific items to be addressed were:

* Oxygen requirements and oxygen utilization efficiency, with pure oxygen and air oxygenation. The control of foam formation when using air was to be studied.
* Minimum retention time in the aerobic reactor while maintaining thermophilic temperatures and effective disinfection.
* Temperature control of the aerobic reactor and the anaerobic digester.
* The disinfection potential of the process and the mode of operation to prevent recontamination.
* The performance of the anaerobic digester with respect to minimum retention time for effective stabilization, gas production, sludge stability, operating stability, and the dewaterability of the final sludge.
* Process operating and control procedures, as well as basic design criteria for future plants.
* Economic and technical assessment of the process. Its performance was to be compared with that of the Zimpro process operating at Milnerton.
* Final Report on the process, including a literature review.

DUAL DIGESTION PLANT LAYOUT AND OPERATION

A schematic layout of the Milnerton dual digestion plant is shown in Figure 1. The plant comprised 3 tanks in series, i.e. a sludge thickener, an aerobic reactor and an anaerobic digester. The thickener and the reactor were identical 50 m^3 closed cylindrical laminated glass fibre tanks with conical bottoms. The sludge thickener had three draw-off points to enable supernatant decanting during gravity thickening, the supernatant being returned to the head of works. A mixture of primary and humus tank sludge was fed to the thickener from the central collection sump of the works.

The aerobic reactor was fully lagged with 50 mm polyurethane to minimize heat losses. Owing to the maximum temperature limit of 70 °C set by the manufacturers, 68 °C was used as the maximum reactor sludge temperature. The operating volume of the reactor was set at 45 m^3. The reactor was oxygenated with pure oxygen by means of a Vitox side stream pumped recirculation loop. The recirculating sludge was returned into the reactor through a special nozzle below the liquid surface which ensured the rapid and intense mixing of the reactor contents.

The aerobic reactor was operated on a batch draw and fill basis to avoid contamination of the pasteurized sludge by the feed sludge. This mode of operation also provided a very accurate means of sludge flow measurement, as each batch transferred from or fed to the reactor was a preset volume of exactly 1/12 of the reactor volume, i.e. 3.75 m^3. The time interval between feeding cycles was varied between 2 and 6 hours to achieve different retention times from 1 and 3 days.

The oxygen fed to the reactor was measured by means of accurately calibrated flowmeters. Vent gas volume was measured by means of a modified positive displacement town gas meter. Water vapour content and gas composition were also measured, enabling accurate calculation of the sludge oxygen consumption rate or equivalently the mass oxygen transfer rate (OTR) to the sludge, the oxygen transfer efficiency (OTE), the degree of vent gas water vapour saturation and the respiration quotient (mol carbon dioxide produced per mol of oxygen consumed).

The anaerobic digester used was a decommissioned 1000 m^3 domed concrete cold unit. Serving as the anaerobic digester of the dual digestion plant, the operating volume ranged between 400 and 900 m^3, depending on the retention requirements. As a consequence of the batch operating mode of the aerobic reactor, the digester was also batch fed, receiving 3.75 m^3 hot transfer sludge from the reactor every 2 to 6 hours, depending on the reactor retention time. To maintain the required retention time, sludge was discharged once daily from the digester in a single batch. The volume discharged was monitored by means of a 6 m high external sight-glass fitted to the digester for sludge level control.

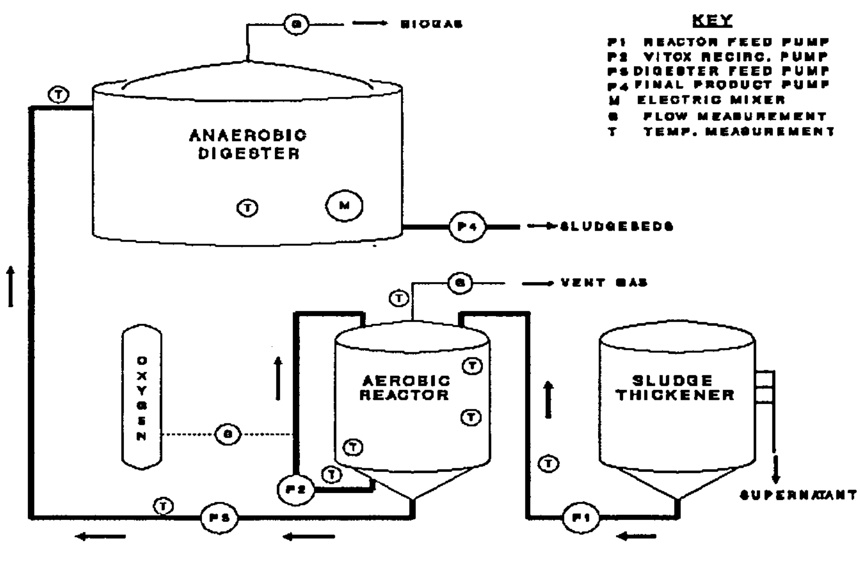

Figure 1: A schematic layout of the dual digestion plant.

