SLUDGE STABILISATION AND DISINFECTION BY MEANS OF AUTOTHERMAL AEROBIC DIGESTION USING OXYGEN

FINAL REPORT

by

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P.O. BOX 4323
JOHANNESBURG
2000

APRIL 1984

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ABSTRACT

The handling and disposal of sewage sludges are major problems in South Africa. In order to assist with the problems of local authorities in this field the Water Research Commission has embarked upon a programme of national research in this field including the project undertaken in conjunction with the City Council of Johannesburg which involved research into the effectiveness of the autothermal aerobic digestion process in terms of inactivation/destruction of selected pathogenic micro-organisms present in sewage sludges.

Research at pilot scale was undertaken into autothermal aerobic digestion of sludge using oxygen to demonstrate that sufficiently high temperatures could be achieved to ensure the degree of disinfection that would satisfy the health authorities. The ova of the helminth Ascaris lumbricoides was used in the disinfection studies and the dissolved oxygen level in the sludge was used as a means of controlling oxygen consumption.

The results achieved indicated that the process was very robust and rapidly attained a stable temperature of the order of 60°C which could be easily maintained and which effectively ensured disinfection of the sludge at retention periods of as low as one day. It was found that the aerobically treated sludge would not settle and was very difficult to dewater. In addition, the treated sludge was found to readily ferment anaerobically thus indicating the need for further treatment prior to final disposal.

ACKNOWLEDGEMENTS

This research project was financed by the Water Research Commission on a partnership basis with the City Council of Johannesburg. AFROX LIMITED provided considerable financial support to the project by way of providing the VITOX oxygen injection and control equipment as well as the total oxygen requirements of the research programme.

The author would also like to express sincere appreciation of the efforts of the following persons:

- Messrs. W.J. ENGELBRECHT, A.P. FISH, B.G. WEBB and other members of the staff of the Olifantsvlei Sewage Purification Works for their unstinting efforts during the research programme.
- MR. S.L.V. VENTER and staff for carrying out all the chemical analyses.
- MRS. L. MELMED and staff for carrying out all the micro biological analyses.
- MESSRS. M. WHITE and R.D. FORREST of AFROX LIMITED as well as J.E. McGLASHAN and A.R. PITMAN for their enthusiasm, encouragement and suggestions.
- The Steering Committee, as detailed below, for their able guidance and support throughout the research period.

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1. INTRODUCTION:

Throughout the world today considerable attention is being given to the treatment and disposal of sludge resulting from the purification of domestic wastewaters. In South Africa there is no doubt that this question has become one of the major problems facing local authorities.

Sewage sludge contains inert particulate matter, oxidisable organic matter (particulate and dissolved), nutrients, trace elements, a variety of persistant substances and a range of pathogenic and non-pathogenic micro-organisms. The organic matter in sewage sludge is a valuable soil improver and in addition the sludge contains substantial amounts of nitrogen, phosphorus, calcium and magnesium and trace elements which are of value to agriculture. However, its universal use in agriculture and horticulture carries with it certain risks to public health. Oberholster (1983) states that South Africa does not differ from any other part of the world in its concern about the health aspects of the disposal and use of sewage sludge and its consequent control and that due to our agrarian way of life, the incidence of ascariasis in the population is high.

As the ova of Ascaris lumbricoides appear to be highly resistant, their presence may be a useful indicator of the hygienic quality of treated sewage sludge under South African conditions.

Not all countries have adopted the strict guidelines implemented by South Africa where sludge is disposed of to land. In the United Kingdom, for example, where the pathogen position is different to that in South Africa, Coker (1983), reports that sludge has regularly been used for market gardening and vegetable growing. Disposal policy in the United Kingdom is, however, steering sludge utilisation away from these outlets towards grain crops and land where any possible health hazard due to pathogens is remote. In the Federal Republic of Germany, on the other hand, Strauch (1983), reports that it is expected that in the near future sludge which is not disinfected will no longer be permitted on pastures and on arable land used for the production of forage.

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The guidelines for the utilization of sludge in South Africa, presented by Oberholster (1983), do not permit the use of raw sludge in agriculture. Secondary sludge (eg. digested sludge) may not be used on tuberous, bulb-type or low growing vegetables exposed to contamination or on lawns (except at planting), forage for animals, sports fields or public parks. Use is permitted for crops not eaten raw by humans, (eg. sugar cane), and for parks and sports fields during development only. Tertiary sludge (i.e. secondary sludge having been matured on drying beds for more than 90 days; raw, primary or secondary sludge that has been composted at 50°C to 65°C, according to accepted criteria or sludge pasteurised at less than 80°C), may be used on vegetables only if pathogen free i.e. no E.Coli, Ascaris lumbricoides ova or pathogenic viruses in 100g of sludge. Its use is unrestricted for other crops if well mixed with the soil, but it is not permitted as a top dressing such as on lawns. Sludge which has received advanced treatment (i.e. irradiation or high temperature treatment (150°C to 230°C)), may be used without restriction.

These guidelines give a clear indication of the degree of treatment required before sludge may be used in agriculture or horticulture and are particularly severe in regard to the presence of the very resistant ova of the parasitic roundworm Ascaris lumbricoides. The guidelines do not take into account the potential health hazards due to heavy metals and other toxic substances and relate principally to the hygienic quality of the sludge.

Due to the stringent health requirements and the lack of suitable disposal options, many of the municipalities are forced to dispose of sludge on the site of the sewage treatment works. Generally land is available for such disposal but the rates of sludge application are far in excess of those normally accepted for agricultural use. Large areas are therefore used for disposal and in the long term will be rendered unsuitable for further agricultural use. These measures are temporary solutions to the immediate problems being experienced but will undoubtedly feature for some time to come.

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In order to assist with the problems of local authorities in this field the Water Research Commission embarked upon a programme of national research in this field. One of the research projects undertaken with the City Council of Johannesburg involved research into the effectiveness of autothermal aerobic digestion in terms of the inactivation/destruction of selected micro-organisms.

2. DESCRIPTION OF THE PROCESS:

Aerobic digestion is a process which involves the direct oxidation of biodegradable matter by the biologically active mass of organisms and the oxidation of microbial cellular material. Unlike anaerobic digestion, it is a process where sludge (primary, waste activated or mixtures of sludges) is aerated in an open tank.

The main objectives of aerobic digestion are to reduce the solids content of the sludge and produce a stable end product. Claimed advantages of the process include a more stable process than conventional anaerobic digestion, a volatile solids reduction approximately equal to that obtained anaerobically, good quality supernatant liquor and the production of a humus-like, odourless,stable end product with good dewatering properties.

Autothermal or thermophilic aerobic digestion means operation in the thermophilic temperature range of 45°C to 55°C (or greater). The digestion process takes place in a well insulated, fully enclosed tank where the heat generated by the biologically active micro-organisms in the degradation of the organic material is utilized to overcome the system heat losses in such a manner that the process will be self-heating (autothermal) and will reach and maintain the required thermophilic temperatures. In most instances pure oxygen is used to supply the dissolved oxygen requirements of the process in order to reduce the large heat losses related to the quantities of air that would otherwise be required.