No external heating was provided, the hot aerobic sludge transferred from the reactor being the only heat source available to maintain the digester at mesophilic temperature. Mixing of the contents was effected by means of a submersible propeller mixer or by an external recirculation pump. Biogas production was monitored with a modified positive displacement town gas meter.

Almost four years after commencement of the project, the research was precipitously terminated as a result of the structural failure of the laminated fibre glass aerobic reactor. Fortunately by this time most of the aspects requiring research had been addressed at least in part, although certain aspects could have been investigated in greater depth, such as minimum anaerobic digester retention time and final sludge dewaterability. Sufficient information had, however, been acquired to make a reliable evaluation of the dual digestion process. The results achieved during this evaluation have been comprehensively documented in a three part final report, viz. "Evaluation and optimization of the dual digestion of sewage sludge".

AEROBIC REACTOR INVESTIGATION

Kinetics of biological heat generation

In order to be able to assess the aerobic reactor performance and behaviour during this investigation, it was necessary to examine the kinetics of biological heat generation. It was realized that a distinction had to be made between the objectives of the thermophilic aerobic reactor in dual digestion and thermophilic aerobic digestion as a stand alone process. In the latter process, the principal objective is sludge stabilization, i.e. to reduce the sludge energy as measured by volatile solids (VS) removal. Accordingly the process kinetics are defined in terms of the rate of VS degradation, from which the retention time required to achieve a specified VS removal can be calculated as well as the rates of biological heat generation and oxygen utilization. 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, as heat generation was the principal objective and not sludge stabilization.

During this investigation it was found that the reactor should be operated under oxygen limiting conditions and that very little VS removal occurred although large quantities of biological heat were generated. Because the reactor could be operated under oxygen limiting conditions and the generation of biological heat can theoretically be shown to be stoichiometrically related to oxygen consumption rate, it was proposed that the oxygen supply rate (OSR) and the sludge oxygen consumption rate (O_c), the latter being related to the OTR of the oxygenation system - are 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 rate of biological heat generation and the oxygen consumption rate via the specific heat yield (Y_H, MJ/kgO); and
- demonstrating that with the OSR, instantaneous and complete control of the reactor sludge temperature could be obtained.

EVALUATION OF THE AEROBIC REACTOR

In order to measure the specific heat yield (Y_H), accurate heat and oxygen mass balances were made across the reactor.

The heat balance was obtained by measuring during the heating phase of the saw-tooth temperature fluctuation:

- the rate of sludge temperature increase, which is proportional to the sludge enthalpy increase rate (H_{net});
- the Vitox recirculation pump mechanical heat input rate (H_{mi});
- the wall heat loss rate (H_{we}); and
- the vent gas water vapour heat loss rate (H_{ve}). From these measurements, the biological heat generation rate (H_{bi}) could be determined.

The oxygen mass balance was obtained by measuring, over the same heating period (1) the influent oxygen supply rate with accurately calibrated rotameters and (2) the oxygen content of the dry vent gas. The oxygen consumption rate (O_c) of the sludge could thus be determined. By dividing the biological heat generation rate (H_{bi}) by the oxygen consumption rate (O_c), the specific heat yield (Y_H) was calculated.

Apart from the heat and oxygen mass balances, influent and effluent sludge volatile solids (VS) and Chemical Oxygen Demand (COD) concentrations were also measured to see if a correlation could be established between VS and COD removal and the rates of biological heat generation and oxygen consumption. Routine analyses on sludge samples were also performed to determine the changes in total solids, volatile solids, COD, ammonia, bicarbonate alkalinity and pH.

AEROBIC REACTOR RESULTS

The aerobic stage operated very reliably with the minimum of operator attention for nearly four years, with an on-line record of 91 %, in spite of it being subject to stoppages for experimental reasons which would not occur in practice. The maintenance of average reactor temperatures high enough to effectively destroy *Ascaris* ova was never a problem, and full temperature control was possible by simply varying the oxygen supply rate. A mathematical model was developed to simulate reactor sludge temperature changes with time so that the temperature response to a wide range of operating conditions could be very accurately predicted.

The retention time in the reactor was varied from 1.0 to 3.0 days, depending on the research requirements. Steady operation at retention periods from 1.25 to 3.0

days was possible under all conditions, while continuous operation at 1.0 day retention was only possible during summer. This showed that with the exploitation of supplementary heat sources such as heat exchange between the influent and effluent reactor sludge or combustion of methane from the anaerobic stage, continuous operation at one day retention was feasible all year. The evaluation of the overall dual digestion system showed that it was necessary to incorporate some means of cooling the aerobically treated sludge before transferring it to the anaerobic digester. By installing a simple batch heat exchanger to transfer excess heat from the aerobic sludge to the influent sludge the process would benefit by (1) requiring shorter retention times in the aerobic reactor, (2) achieving disinfection temperatures and oxygen limitation at lower oxygen transfer rates, (3) reducing oxygen consumption and power requirements for oxygen transfer and mixing.

Over the test period the average mass of oxygen supplied to treat 1 m^3 of sludge was 12.8 kg, but this varied between 6.0 to 24.3 kg O/m^3 depending on the operational requirements. The oxygen utilization efficiency (O_{eff}) varied from 66 to 100 %, with the efficiency decreasing as the supply rate was increased. This was attributed to the loss of efficiency in the Vitox oxygenation system at higher transfer rates.

The Vitox recirculation pump uses more than 98 % of the electrical power required by the aerobic reactor. The nominal power drawn by this pump is 20.5 kW, but some 17.4 kW of this goes towards heating the sludge. This pump operates continuously and has a daily power consumption of about 1772 MJ. The feed and transfer pumps operate intermittently and their power consumption varies with reactor retention time, but even at one day retention their combined consumption was less than 2 % of the total. On average, the overall power consumption was 1800 MJ/d or 500 kWh/d.

A total of 116 heat and oxygen mass balances performed on the aerobic reactor yielded the following results:

(1) The biological heat generation rate (H_{bi}) was directly proportional to the OTR, or equivalently to the sludge oxygen consumption rate (O_C). The constant of proportionality is the specific heat yield rate (Y_H), which was measured to be 13.1 MJ/kgO. This value conforms closely to thermodynamically and bio-energetically calculated values. It was found that Y_H was independent of reactor sludge temperature or retention time, but was slightly dependent on the degree of oxygen limitation [defined as (1 - OTR)/OUR, where OUR is the sludge oxygen utilization rate in the absence of oxygen limitation], increasing as oxygen limitation increased.

(2) The reactor sludge temperature could be completely and almost instantly controlled by means of the OSR, while the reactor was operated under oxygen limitation, i.e. while the OTR was less than the maxim OUR. The Milnerton sludge, which is a mixture of primary and humus sludge, had an OUR of about 0.38 kgO/(m^3.hour) at an average concentration of 30 kgVS/m^3. Step increases in OSR as high as 330 % [from 0.13 to

0.43 kgO/(m^3.hour)], which increased the OTR and hence the biological oxygen consumption rate by 300% [from 0.13 to 0.39 kgO/(m^3.hour)], caused an immediate increase in the biological heating rate (H_{bi}), which increased the reactor sludge temperature. Similarly, decreasing the OSR caused an immediate decrease in H_{bi}, resulting in a lower steady reactor sludge temperature. Increases in OSR did not result in an equivalent increase in OTR, as the oxygen transfer efficiency (OTE = OTR/OSR) decreases with increasing OSR.

(3) The respiration quotient, (Y_{CO2}), i.e. the number of moles of CO_2 generated per mole of oxygen consumed by the sludge, was found to be 0.66 instead of the usually assumed value of 1.0. This anomaly could not be explained as yet, but had the value of 1.0 been accepted, Y_H would have been over-estimated by more than 20 % during this evaluation.

(4) The vent gas from the reactor was found to be saturated with water vapour at all vent gas flow rates. This is important in calculating heat losses in the vent gas.

(5) COD and/or VS removal rates were poor parameters for quantifying the biological heat generation rate and for controlling the reactor sludge temperature. The tests for these parameters are prone to such a high degree of variability when dealing with sewage sludges that it is virtually impossible to reliably establish 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) makes the OTR a pivotal parameter in design and process simulation of autothermal thermophilic reactors in dual digestion.

The results of routine monitoring of the reactor showed that, on average, a VS reduction of 12.8 % and a COD reduction of 17.9 % occurred. The removal of more COD than VS by the aerobic process caused a decrease in the COD/VS ratio from 1.649 to 1.552 for the influent and effluent sludges respectively. As the COD/VS ratio forms the link between the kinetics of biological heat generation and oxygen consumption in the models of autothermal aerobic digestion where the kinetics are controlled by the VS degradation rate, it is clear that this approach is inappropriate in the case of the aerobic reactor in dual digestion as the COD/VS ratio changes through the reactor.

The routine analyses showed that significant increases occurred in ammonia nitrogen and bicarbonate alkalinity levels which would benefit the subsequent anaerobic digestion process.

DESIGN AND SIMULATION ASPECTS

Steady state heat balances carried out across the aerobic reactor under various conditions produced data that were required for design purposes. In simplified form, the steady state heat balance equates the heat sources i.e. biological heat generation and mechanical heat input from pumping for oxygenation and mixing, with the heat losses i.e. hot effluent sludge, vent gas water vapour and sensible heat loss, and heat lost from the reactor walls and pipework. Although the reactor was batch fed to avoid recontamination of the disinfected sludge and therefore not at a constant temperature, a steady state approach was used as this would simplify the design procedure.