The basic reactions involved in autothermal aerobic digestion as summarised by Booth and Tramontini (1983) are as follows:

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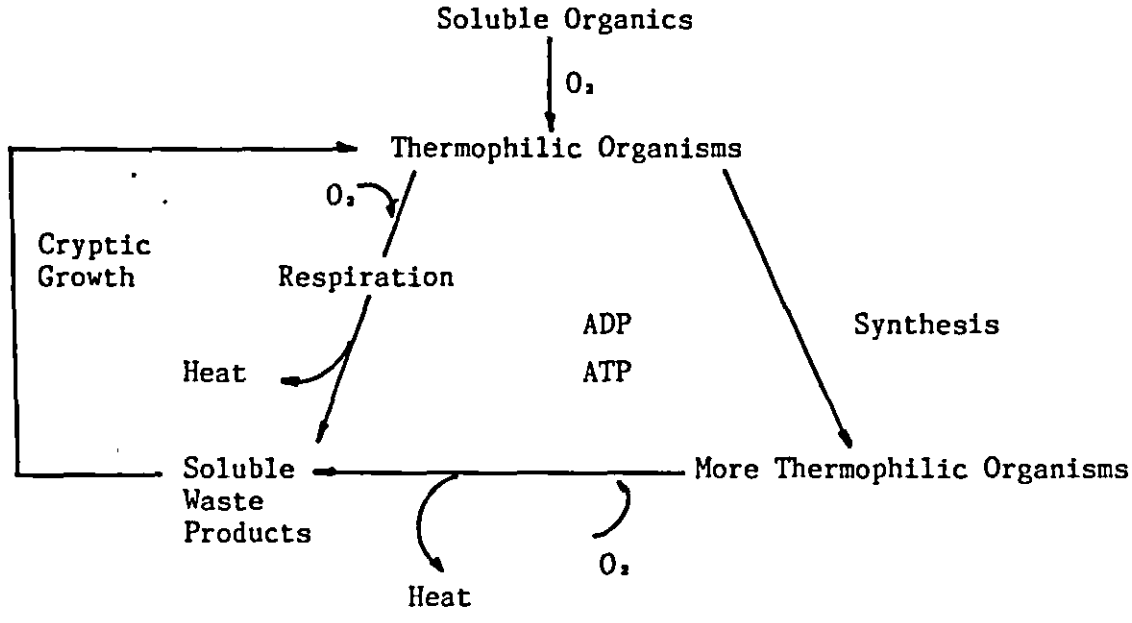
1. Solubilisation of organic matter (substrate) in order to pass through cell membranes. This is achieved by the excretion of extracellular enzymes or intracellular enzymes released by cell lysis. The rate of solubilisation increases with temperature as many organic compounds, e.g. lipids, are more soluble at higher temperatures.

2. Oxidation of soluble organic matter. The oxidation process can be represented schematically as follows:-



The oxidation of matter to CO_2 and water during respiration yields energy, some of which is stored in ATP. As micro-organisms are not 100% efficient a proportion of this energy is released as heat energy. Some of this energy is used for the maintenance of existing cells but as the micro-organisms decay the cell matter is solubilised and used for endogenous respiration thus producing more heat. At higher temperatures, such as those found in autothermal digestion, the decay rates are faster so there is more cryptic growth where micro-organisms grow on the products of decay.

The oxidation reaction can be summarised as follows:-

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Total organic solids + oxygen $\xrightarrow[\text{Nutrients}]{\text{Micro-organisms}}$ non-biodegradable organics- and $CO_2 + H_2O + NO_Y$

Assuming that the formula $C_5 H_7 NO_2$ is representative of sludge organic matter, then the above equation can be expressed as:

$$C_5H_7NO_2 + 5O_2 \longrightarrow 5CO_2 + 2H_2O + NH_3 \qquad (1)$$

From this equation it can be calculated that the theoretical oxygen demand is 1,42 kg O_2/kg organic matter oxidised. In practice this figure has been found to be in the region of 2,0kg O_2/kg organic matter and above (Gould and Drnevich (1978), Water Research Centre (1983), Booth and Tramontini (1983)). As nitrification is totally inhibited at temperatures above ~ 40°C it is very unlikely that there would be any enhanced oxygen demand from this source.

A stated advantage of the autothermal aerobic digestion process is that the potential for inactivation or destruction of pathogenic micro-organisms is so much greater than can be achieved through mesophilic digestion processes. In addition, the rate of reaction of the process is substantially faster, thus allowing shorter retention times and subsequent reductions in capital costs. Two disadvantages of the process are that it is fairly energy intensive and does not produce a useful by-product such as methane gas which is produced in the anaerobic digestion process.

Recent studies, including the EPA demonstration project at Hagerstown, have shown that a combination of autothermal aerobic and conventional anearobic digestion processes would appear to result in a system which incorporates the advantages of each of the processes while minimising their drawbacks. This study, however, deals exclusively with the aerobic treatment phase.

3. AIMS AND OBJECTIVES:

In general terms, the aim of the three year research programme into pilot scale autothermal aerobic digestion of sludge using pure oxygen, was to demonstrate that the process can be used successfully to disinfect sewage sludges.

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More specifically, the objectives were to:

- Investigate the effectiveness of autothermal aerobic digection in terms of the inactivation/ destruction of selected mirco-organisms (Ascaris ova, Salmonella)

- Investigate, where possible, the mode of destruction and factors which contribute towards the shielding of the organisms from the hostile environment.

- Maintain a close check by means of regular sampling and analysis on such parameters as pH, temperature, loading rates, COD, retention period, total solids, volatile solids, alkalinity, nutrients and toxic materials and measure solids breakdown, gas flow and composition with a view to the evaluation of the process for sludge stabilisation and sludge mass reduction efficiency.

- Assess the effect of varying such parameters as solids loading rate and retention period.

- Assess the significance of such operational problems as odour release from the treated sludge, supernatant quality, temperature control and adequate mixing.

- Assess as far as possible the economic implications of operating at thermophilic temperatures utilising pure oxygen, including any benefits due to lower retention periods.

- Assess the effects that the process has on the dewatering properties of the treated sludge.

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- Assess the potential, in the light of initial results, of the combination of autothermal aerobic and anaerobic digestion with a view to motivating further work in this field should the combined system appear attractive, especially from the point of view of cost-effective stabilisation combined with pathogen inactivation.

- Optimise the performance of the autothermal aerobic digestion plant with respect to pathogen inactivation/ destruction and economic considerations.

4. REVIEW OF RECENT STUDIES:

During the past 14 to 15 years there has been ever increasing interest in the autothermal aerobic digestion process, both as a stand-alone process and as the first stage of a two stage aerobic-anaerobic digestion process. Numerous studies, both at pilot plant and large scale, have been carried out in the United Kingdom, U.S.A. and Europe. Most of these studies were aimed at proving the process itself while investigations into the potential of the process for inactivation or destruction of pathogenic micro-organisms, although being recognised and noted in most cases, were not normally considered as one of the major goals of the experimental programme.

It is accepted by many authors that Andrews and Kambhu (1970), first developed a steady state model to investigate the parameters affecting the process. Although much of the data on sludge characteristics and heat losses had to be assumed, their studies supported the basic theory that autothermal aerobic digestion could be self sustaining with respect to temperature. They suggested that pilot testing of the process be undertaken using both air and high purity oxygen in order to test the validity of their model.