To meet the two main objectives for the aerobic reactor in dual digestion i.e. effective pasteurization and sludge pretreatment, the design approach has to ensure that:

1. the specified pasteurization temperature and times are maintained; and

2. the sludge is oxygen limited. Oxygen limitation is essential not only for pretreatment, but also for reactor temperature control. As stabilization is not an objective of the reactor, the oxygen supply rate is governed solely by the requirement of generating sufficient biological heat for pasteurization.

The aerobic reactor design would therefore attempt to minimize retention time by maximizing the heat sources and minimizing the heat losses. The steady state heat balances showed that three parameters are of crucial importance to design, viz:

(a) The sludge OUR, which determines the maximum biological heat generation rate via the specific heat yield (Y_H).

(b) The OTR of the oxygenation system. The biological heat generation rate is directly proportional to the OTR via Y_H. The OTR should be less than the OUR to ensure that the process is oxygen limited.

(c) The OTE of the oxygenation system. The OTE controls the vent gas volumetric flow rate for a particular oxygenation system. The lower the OTE the greater the vent gas flow rate and hence the greater the vent gas heat losses.

At a given OTR and mechanical heat input, the heat sources are fixed. If the OTE is high (> 0.80) and oxygenation is with pure oxygen, vent gas heat losses are small and most of the heat is lost via the hot effluent sludge allowing short retention times (1.25 to 2 days). If the OTE is low (0.1 to 0.2) and oxygenation is with air, vent gas heat losses are high and much less heat is lost via the effluent sludge which necessitates long retention times (4 to 6d). At Milnerton, where the sludge OUR was about 0.38 kgO/(m^3.hour), and high OTR's [0.37 kgO/(m^3.hour)] and OTE's (> 0.80) were achieved with the use of pure oxygen, the vent gas heat losses were very low allowing 1.25 day retention time operation and reactor temperatures above 60 °C. Air oxygenated systems typically have much lower OTR's and OTE's [e.g. 0.14 kgO/(m^3.h) and 0.12 respectively at the Athlone plant], thus most of the heat is lost via the vent gas with the result that the amount lost in the effluent sludge is small thereby requiring long retention times if sludge temperatures are to be maintained above 60 °C.

Increasing the biological heat rate requires an increase in the OTR. This in turn requires a higher oxygen or OSR which usually reduces the OTE. This results in higher vent gas heat losses. The use of supplementary heat sources, such as heat exchange between reactor effluent and feed sludge, increased mechanical heat input, or by combustion of part of the biogas from the anaerobic digester, have the effect of increasing the heat sources without increasing the heat losses, allowing a reduction in the retention time.

The design procedure used is based on a steady state heat balance which assumes a constant sludge temperature, i.e. a continuously fed reactor. Batch feeding is used in practice to prevent recontamination of the pasteurized sludge, which results in a continuously changing reactor sludge temperature over about 3 °C in a saw-tooth pattern. By assuming steady state conditions the error is small and well justified by the simplification it affords. The saw-tooth temperature profile can only be determined by solving the unsteady state heat balance by a forward integration method. An algorithm and computer programme were developed which solve the unsteady heat balance in order to simulate the temperature profile of the batch fed aerobic reactor. For specified input conditions identical to those observed in the Milnerton reactor, the simulation programme was found to simulate the reactor sludge temperature to within 0.5 °C. Whereas the steady state design allows only the required pasteurization temperature to be specified, the simulation programme allows both the sludge pasteurization temperature and the undisturbed sludge detention period to be defined, the latter in terms of the interval between consecutive batch feeds.

ANAEROBIC DIGESTER EVALUATION

The anaerobic digester in a dual digestion plant has the advantage of operating on a pre-treated sludge and should, according to the claims, perform significantly better than a normal high-rate anaerobic digester. Process stability is supposed to be improved due to solubilization of particulate organics and production of alkalinity in the aerobic stage, which should allow full stabilization to occur at shorter retention times. In general, the operation and performance of the anaerobic digester at Milnerton did not differ significantly from those of a conventional high-rate mesophilic anaerobic digester except for the start up and temperature control.

Routine process monitoring included analyses for TS, VS, COD, ammonia N, alkalinity (to pH 5.75 and 4.3), volatile acids and pH. Digester sludge temperature, daily feed volume and draw-off, average daily digester operating volume and gas production were carefully monitored. The dewaterability of the final sludge was only evaluated towards the end of the test, as it was intended to include this step in the overall evaluation of the process once a heat exchanger had been installed to provide manageable temperature control for the anaerobic digester.