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Matsch and Drnevitch (1977), investigated high purity oxygen for aerating aerobic digesters both at full scale at Speedway, Indiana and at pilot scale in the Union Carbide laboratories at Tonawanda, Indiana. They found that aerobic digesters using pure oxygen could maintain elevated temperatures in excess of 45°C and that these temperatures increased as the concentration of volatile suspended solids increased. The process was found to be self-regulating at around 60°C and readily able to recover from shock loadings caused by operator error or equipment malfunctions. The sludge produced during these experiments was found to dewater as well as any aerobically digested sludge. Their study also concluded that reduction in pathogen concentrations to below detectable limits occurred within a period of five hours at temperatures of around 50°C.

Gould and Drnevich (1978) extended the work done at the Tonawanda pilot plant to examine some of the theoretical considerations of the process. They concluded that the results obtained on the pilot plant, especially those related to heat losses, could not be compared to full scale facilities, the heat leak being of the order of twice that expected in the field. Some results obtained indicated volatile solids reductions of 30% - 40% at three to five day retentions and reductions of Salmonella to below detectable limits in seven hours at 50°C. One observation made by the authors was that the operation of the system depends largely on the purity of the feed gas and that as the feed gas purity drops (eg. use of air) the gas sensible heat losses become large and it becomes impossible to maintain thermophilic temperatures.

Jewell and Kabrick (1980) presented the first successful large-scale application of an autothermal aerobic digestion process using air-aeration on a typical municipal sludge. They proved that air-aeration was feasible at system retention times ranging between 5 and 13 days as long as the injection methods used allowed for efficient oxygen dissolution and reduced the gas sensible heat losses as far as possible. The overall performance of their plant was influenced by numerous practical operating problems, mainly relating to variable climatic

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conditions as well as mixing and aeration problems which resulted in the production of a foam layer with the texture of a thick milkshake.

Jewell and Kabrick developed a relationship for the estimation of biological heat generation as follows:

$$\Delta F = 3,5\ \Delta COD \qquad (2)$$

Where ΔF is the total heat released in kilocalories per litre and ΔCOD is the measured change in COD in grams per litre. These units are convenient in estimating liquid temperature change because the heat released, expressed as kilocalories per litre, is equal to the temperature change. This simplified equation was then modified to take into account that approximately 30% of the biological heat of oxidation was lost from the system and becomes:

$$\Delta T = 2,4\ \Delta COD \qquad (3)$$

For example, with an influent COD of 50g/ℓ and a COD reduction of 35%, the expected temperature increase is 42°C which will raise the system temperature from an influent temperature of 18°C to 60°C, a result which compares favourably with experimental findings.

Investigations carried out by the same authors into the dewaterability of autothermally digested sludge showed that this was adversely affected in their large scale reactor with substantial increases in capillary suction time, CST, over the influent sludge. This increase became larger at higher loading rates. Contrary to the above, the sludge from their long-term bench scale digester dewatered well. They reasoned that these differences could be attributed to deflocculation caused by the type of mixer used in the large scale test versus the more gentle action of the turbine aerator used in the bench scale tests.

A study into pathogen destruction was carried out by Kabrick and Jewell (1982) as part of the previous investigation. The fate of three groups of pathogenic organisms namely Salmonella sp, Pseudomonas aeruginosa and Ascaris were compared under conditions of mesophilic anaerobic

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and autothermal aerobic digestion. Their findings showed that the autothermal aerobic digester exhibited superior performance over the mesophilic anaerobic digester with respect to the inactivation of pathogenic bacteria, viruses and parasites. The aerobic system yielded complete inactivation of Salmonella sp and viruses to below detectable limits at temperatures of 40°C and above. Parasite numbers were reduced but not completely eliminated. This was considered to be indicative of the need for better control of the system to prevent short circuiting and increased reactor temperatures to around 60°C for the control of environmentally resistant parasites such as Ascaris.

An engineering and economic assessment of the previous study carried out by Camp Dresser and McKee Inc. (1981), indicated that for a small treatment plant (3,8 Mℓ/day), autothermal aerobic digestion is cheaper than anaerobic digestion for sludge treatment ($ 160/tonne versus $ 220 /tonne). As plant size increases the situation changes due to the increased energy requirements for the aerobic system. For a large treatment plant (380 Mℓ/day), anaerobic digestion becomes substantially cheaper than autothermal aerobic ($ 35/tonne versus $ 90/tonne).

Pilot plant autothermal studies undertaken by Booth and Tramontini (1983), at Palmersford in the United Kingdom revealed that volatile solids destruction of between 17,5% and 25% was possible while temperatures of up to 60°C could be maintained consistently in a 60m³ pilot plant operating at between five and 10 day retention times and using pure oxygen to supply the dissolved oxygen requirements. At the temperatures attained virtually all the pathogenic bacteria were destroyed. The sludge produced by this system was also found to exhibit very poor thickening qualities and was not odour free. Oxygen utilization ranged from 2,03 to 4,21 kg oxygen used/kg volatile solids destroyed. It was concluded by the authors that the combined use of air and oxygen was theoretically feasible and would lead to a substantial reduction in operating costs.

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A pilot scale autothermal aerobic digester is presently being successfully operated using air as a feed gas by the Water Research Centre at Palmersford. Temperatures in excess of 55°C have been achieved at retention times of three days. Further results on this experiment are still awaited.

Although this study deals exclusively with autothermal aerobic digestion it is interesting to note that considerable success has been achieved in experimentation into dual digestion. One of the most recent investigations in this field was the EPA sponsored demonstration study at Hagerstown, Maryland, U.S.A. (1981). The process, which employs a one day aerobic digestion period using oxygen, followed by eight days anaerobic digestion, produced favourable results which, unfortunately, could not be optimized due to the incompatible match of the aerobic and anaerobic phases of the plant. (The anaerobic digester had to be operated at half of its volumetric capacity). Although retention time in the anaerobic system was reduced as far as possible it was still too long to allow stressing of the anaerobic stage of the digestion process. Not withstanding this problem the fact that anaerobic digester retention times could be reduced to the order of eight days could lead to a substantial overall capital cost saving when compared to a conventional mesophilic digestion system.

5. PLANT DETAILS:

The basic details of the pilot plant are given in Figures 1 and 2.

5.1 Digestion System.

The pilot plant consisted of a $10m^3$ ($8m^3$ liquid volume) closed steel tank, fully insulated with a 50mm layer of expanded polystyrene. The tank was provided with sampling points for both sludge and head gas analyses.

Sludge consisting of either a mixture of primary and thickened waste activated sludge or just the thickened waste activated sludge was obtained from the waste sludge system of the Olifantsvlei Sewage Purification Works and screened to give a maximum solids size of approximately 10mm. It was then stored in a $10m^3$ holding tank from.

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which it was fed to the pilot digester via a MONO SH40 feed pump. This feed system could be controlled by means of the pump's variable speed gearbox and timer to provide either a continuous feed or a step feed as required. For the duration of the test programme a two-hourly step-feed was used. This system had the capacity to provide a retention time of less than one day in the pilot digester if required.

Sludge was wasted from the digester during the feed cycles via a top overflow pipe back to the purification works.

The digester contents were mixed solely by the action of the sludge recycle system which consisted of approximately 20m of 50mm galvanised steel pipe, insulated with asbestos lagging and incorporating a MONO C91M recirculation pump and an oxygen supply venturi.