ANAEROBIC DIGESTER RESULTS

The anaerobic digester was only started up once the aerobic reactor had reached a stage of development such that it could reliably provide aerobically treated sludge for the digester. Starting up the anaerobic digester without seeding it with sludge from an active digester took about 3 to 4 months during which chemical addition was required to keep the pH above 6.8. It was not possible to seed it because it would have compromised the disinfected status of the digester and it would have taken a considerable time for the pathogenic organisms to be washed out of the system.

The initial start up took place during relatively warm conditions (summer/autumn) and normal operation was only established after 96 days. The next time the digester was restarted was during late autumn and after numerous problems normal operation was only achieved 153 days later. Apart from the drawback of not being able to "seed" the digester when starting from scratch, the problem was compounded by the fact that the sludge temperature could not be maintained without feeding the digester. Feeding increased the volatile acids, hence the need for chemical addition for pH control. The need for some means of feed sludge temperature control was obvious during the initial start up phase.

Throughout the investigation all the heat required to maintain the digester at mesophilic temperatures was derived from the hot sludge transferred batchwise from the aerobic reactor. It was attempted to maintain the digester temperature at about 38 °C. Problems were experienced during summer when the heat lost by the digester was reduced and it would overheat unless the heat input, i.e. the feed volume, was reduced. This considerably compromised the maintenance of predetermined retention times and emphasized the need for some means of controlling the aerobic feed sludge temperature by, for example, fitting a heat exchanger. A simple jacketed batch heat exchanger was manufactured and installed during 1990, but it was not used as the collapse of the aerobic reactor stopped further research.

The average retention time in the anaerobic digester was about 21 days. It was found that stable operation could be maintained at 15 days retention, if temperature conditions were suitable, but that instability occurred after operating for five weeks at 12 days retention. It seemed most unlikely that the claims of ten days retention would have been achieved at Milnerton even under ideal conditions.

The volume of biogas produced by the digester varied considerably, but it was at least as much as is produced by a normal mesophilic anaerobic digester operating under similar load conditions. At an average VS removal of 12.6 kg VS/m^3 (calculated at digester operating volume) a specific gas production (at STP) of between 0.94 and 1.09 m^3/kgVS removed was obtained. This is in line with the specific gas production of normal heated mesophilic anaerobic digesters which produce form 0.75 to 1.1 m^3/kgVS destroyed (at STP).

On average the digester effected a large reduction in VS (49 %) and in COD (44 %), but this was achieved at more than double the retention time claimed possible for dual digestion plants. Extrapolation of the data produced during this evaluation indicated that at 10 days retention a COD removal of about 25 % could be expected, which appears to be much to low for effective stabilization.

The stability of the digestion process was very good while operating at retention times of 15 days or more. The pH and bicarbonate alkalinity remained high while volatile acid levels remained low. The physical appearance of the sludge clearly reflected the degree of solids breakdown in the digester, the general appearance being that of black ink, with very small solid particles suspended in it. In general, the stability of the anaerobic digestion process was excellent when not over-loaded and was unaffected by daily fluctuations in load and temperature. When signs of instability occurred when the retention time was reduced to 12 days, recovery was rapid once the load had been reduced.

The final sludge produced by the digester dewatered reasonably well on sludge drying beds during hot weather at Milnerton, where it neither attracted flies nor generated offensive odours. In spite of the high degree of VS reduction by the dual digestion process, the sludge continued to generate gas after being discharged to the drying beds. The gas floated some of the sludge to the surface, while the remainder settled and tended to blind the drying bed media. The relatively clear layer in between could be drained off after which the sludge dried reasonably well during hot weather and could be manually removed from the beds 6 to 8 days after being discharged onto the beds.

Three series of sludge dewaterability characterization tests were carried out in the laboratory on samples of final sludge from the anaerobic digester. In terms of capillary Suction Time (CST) and Specific Resistance to Filtration (SRF) values, the results of trial dewaterability test runs showed that it was very difficult to dewater the sludge produced by the dual digestion process with filtration based technology. It was found that the high content of fine particles caused blinding of the filter media and blocked the drainage passages through the sludge cake that forms on the filter media. Addition of polyelectrolyte improved filtration slightly but did not produce a significant increase in cake solids content during pressure filtration. It did, however, improve gravity settling significantly. Electro-osmotic dewatering techniques also proved ineffective. The most effective means of dewatering was by centrifugation, after additional of char (pyrolyzed domestic refuse) and a small quantity of polyelectrolyte, which would produce an end product with a solids content of around 20 %.

As the sludge settles well once gas production had ceased, gravity thickening, as applied in Europe, is a viable option to reduce the sludge volume before dewatering. Other disposal options, either in thickened or dewatered form, include application as a liquid or solid fertilizer, addition to compost.