Sludge was pumped continuously from the bottom of the digester through the recirculation loop at a rate of approximately 9 litres per second and then re-introduced into the digester via a nozzle approximately 0,5m from the base of the tank. The fact that the recirculation pump had to run 24 hours per day, pumping a sludge with a high grit content, necessitated fairly frequent replacement of wearing parts such as seals, rotors, stators etc. These replacements were carried out on a routine basis and apart from one major failure of the rotor drive the pump ran faultlessly for the duration of the investigation.

The mixing energy produced by this particular system would normally be sufficient for a reactor vessel of some 4 to 5 times that of the pilot digester. This requirement was related to the oxygen feed system discussed later in this section.

5.2 Temperature and Dissolved Oxygen Measurement.

The temperature and dissolved oxygen contents of the digester contents were monitored by means of an Orbisphere Model 2716 dissolved oxygen/ temperature monitoring system and the results thus obtained plotted continuously by a two pen Servogor Model 220 plotter.

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The Orbisphere unit was chosen after considerable investigation into dissolved oxygen measuring instruments available on the local market. One of the requirements of the experimental programme was to be able to control the oxygen input to the system automatically if possible and this entailed obtaining accurate dissolved oxygen readings at temperatures in excess of 60°C. The probe supplied with the abovementioned oxygen system (model 2115) was, according to the available literature, capable of highly stable, accurate, long term monitoring of dissolved oxygen in natural waters, effluents and aeration basins through a temperature range of 0°C to 70°C. All of these claims with the exception of the durability of the probe proved to be correct. Numerous detailed examinations of the probe by the local agents and the manufacturers in Switzerland indicated that the method of sealing of the delicate sensing equipment within the probe itself was not capable of withstanding the environment which existed at the high temperatures reached in the autothermal aerobic digester. It should be noted that this was the first time that this system had been used under these conditions and investigations into the continual failure of the probe are proceeding both in the Republic and in Switzerland.

5.3 Oxygen Supply

Oxygen was supplied to the system via the patented VITOX SYSTEM venturi supplied by AFROX LIMITED in conjunction with the British Oxygen Company. The method of operation of this system was to withdraw a stream of sludge from the pilot digester via the recirculation system described previously and to pressurise it to 200kPa at the venturi. Oxygen received from the 1,4 tonne capacity bulk storage tank via the evaporators was then injected into the sludge via the venturi and the mixture conveyed back to the digester at a velocity of between 4 and 5 m/sec, allowing for very turbulent conditions in the pipeline which aided dissolution of the oxygen into the sludge. The mixture was then discharged through a specially designed nozzle (supplied by AFROX LIMITED) which shattered any remaining gas bubbles and caused rapid mixing of the oxygen rich sludge and the digester contents. This nozzle was initially placed tangentially to the side of the digester but this was

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found to have adverse effects on the mixing pattern with a large "dead spot" occurring at the centre of the tank. The nozzle was subsequently re-positioned at 90° to the tank wall which effectively eliminated the mixing problem.

The VITOX system used on the pilot plant was capable of delivering a maximum oxygenation capacity in excess of 6 kg O_2 per hour which more than adequately provided for the peak oxygen demand of the pilot unit of approximately 100 kg per day at a sludge retention time of one day. The VITOX unit was rated at this level on practical grounds as a reduction in sludge recycle pipe size below the 50mm used could have led to blockages at the throat of the venturi. Apart form a few minor blockages of the venturi, which were eliminated by a routine cleaning programme, the system performed faultlessly throughout the experimental programme.

The oxygen supplied to the unit was supplied free of charge by AFROX LIMITED for the duration of the experimental programme.

5.4 Oxygen Control System

The oxygen supply control panel was supplied by AFROX LIMITED. It consisted of an oxygen flow rotameter, solenoid operated control valves and non return valves, electrically controlled dissolved oxygen set-points, oxygen hour-run meter and hour-run meters for the feed and recirculation pumps. The system could be controlled manually by setting a constant flow through the rotameter or automatically via the dissolved oxygen signal received from the Orbisphere meter and pre-determined dissolved oxygen set-points in the control system. For example, if the lower set-point was selected as 2mg/ℓ and the upper one at 4mg/ℓ then the oxygen feed to the unit would be switched on as the dissolved oxygen level decreased below 2mg/ℓ and would remain on until the dissolved oxygen level increased above 4mg/ℓ. These set-points could be varied as required. A typical plot of dissolved oxygen and temperature as achieved using automatic control is given in Figure 3.

The operation of the automatic control system was dependent on the

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reliablility of the dissolved oxygen probe. As described prevoiusly this instrument was not entirely reliable resulting in long periods where the system, had to be run on manual control. However, during periods where the probe was operational the automatic control system proved to be an effective method of supplying oxygen to the system.

6. EXPERIMENTAL PROGRAMME, METHODS AND MATERIALS

6.1 Experimental Programme

The pilot digester was operated at retention times of three, two and one day using a 50/50 mixture of primary and thickened waste activated sludges as a feed and using automatic control of the oxygen injection system.

An experimental run was also carried out using only thickened waste activated sludge as a feed to the system at a retention time of three days. Oxygen was injected into the system on a continual basis during this run due to problems with the dissolved oxygen probe as mentioned previously.

A further experimental run was carried out using the 50/50 mixture of sludges at a retention time of three days and using manual (continual) control of the oxygen injection in order to assess the benefits (if any) of automatic versus manual control of oxygen injection. (A three day retention time was chosen purely to minimise the oxygen used during the test period).

The duration of all the abovementioned experimental runs was between one and two months to ensure that the results would be representative of the system performance under the prevailing conditions.

During the experimental runs, digester temperature, dissolved oxygen, sludge recirculation rate and sludge feed rate were monitored continuously. Feed sludge temperature and ambient temperature were monitored on a four hourly basis, while feed sludge and digester sludge suspended solids, volatile suspended solids and pH were monitored on

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a daily basis. Weekly monitoring of feed sludge and digester sludge was undertaken for chemical oxygen demand, total Kjeldahl nitrogen, ammonia, nitrates, phosphorus (total and soluble) and capillary suction time, and on a twice weekly basis for Ascaris and Salmonella total count and viability.

Sludge dewaterability, heat balance and head gas analyses were carried out as specific experiments and not on a regular or routine basis.

6.2 Chemical Analyses.

Determinations of suspended solids (SS), volatile suspended solids (VSS), pH, chemical oxygen demand (COD), ammonia (NH_3), nitrate (NO_3), total Kjeldahl nitrogen (TKN) and phosphorus (total and soluble) were carried out in all cases using the methods employed by the City Council of Johannesburg Laboratories, most of which were based on Standards Methods, (1965) as revised.

6.3 Physical Analyses

Ambient temperature was measured by means of a maximum - minimum thermometer while that of the feed sludge was measured by means of a Negretti and Zambra probe thermometer with the sensor positioned approximately midway in the holding tank. Measurements of the temperature of the digester contents was by means of a temperature sensor incorporated in the dissolved oxygen probe. This system provided a continual readout which was plotted by means of a chart recorder. When required, temperatures relating to the digester insulation and pipe lagging were measured using a thermocouple attached to a Fluke Multimeter model 8024 A.

Gas analyses were carried out using an ORSAT gas analysis apparatus. This apparatus measured the percentage of both oxygen and carbon dioxide present in the vent gas of the digester. Gas analyses were carried out as specific experiments and not on a regular basis as was the case with some overseas experimental studies. The results obtained are considered to be acceptable but cannot be as accurate as would

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be expected from a continual analysis. The automatic control of oxygen injection posed numerous problems in that the cutting in and out of the oxygen feed resulted in large variations in oxygen levels in the vent gas. It was finally decided to carry out vent gas analyses on the system with oxygen being injected at a constant rate equal to the average daily consumption of the system when operating with automatic oxygen feed. This procedure resulted in acceptably reproduceable results being obtained.

Sludge settling properties were examined both on laboratory scale using beaker studies and on a larger scale at the site of the pilot plant where a tray 1,5 m long, 1,0 m wide and 150 mm deep, which was divided into three compartments, was used. These compartments were filled with sludge at staggered intervals and any settlement noted over a period of days,

Sludge dewatering properties were evaluated using both the buchner funnel method with glass fibre paper (GFC) and the CST apparatus. The effects of polymer addition (ZETAG 57) asmanufactured by Allied Colloids) was also investigated.

Calculation of heat balances was carried out using generally proven theory used by the Water Research Centre (1983) and further checked by AFROX LIMITED (1983). The heat balance equation at steady state is given below:

$$H_B + H_p = H_L + H_S \qquad (4)$$

where,

H_B = Biologically produced heat
H_P = Heat produced by pump
H_L = Heat leak to surroundings
H_S = Sludge sensible heat losses.

By calculating the sludge sensible heat loss, the heat leak to the surroundings and the heat produced by the feed and recirculation pumps and feeding these into equation (4), the biologically produced heat may be deduced. From a knowledge of the amount of volatile solids concerned the biological heat of reaction can be calculated.

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The heat balance calculations were carried out using specific data as a number of the required parameters were not measured on a continual or regular basis. The results obtained are however considered to be representative of what can be expected from the autothermal aerobic digestion process.

6.4 Biological Analyses

Microscopis analyses using a light microscope and all micro biological analyses were carried out at the Council's Cydna Laboratory during the entire experimental programme.

Biological stability and fermentability analyses were carried out on samples innoculated with 10% digested sludge from the Olifantsvlei Works and 10% "acid" sludge obtained from Northern Works. The samples were incubated in anaerobic jars for seven days at 37°C and then examined for signs of anaerobic fermentation . The volatile acids concentration and pH of the samples was also monitored.

Ascaris determinations were carried out using the method developed by the Cape Town City Council, (Le Roux, 1982) as described briefly hereafter. This method was found to be quick and effective and allowed for more frequent Ascaris determinations to be made.

Method of Ascaris Determination

About 2 litres of liquid sludge was macerated in a Waring blender at low speed for about one minute. If dry sludge was to be tested an appropriate amount was suspended in about 2 litres of water, allowed to soak for a few hours and then macerated as above.

Total Count per Gram: Approximately 1 to 5 grams of sludge (depending on the moisture content) were weighed out into a small glass beaker and immediately transferred quantitatively into a Visser filter. The sludge was filtered by washing with a strong jet of tap water to which a little 1,0% Tween 80 solution had been added periodically.

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The washing water was directed onto the sludge and sides of the inner and outer filters and both the filter and the water streams were manipulated in such a way as to ensure thorough washing of the filter and sludge. After washing for 3 to 5 minutes the inner filter (95μ) was removed. The outer filter (50μ) was washed for a further 1 to 2 minutes.

The material remaining in the outer (50μ) filter was quantitatively transferred into a 1 litre glass beaker and then filtered through a 12μm Sartorius SM 12500 membrane filter. The filter was dried at 37°C on a stainless steel support which was weighed down with the correct diameter stainless steel ring to prevent curling up. After drying the filter was cut in half using a scalpel. Each half of the filter was then transferred onto a microscope slide. Microscope oil was applied and the filter allowed to clear. The slide was then examined microscopically under 100X and 250X magnification. All Ascaris ova on both halves of the membrane filter were counted and the results expressed as number of eggs per gram of dry sludge. The moisture content of the sludge was determined after drying for approximately 24 hours at 105°C.

Viability Count This was determined by weighing out approximately 100 grams of the blended sludge and filtering through the Visser filter without using Tween 80. About one third of this mixture was passed through the filter and the ova collected into a one litre erlenmeyer flask (previously marked at 250 mℓ). The inner filter was rinsed out and the second third of the sample passed through it and collected in the same flask. The inner filter was again rinsed and the last third of the sample passed through it into the flask. The filter was again rinsed and the rinsings collected into the flask. The flask was then filled to the 250mℓ mark using water. Approximately 5 mℓ of 40% formaldehyde solution was then added to the flask. The flask was plugged with cotton wool and left at a temperature of 25 - 28°C for at least a month before being examined for viability. The flask was shaken occasionally during this period. After a month the culture was examined at weekly intervals until at least four similar results

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were obtained showing that peak viability had been reached. The average of the last three results was taken as the viability count. In some instances it was necessary to examine the cultures for a further few weeks if the peak had not been reached as described above.

Slides were prepared for viability counts by pipetting 2 to 3 drops of the sediment from the viability flask onto a microscope slide, adding a drop of stain and covering with a cover slip. At least 100 eggs per sample were counted so as to obtain a reasonably accurate classification and were screened with the 10X objective and confirmed with the 40X objective.

Classificaiton: Samples were classified as follows:

1. Fully developed worm inside the egg shell (motile or quiet)
2. Partly developed egg i.e. divided egg.
3. Single cell egg, no apparent change. (Includes infertile egg).
4. Degenerate egg with or without vacuoles.

The eggs in (1) and (2) are viable and only those which at the end of the culturing period had developed into worms, i.e. (1), were classified as potentially infective. All the ova in (3) and (4) were classified as non-viable.

Stain: The stain consisted of a mixture of 10mℓ of grams iodine and 5 mℓ of a 1% aqueous solution of eosin made up to 100 mℓ by addition of distilled water.

Salmonella determinations were carried out at the same intervals as those for Ascaris using the following method:

Pre-enrichment: 10 mℓ of sludge was innoculated into 35 mℓ phosphate buffered peptone (PBP) and incubated for 24 hours at 37°C.

Selective enrichment: 10 mℓ portions of sludge were transferred into 35 mℓ Muller Kauffman Tetrathianate Broth and Selenite. The innoculated Tetrathionate was incubated at 43°C and the innoculated Selenite at 37°C for 48 hours. The samples were plated out after

24 and 48 hours onto Brilliant Green Agar (modified) and McConkey plates. The Brilliant Green Agar plates were incubated at 43°C overnight and the McConkey plates at 37°C.

Biochemical confirmation;

1. Triple Suger Iron Agar slopes were innoculated with the culture and incubated at 37°C for 24 hours.
2. Positive reactions in the Triple Sugar Iron were confirmed by urease, lysine and B galactosidase reaction following the same pattern of identification of Salmonella used in food.

Modified Brilliant Green Agar was produced by adding one vial of Salmonella Sulpha Mandelate supplement previously dissolved in 5mℓ distilled water to 500mℓ Brilliant Green Agar.

7. RESULTS

Detailed results obtained during the experimental programme are given in Figures 1 to 10 and Table 1 to 14.