DISINFECTION

On the basis of the indicator organisms selected for evaluating the disinfection capabilities of the dual digestion process, the results were satisfactory. On average, the aerobic stage of the dual digestion process effected a 9 log reduction in faecal coliforms and only on one occasion was a positive count obtained for viable *Ascaris ova* while the reactor was operating at or above 60 °C. This exception could have been due to a sampling error. The anaerobic stage does not effect a significant further change in the indicator organism numbers and indications are that regrowth of coliforms occurs to some degree. Three positive viable *Ascaris* counts occurred, but as no contamination could have occurred in the digester, it was impossible to explain this anomaly other than by assuming contamination during sampling.

If information cited in the literature with regard to the destruction of *Ascaris* ova is correct, it is impossible for any viable *Ascaris* ova to survive the conditions in the aerobic reactor while it is operating at a temperature of 60 °C or higher at a minimum batch retention time of two hours or more. It is also unlikely that viable ova would be present in the final treated sludge from the anaerobic digester if they had all been destroyed in the aerobic reactor as these organisms do not regrow.

OVERALL ASSESSMENT OF THE DUAL DIGESTION PROCESS

The dual digestion process as applied at Milnerton proved to be easy to operate and control and performed well, both in adequately stabilizing the sludge and in providing a high degree of disinfection.

Overall TS reduction was 50.8 %, with VS reduction of 56.6 % and COD reduction of 54.4 %. Stabilization at the relatively high retention times used in the anaerobic digester was therefore very good with more than half of the solids being removed, considerably reducing the problem of final disposal. The dewatering of the final sludge is similar to that of anaerobically digested sludge. The sludge could be dewatered and subjected to normal disposal practices, or otherwise it could be used as a liquid soil conditioner.

The overall process stability was excellent with minimum retention times of 1.25 days in the aerobic reactor and 15 days in the anaerobic digester. The added buffering provided by the increased bicarbonate alkalinity, ammonia N and pH from the aerobic stage improved the anaerobic process stability, but did not significantly reduce the retention time that could be used in practice. Biogas production (at 21 days retention) appeared to be approximately the same as that of a normal high-rate anaerobic digester. Both the gas production and the solids/COD reductions will decrease at 15 days retention in the anaerobic digester, but overall stabilization should still be adequate. Digester instability occurred at 12 days retention, so it is unlikely that the claims of 10 days retention will be possible with the Milnerton sludge.

At 1.25 days retention time in the aerobic reactor, at which the reactor could maintain temperatures above 60 °C during summer and winter, about 80 % of the required heat was supplied by biological means, the remainder was mechanical heat input via the recirculation pump. At Milnerton, the mechanical heat input was excessive and a lower value can be expected in other full scale plants. A greater proportion of the heat would then be biologically generated. This substantiates the claim that most of the heat for the process is biologically produced. The maximum reactor sludge temperature was restricted to 69°C at Milnerton owing to the limitations of the laminated fibre glass reactor vessel. Temperatures in excess of

70 °C could have readily been achieved by increasing the retention time to 1.5 days and increasing the oxygen supply rate to increase the biological heat generation. At temperatures above 70 °C for more than 30 minutes undisturbed retention time, the reactor would comply with pasteurization specifications and qualify as a process to further reduce pathogens rather than only as a process to significantly reduce pathogens.

During winter, all the heat of the aerobically treated sludge, with the reactor at 1.25 days retention, was required to maintain 37 °C in the anaerobic digester at 15 days retention. During summer, the heat input was too large with the result that the digester overheated unless the aerobic reactor retention time was increased or the hot aerobic reactor sludge was diverted to reduce the heat input to the digester. This substantiates the claim that the heat from the aerobic reactor is sufficient to maintain mesophilic temperatures in the anaerobic digester. In a properly designed dual digestion system the anaerobic digester would be lagged with the result that a heat exchanger would be required to avoid overheating of the digester even during winter. An additional benefit of a system employing heat exchange between the effluent and influent aerobic reactor sludges would be the reduced oxygen requirement, as the supplementary heat from the exchanger would reduce the amount of biological heat that must be generated.

Operating the aerobic stage with air or an air/oxygen mixture was not attempted at Milnerton, but the design criteria developed which were based on the thorough evaluation of the aerobic reactor using pure oxygen would be applicable to any oxygenation system.

The overall degree of disinfection/pasteurization achieved was good. The process as applied at Milnerton eliminated any possibility of short-circuiting in the aerobic stage which could compromise disinfection. Ascaris ova were inactivated in all but a few cases and considerable reductions in faecal coli occurred in the aerobic reactor, but it appeared as if regrowth of the latter organisms occurred in the anaerobic stage.