Feed sludge was either obtained from a dissolved air flotation unit or from the underflow from the primary sedimentation tanks. This sludge comprised of a mixture of raw and waste activated sludge in approximately equal proportions. Sludge characteristics for all the experimental runs are given in Table 1 and sludge analyses in Table 2.

The autothermal aerobic digestion pilot plant was initially run on thickened waste activated sludge received via a dissolved air flotation unit from the Olifantsvlei extended aeration plant. The retention time of the pilot digester averaged 3,5 days and the feed sludge had an average concentration of 3,7% (Table 1). The temperature of the influent sludge averaged 12°C and that of the digester contents 44°C (Table 4, Figure 6). Volatile solids destruction averaged 28% and COD reduction 21% (Table 2). Oxygen was fed to the system on a continual basis for the duration of this run due to problems experienced

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with fouling of the oxygen probe within the digester. Oxygen and power utilisation averaged 4kg O_2 supplied/ kg VS destroyed and 5,2 kWh/kg VS destroyed respectively (Table 5). Ascaris ova reduction was of the order 50% and complete inactivation of Salmonella was not achieved (Table 10).

Towards the end of this test period a failure of the recirculation pump forced a closedown of the plant in order that repairs could be carried out. This opportunity was used to implement the following modifications:

1. The inlet nozzle in the recirculation pipework was re-positioned at 90° to the tank wall i.e. the fluid flowed across the tank rather than tangentially as was previously the case. This modification resulted in much improved mixing characteristics within the digester.

2. The dissolved oxygen probe was moved to a position in the suction pipe to the recirculation pump thus providing a constant flow of liquid past the membrane. This modification proved to be almost totally successful from the point of view of fouling of the probe and allowed the plant to be run on automatic control with the resultant improvement in the control of oxygen usage. The only problem still experienced was the regular failure of the probe due to faulty sealing of the sensitive sensors within the probe body.

Once the above modifications had been completed the plant was re-commissioned using a mixture of approximately 50/50 waste activated and primary sludge. Several experimental runs were undertaken using this sludge mixture, retention times of 3,0; 1,8 and 1,0 days being achieved. During these runs the oxygen feed to the system was at all times controlled automatically. Initially dissolved oxygen control set-points of 2 to 4 mg/ℓ were used but it was found that the system would go anaerobic for quite lengthy periods immediately after completion of a feed cycle. The set-points were subsequently

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increased to between 3 and 6 mg/ℓ which effectively cured the problem. These set-points were maintained throughout the rest of the test period.

During these experimental runs the average feed solids concentration averaged 4,2%; 3,9% and 3,4% respectively (Table 1). Influent sludge temperatures were 16°C, 22°C and 24°C while the digester temperature in all cases was of the same order at 58°C to 60°C (Table 4 and Figures 7 to 9). Volatile solids destruction averaged 28%, 23% and 21% while COD reductions were similar with reductions averaging 35%, 32,5% and 30,5% respectively (Table 2). Volatile solids loading rates increased with decreasing retention times, average values being 9,9; 15,6 and 23,7 kg VS/m³/ day (Table 3). Oxygen usage was 2,4;2,7; and 2,2 kg O_2/kg VS destroyed while power consumption reduced with reduction in retention time, average values achieved being 4,1; 3,0 and 2,5 kWh/kg VS respectively. Complete inactivation of Ascaris ova and Salmonella was achieved during all three experimental runs (Tables 11 to 13).

An additional experimental run (N°5) was carried out at a retention time of 3,2 days using manual (continual) oxygen injection in order to compare results with the automatic injection of oxygen. The results obtained were in all cases very similar to those obtained in run N° 2 and are detailed in the various tables and figures.

Oxygen use efficiencies (Table 4) and heat balance analyses (Table 7) were carried out as specific experiments as the necessary equipment and manpower was not available for the continuous monitoring of these parameters. Average oxygen efficiency was of the order of 86% to 90% while the heat of reaction varied from 15 x 10³ kJ/kg VS destroyed at 3 day retention time to 25 x 10³ kJ/kgVS destroyed at 1 day retention time. (3610 kCal/kgVS to 6010 kCal/kgVS).

Samples of digested sludge were taken from the pilot digester when the system was being fed a 50/50 mixture of sludge at both 3,0 and 1,8 day retention times. These samples were examined microscopically and for biological stability and fermentability. The temperature

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of the samples ranged from 57°C to 62°C on extraction but these were allowed to cool to room temperature before any experimentation took place.

Examination of a wet preparation of the 3 day retention sludge under a light microscope revealed two solid phases. The larger solids appeared to be debris or other inert material from the feed sludge while the small solids were almost entirely dispersed bacteria. These were coccoid in shape and moved around under the slide in small rivulet type streams together with the other colloidal material. No flocculation of the biomass occurred with the solids having an extremely dispersed appearance when compared to activated sludge.

The digested sludge samples, when tested for biological stability and fermentability by addition of 10% acid sludge or 10% anaerobically digested sludge, showed signs of anaerobic fermentation after seven days incubation in anaerobic jars at 37°C. The results obtained are given in Table 8. These results indicate that the sludge product was not stable and could ferment readily to acids thus being a potential nuisance if disposed of without further treatment.

Results obtained from similar experiments on the 1,8 day retention sludge showed the same dispersed growth appearance and produced similar results to the 3 day sludge with regard to anaerobic fermentation.

Investigations into the settling and dewatering properties of the digested sludge from both the 3 day and 1,8 day retention experiments indicated that the sludge solids would not separate away from the liquid phase under gravity settling. Even after 3 to 4 days of standing no separation of the sludge layer occurred. This confirmed the dispersed colloidal nature of the sludge solids as observed under microscopic examination. Attempts to filter off a liquid phase when filtering samples on a buchner filter with glass fibre paper proved to be quite impossible and CST values of the order of days were not uncommon. The addition of polymer to various sludge samples was then investigated to try and ascertain the amount of polymer required to render the

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sludge dewaterable. The polymer used in all tests was ZETAG 57 as supplied by Allied Colloids. Typical results obtained are given in Table 6.

It is evident that about 14 kg/dry ton of polymer would be required to render this sludge dewaterable. This should be compared with the usual dose of 1,3 to 2,0 kg/dry ton usually required to dewater waste activated sludge.

Process costs were analysed at pilot plant scale using oxygen and power consumption as the main cost parameters. Overall costs on this basis ranged from R109/dry ton at 3 day retention to R46/dry ton at one day retention time (Table 9).

8. DISCUSSION

This study has shown the autothermal aerobic digestion process to be of a very robust nature and quite capable of surviving shock loads such as the doubling of the feed rate, a drastic reduction in oxygen injection rate or a complete shut-down for a number of hours for maintenance purposes without any detrimental effect on the process itself.

The process proved to be very easy to establish as is evidenced by the following example: From a cold start-up, i.e. the digester filled with a mixture of primary and waste activated sludge at ambient temperature, the contents were recirculated, fed with oxygen on automatic control and with sludge every two hours to give a nominal two day retention time. Under these conditions the digester temperature had increased from 24°C to 61°C in a matter of 50 hours after which time stable operating conditions were established. A temperature plot related to this start-up is given in Figure 4.

Temperatures of the order of 60°C were common at retention times as low as one day and although Andrews and Kambhu (1971) indicated that the process would be self limiting at about 65°C, temperatures of up to 74°C were measured at times where excess oxygen was fed to the system. Similar temperatures were recorded by Booth and Tramontini (1983) under summer operating conditions.