It would be entirely feasible to operate the aerobic stage at a higher temperature or at a longer retention time to effect a higher degree of disinfection if required. It would also be possible to operate the anaerobic digester at thermophilic temperature to obtain more effective digestion and disinfection. Operating both stages at thermophilic temperatures would obviate the need for a heat exchanger between the stages but would require effective insulation of the anaerobic digestion vessel. Part of the biogas produced could be used for supplementary heating, if required, but the benefits gained by employing thermophilic temperatures in both the aerobic and anaerobic stages would offset the loss in biogas produced for external use.

To make a cost evaluation of the dual digestion process is difficult as there are numerous factors to consider and most of these are related to the specific application. The requirements and objectives, as well as the unit treatment cost could differ considerably from plant to plant. In many cases existing plant would be adapted and converted to dual digestion, while others would be built from scratch. The sludge characteristics may also affect the cost. A meaningful economic evaluation of the dual digestion process therefore cannot be done unless details of the particular application are known.

The running costs of the dual digestion plant at Milnerton during 1989 was R5.29/m^3 (wet), or R132.25/ton dry solids, with power cost taken as 10c/kWh and oxygen cost as 30c/kg. During the same period running costs for the Zimpro plant at Milnerton was R 5.13/m^3 (wet), with fuel cost taken as 96c/litre. The dual digestion plant at Athlone, Cape Town, which uses air for oxygenation of the aerobic stage, appeared to be operating at R 1.63/m^3 (wet). The latter plant operates at a very low oxygen transfer efficiency, has long aerobic reactor retention times (4 to 6 days) and does not reach disinfection temperatures.

Only running costs associated with energy and oxygen supplied have been considered in the above comparison. A full cost evaluation or comparison would have to include costs associated with capital requirements, personnel and maintenance. Such an evaluation would be very specific to the application, the site location, the type of treatment works etc. It is considered beyond the scope of this investigation to do a detailed costing of a specific plant as this would have very limited value. Instead, Part 3 of the Final Report highlights the factors that must be considered which will affect costs as this is considered more meaningful and does not relate to a particular site or application.

CONCLUSIONS

The conclusions to be drawn from the evaluation of the dual digestion process must first of all, be considered in the light of the claims made for the process as set out earlier. The claims, with the conclusions drawn,if possible, are detailed below:

1. **Claim: Disinfection and stabilization of the sludge occurs in a single process.**

This has been adequately established during the evaluation at Milnerton.

2. **Claim : The energy requirement for supply and dissolution of oxygen is low since the degree of oxidation of the sludge is limited, the only requirement being the maintenance of disinfection temperature. Stabilization is completed in the anaerobic digester, which requires no oxygen.**

It was concluded that this claim was essentially correct, although at Milnerton good oxygen dissolution was ensured by an efficient oxygenation system (VITOX) and an oversized pump. The excess energy input of this pump helped to raise the sludge temperature. Less oxygen was therefore required. Because the cost of electrical energy and that of the equivalent amount of oxygen required to generate the same amount of heat does not differ significantly, nothing is lost by using a larger recirculation pump for mixing and oxygen dissolution.

3. Claim : **No external heating of the anaerobic digester is required as all the necessary heat is provided by the hot sludge fed to the digester from the aerobic reactor.**

The above claim is valid as adequate heat was produced to maintain the temperature of the anaerobic process at its optimum level. During summer conditions far more heat that required was produced, resulting in overheating of the anaerobic process. It was concluded that a batch heat exchanger which would cool the effluent sludge from, and heat the influent sludge to the aerobic reactor was an essential requirement. This would enable proper temperature management of the anaerobic process to be practised and reduce the oxygen requirement in the aerobic process.

4. Claim : **The process is an overall net producer of energy, since all the biogas, which contains approximately 65 % methane, is available for use outside the dual digestion plant.**

Depending on the approach taken, the aerobic reactor could be considered to be a net producer of energy. The maximum biological power generated by the aerobic stage at Milnerton was 73kW as low grade heat. The oxidation reaction consumed 20 kg/h pure oxygen from the 24 kg/h supplied. The electrical power to dissolve the oxygen at 83 % efficiency was 19 kW, but 17kW was recovered as heat by the sludge. Thus a total of 90 kW of power as heat was obtained from 19kW electrical power. But the oxygen also represents a power input. To produce liquid oxygen requires 1100 kWh per ton, therefore each kg pure oxygen supplied is equivalent to 1.1 kWh electrical energy. The 24 kg/h therefore represents an additional 26 kW power input which is not recoverable.

In total, therefore, 45 kW electrical power (= 19 + 26) was converted into 90 kW heat, which gives an effective gearing of 2.0.

If the oxygen had been produced on site as gaseous oxygen of 95 % purity using a pressure swing absorption (PSA) plant of 10 tons/day capacity, this would consume 300 kWh energy per ton. Therefore 1 kg O2 would be equivalent to 0.3 kWh electrical energy. The oxygen supplied (24 kg/h) thus represents 7 kW power which is not recoverable. The total power supplied is thus 26 kW (= 19 + 7), for an output of 90 kW.