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As was to be expected at the temperatures achieved pathogenic bacteria, which are capable of surviving anaerobic digestion, were eliminated. This study has shown that a sludge consisting of a mixture of primary and waste activated sludge (in approximately equal proportions) can be disinfected (in terms of Ascaris ova inactivation) in the process at a system retention time of one day. Although this particular experimental run was carried out under summer conditions it is quite confidently expected that the system would perform as well at a retention time of one day under winter conditions. This is borne out by the fact that the system operated quite satisfactorily and maintained temperatures continually in excess of 55°C when run at an actual retention time of 1,8 days under winter conditions where the influent sludge temperature dropped as low as 8°C occasions.

At the temperatures achieved at a one day retention time a 100% destruction of viable Ascaris ova was achieved (Table 13) with only one instance being recorded where destruction was 99% (system operating correctly), this probably being due to short circuiting. The results achieved do not necessarily mean that a one day retention period is required for disinfection as the random method of sampling employed and the fact that the system was fed at two-hourly intervals tends to indicate that the minimum time required for complete inactivation must be less than two hours. Unfortunately these results cannot be compared with those achieved in other studies such as Gould and Drnevich,(1978); Kabrick and Jewell,(1982) or Booth and Tramontini, (1983) as the reactors in all these studies were fed on a batch basis using a once per day cycle and retention times were far longer than those achieved in this study. The results do, however, confirm the results reported by Krusé, (1977) and Brandon and Langley, (1977) that a temperature of approximately 55°C is the minimum required to ensure that there are no viable Ascaris ova in the treated sludge.

Destruction of Salmonella was also effectively achieved although the use of this pathogen as an indicator should be questioned as it was not always present even in the feed sludge. Kabrick and Jewell,(1982) indicated that complete inactivation of Salmonella was achieved at

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temperatures of 42°C - well below the digester temperatures achieved in the study. Some instances where Salmonella was found to be present in the digested sludge have been put down to re-infection of samples in the laboratory.

An experimental run undertaken at a retention time of 3,5 days using only thickened waste activated sludge from the Olifantsvlei extended aeration plant at no time achieved the required temperature for the complete inactivation of Ascaris ova. The average temperature achieved during this run was only 40°C - 46°C with a maximum of 52°C being recorded. The average viable Ascaris ova reduction at no time exceeded 50%. The failure of the system to produce the desired results was due to the limited biodegradable fraction of the feed sludge which was insufficient to support the degree of microbial reaction required to generate higher temperatures.

Inactivation of Salmonella during this run was poor and, although some of the results obtained could have been due to re-infection as mentioned previously,it is likely that the temperature achieved was not sufficient for complete inactivation. This would tend to agree with the findings of Kabrick and Jewell (1982).

One of the advantages of the autothermal aerobic digestion process is the high loading rate that can be achieved due to the increased rate of reaction. During the experimental runs tabled in this report the solids loading rates achieved ranged from 9,4 kgVS/m³/day to 23,7 kg VS/m³/day at retention times ranging from 3,2 to 1,0 days. (50/50 sludge mixture). The result achieved at 3,2 days compares favourably with that achieved at a similar retention time by Matsch and Drnevich (1977) and the five day value presented by Booth and Tramontini, (1983) while the result achieved at a one day retention time far exceeds any results reported due to the fact that no study reported achieving retention times as low as one day. If these results are compared with generally accepted figures for aerobic digestion of approximately 1,6 to 4,0 kg VS/m³/day at retention times of 15 to 20 days and those for anaerobic digestion of 1,6 to 6,4 kgVS/m³/day

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at 10 to 20 day retentions (Wastewater Engineering, 1979)it becomes evident that the autothermal digestion process is capable of accepting much higher loading rates at substantially lower retention times than either of these two well-used digestion processes.

The actual destruction of volatile solids at the loading rates achieved varied from 21% to 28% (Table 3), the lowest reduction being achieved at one day retention. These figures compare favourably with those achieved by Matsch and Drnevich, (1977); Gould and Drnevich, (1978); Jewell and Kabrick, (1980) and Booth and Tramontini, (1983). These values are lower than the generally accepted value of 40% reduction reported for the stability of anaerobically digested sludge which can be achieved at retention times of 10 to 20 days.

The results for COD reduction given in Table 1 show that the reductions achieved varied from 31% at 1,0day retention to 38% at 3,2 days. These results also compare favourably with those obtained by the authors mentioned above.

The average COD: Volatile solids ratio achieved during this study was 2,1 kg COD/kg VS. Comparison with the value for anaerobic digestion of 1,3 kg COD/kgVS given by Booth and Tramontini,(1983) indicates that a higher degree of treatment was actually being achieved in the aerobic system. A possible explanation for this discrepancy given by the same authors is that the aerobically digested sludge contains a higher oxygen ratio in its constituents than the raw sludge.

From the above results it is evident that both volatile solids destruction and COD removal decrease with a decrease in retention time. This fact would have to be taken into consideration if the process were to be used for overall sludge treatment rather than primarily for inactivation of pathogenic micro-organisms.

The formula presented by Jewell and Kabrick, (1977) relating change in temperature to change in COD i.e. $\Delta T = 2,45\ \Delta$ COD was found to predict fairly accurately the change in temperature for retention

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times in the region of 3,0 days, (which is the lowest achieved by the authors) but becomes less accurate when applied to the results achieved at a one day retention time. (Predicted final temperature at 3,0 days = 57°C (58°C) while at 1,0 day predicted temperature = 54°C (58°C)). Nevertheless, it would seem that this simple formula can be used to predict the final system temperature with a reasonable degree of accuracy, making it a useful design aid.

One of the aims of this study was to investigate the feasibility of using automatic oxygen injection to control the supply of oxygen to the digester. The system employed is described in Section 6. It was envisaged that such a system would lead to a more efficient use of oxygen in the process thus reducing one of the major cost factors When operational the system was able to accurately pace the oxygen demand of the digester and allow for efficient oxygen use within the system. However, the problems involved in monitoring dissolved oxygen concentrations at high temperatures have not yet been overcome and accordingly such a control system should not be considered on a large scale as it can lead to very inefficient oxygen utilisation during or after failure, (tends to lead to continual oxygen addition to the system).

A theoretical oxygen demand for sludge under ideal conditions was given by Matsch and Drnevich,(1977) as 1,42 kgO_2/kg VS destroyed. Actual oxygen utilisation obtained during experimental runs from 1,0 to 3,2 day retention ranged from 2,2 to 2,7 kg O_2 used/kg VS destroyed (2,5 to 3,0 kg O_2 supplied/kg VS destroyed). These figures compare favourably with those obtained by Booth and Tramontini, (1983), who employed continual oxygen injection, and the tests carried out by the Water Research Centre, (1983) where both automatic and continual injection modes were used. The higher oxygen use is in part due to unavoidable inefficiencies within the system and possible non-biological uptake of oxygen.

In order to assess the efficiency of oxygen utilisation head gas analyses were performed using an ORSAT apparatus as described in

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Section 6. With the system operating on automatic oxygen injection control it was found to be impossible to carry out these gas analyses due to the frequent cutting in and out of the oxygen feed as evidenced in Figure 3. It was thus decided to use the average daily oxygen input as calculated from the runs using automatic oxygen injection control as a continual oxygen feed to the system for the purposes of these analyses. This system worked successfully and results of between 86% and 90% oxygen utilisation were measured. These compare favourably with figures given by the Water Research Centre, (1983) and Booth and Tramontini, (1983). The Water Research Centre results were achieved under the same conditions as employed above, i.e. using a similar VITOX system and continual oxygen feed to the digester.