In real (cost associated) terms, the aerobic reactor can therefore be considered a net energy producer.

The anaerobic digester produces about 350 m^3/day of biogas. This is approximately equivalent to 8330 m^3/day or 96 kW of power which is available for heating or for fuelling a gas engine which may, for example, be used to generate electrical power.

The overall dual digestion process can therefore be considered to be a net producer of energy.

5. Claim : **The process may be started up much more quickly than an anaerobic plant, eight to ten days being required instead of thirty to forty days.**

It was found that the aerobic reactor could be started in approximately four days, To start the anaerobic digester without seeding it from another pathogen free anaerobic digester may take a month or more. At best the overall dual digestion process will require as much time to start up as a normal mesophilic anaerobic digester.

6. Claim: **Although the system required two separate digestion tanks, the overall capital cost is reduced compared with conventional anaerobic digestion. This is a consequence of the reduced tank volumes required (60 % less volume is needed for the anaerobic stage) and the fact that no heating equipment is necessary.**

It is not possible to comment on this statement based on the Milnerton experience. There it was found that 15 days was about the lowest retention time that could be employed without endangering the stability of the process. This was approximately half the retention required with relatively inefficient older type mesophilic digesters, but not significantly better than can be achieved with modern high rate digesters which reputedly give effective stabilization in 15 to 20 days. A new dual digestion process may therefore not necessarily be less costly than a new high rate anaerobic digester, but the latter does not provide disinfection of the sludge. The capital cost of an anaerobic digester plus a pasteurizer will in all likelihood be considerably more than a dual digestion plant.

7. Claim: **The stability of the anaerobic stage is considerably enhanced by the conditioning effect of the aerobic stage by:**

* *Reducing the effects of toxic organic contaminants in the feed sludge.*

This was not evaluated at Milnerton.

* *Oxidizing the rapidly degradable components of the sludge which helps to maintain the balance of growth rates of acid formers and methane producers in the digester.*

It was not attempted to prove this theory. It may have been a factor in the good stability achieved.

* *Solubilizing part of the solid organic material at the thermophilic temperatures reached in the reactor.*

This was not specifically investigated. The aerobically treated sludge did contain a significant quantity of extremely fine particles which would not settle on standing. This colloidal nature made the aerobic sludge virtually non-filterable. The larger particles present in the feed sludge had definitely been broken down, but to what degree solubilization had occurred was not established.

* *Ammonium ions are produced by the deamination of organic nitrogen compounds, increasing the alkalinity.*

Ammonia N increased on average by 80 %, while the bicarbonate alkalinity (as approximately determined by titration to pH 5.75) increased by over 4000 %. The pH on average increased from 5.6 to 7.1. This claim is therefore correct.

* *Temperature fluctuations are minimized by controlling the heat input from the aerobic stage.*

The temperature of the anaerobic digester can be controlled as stated, but not without either changing the aerobic reactor throughput, or by changing its operating temperature, or by bypassing some of the aerobic sludge to waste or to a storage tank.

None of these methods provide a satisfactory means of controlling the digester temperature, as either the treatment capacity or the disinfection potential of the overall process is affected. By employing a batch heat exchanger to transfer excess heat from the aerobically treated sludge to the untreated sludge, the temperature of the anaerobic stage could be accurately controlled.

8. Claim: **The dual digestion process is particularly suited to cases where an existing anaerobic plant has to be upgraded, by installing an aerobic reactor ahead of the existing digester. The capacity of the plant may be increased by a factor of 2 or 3.**

This claim is essentially correct. A number of anaerobic plants have been upgraded by addition of an aerobic reactor in Europe and America. Information on the improved treatment capacity achieved has not been available. Judging by the performance of the Milnerton plant (which was also an "upgrade") where the capacity of the anaerobic digester was in effect, doubled, similar improvements in performance were probably achieved elsewhere. But as a 15 day retention was found to be necessary in the anaerobic digester, a plant's capacity would be trebled only if the original anaerobic plant had operated at a retention of 45 days or more.

In summing up the results of the evaluation, it was found that most of the claims made for the dual digestion process are essentially correct. The process is very flexible and easy to operate and control. It effectively disinfects and stabilizes sludge and produces biogas which may be used for other applications. By adding an aerobic stage to existing anaerobic digesters it can effectively enhance the performance of an overloaded plant.

The disadvantages are the relatively slow start up of the anaerobic process and the dewatering characteristics of the treated sludge. The latter may not be a disadvantage if the sludge is to be used as a liquid soil conditioner.

EVALUATION AND OPTIMIZATION OF DUAL DIGESTION OF SEWAGE SLUDGE

PART 1 : OVERALL SYSTEM PERFORMANCE

by

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