It is interesting to note that by using the head gas analysis results it was possible to "fine tune" the oxygen consumption of the system to a point where there was just a trace of oxygen remaining after a feed cycle (of the order of 2%) and up to 93,5% use efficiency during the remainder of the cycle prior to the following feed. This procedure produced average oxygen comsumptions of the same order as those achieved using automatic injection control (compare Table 5: Experimental runs 2 and 5) as well as almost identical performance results in other areas.

Taking into consideration the continual problems experienced with the automatic injection control system it appears that, given a reliable form of head gas analysis, which could be carried out at pre-determined intervals, the system could be run very efficiently without complicated control equipment. It should be noted, however, that continual head gas analysis has been found to be just as prone to problems as automatic injection control of oxygen by the authors mentioned above.

In order to assess the affects of gross over oxygenation of the system the oxygen feed was increased to the equivalent of 3,5 kgO_2/kg VS destroyed whilst running at a retention time of 1,0 days.

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The effect was an immediate reduction in the temperature of the digester contents (Figure 9) due to the cooling effect of the oxygen. In contrast, on occasions where the imminent failure of the automatic injection system led to an increase in oxygen feed to a level slightly above the optimum, an increase in temperature was experienced, a maximum of 74°C being recorded.

Power consumption for any particular experimental run was almost constant as the major power consumer, the recirculation pump, ran continually throughout the experiment. The figures obtained (Table 5) of 2,5 to 4,6 kWh/kg VS destroyed compare well with those obtained by Booth and Tramontini, (1983), but it should be noted that as in the case of their experiment the recirculation pump used in this study was oversized and thus the figures cannot be considered as representative of a large scale facility.

Heat balance calculations were carried out as specific experiments as mentioned previously in the report. It was found that the insulation of the digester (50mm expanded polystyrene) formed a very effective heat trap with the external temperature remaining constant at approximately 33°C through a large range of ambient temperatures. There was a substantially larger heat loss from the pipework which was only insulated with asbestos lagging. The major heat loss from the system was the sludge sensible heat gain of the influent sludge while the heat input due to the pump remained constant as it was operational for 24 hours per day. The heat of reaction as calculated from these tests (Table 7) averaged 20 000 kJ/kg VS destroyed (4760 k Cal/kg VS destroyed). This value, although not as accurate as would be expected from continual heat monitoring techniques, compares with the findings of Andrews and Kambhu, (1970); Jewell and Kabrick,(1977); Booth and Tramontini, (1983) and the Water Research Centre, (1983).

The final product produced by the autothermal aerobic digestion process exhibited some very unusual properties. Initial investigations showed that on passing through the digester the feed sludge (either waste activated or a nominal 50/50 mixture of waste activated and primary sludge) became more fluid and would not settle.

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These findings confirm the experience of Jewell and Kabrick (1980); the Water Research Centre, (1983) and Booth and Tramontini,(1983), all of whom agree that the sludge produced by this process was very difficult to deal with.

As is evident from the results the aerobically digested sludge readily ferments when seeded with 10% acid fermented sludge or anaerobically digested sludge (Table 8). Additional treatment of the sludge, such as anaerobic digestion, appears to be necessary in order to further stabilise it. Notwithstanding the above, when the sludge was decanted into a tray and left standing exposed to the elements for a long period no unpleasant odours were obvious although a large number of flies were attracted.

The dewatering properties of the digested sludge (Table 6) were found to be extremely poor with capillary suction times of the order of days being measured while filtration of samples on a buchner filter proved to be impossible. As detailed in the results about 14 kg/ dry ton of polymer would be required to render the sludge dewaterable. At present day prices this equates to a polymer cost of approximately R70/ton dry solids treated. This should be compared with a cost of approximately R10/ton day solids required for the dewatering of waste activated sludge.

The above results are a decided disadvantage of the process where dewatering would be required prior to disposal. If the sludge could be disposed of directly to land or further treated by anaerobic digestion then this problem, and the additional cost involved, would be eliminated.

It is evident from the above that further treatment of the sludge would be desirable . An attractive possibility in this regard is dual digestion, the combination of a short retention period autothermal aerobic first stage followed by anaerobic digestion. Advantages of such a system would include effective disinfection, reduced net anaerobic retention period, no external heating required, stable process

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performance, methane production equivalent to conventional anaerobic digestion and simplified operation and control. Favourable results have been achieved on this process to date including those of the Hagerstown demonstration project, (1981).

The process costs were worked out on the basis of oxygen and power utilisation on the pilot plant. It must be emphasized that these costs cannot be used to compute the cost of the process on a larger scale due to the over-sizing of equipment such as the recirculation pump and VITOX system required for reliable operation. The costs given in Table 9 vary from R46 to R109 at retention times of 1 to 3 days, the major contributor in each case being the cost of oxygen. All of these values are substantially in excess of the cost of anaerobic digestion (R35-40/dry ton in Johannesburg) and in fact, as previously discussed, if the sludge were to be further treated an amount (less than that mentioned above due to reduced size, retention etc) would have to be included for anaerobic digestion or approximately R70/dry ton for sludge dewatering, making the process very expensive when compared with present disposal methods. (See Appendix 1.)

Experimental work being carried out at present at the British Water Research Centre indicated that the autothermal process can be made to operate efficiently using air as a feed gas at a retention time of three days with temperatures in excess of 55°C being achieved. If the final outcome of this experiment indicates that the system can be operated reliably using air instead of oxygen as a feed gas then one of the major cost factors is removed and the process becomes economically viable, especially when considered as the first stage in a dual digestion process.

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9. CONCLUSIONS

9.1 The autothermal aerobic digestion process can be made to operate successfully at temperatures of up to 60°C at retention times as low as one day using a mixture of primary and waste activated sludge. Thermophilic temperatures could not be achieved when using thickened waste acitvated sludge alone as a feed to the system.

9.2 The process is self-sustaining with regard to temperatures in the thermophilic range and is very resistant to changes in loading and physical abuse.

9.3 Temperature of the system can be increased by increasing oxygen input to some degree;temperatures of up to 74°C being measured. A large excess of oxygen fed to the system does however lead to cooling.

9.4 At the temperatures attained (55 - 60°C) and a retention time of 1 to 3 days virtually all pathogenic bacteria are eliminated.

9.5 The destruction of volatile solids ranged from 21% to 28% and that of COD form 30% to 38%.

9.6 Solids loading of between 9,9 and 23,7 kg VS/m^3/day were achieved at retention times between 3 and 1 days.

9.7 Across the range of operating conditions oxygen utilization varied from 2,5 to 3,7 kg oxygen supplied/kg volatile solids destroyed (2,2 to 2,7 kg oxygen used/kg volatile suspended solids destroyed.)

9.8 Efficiency of oxygen utilization ranged from 86% to 90%. This efficiency could be further fine - tuned by careful monitoring of the head gases and subsequent alterations of oxygen feed, a maximum efficiency of 94% being noted.

9.9 Automatic control of oxygen input proved to be effective in that the degree of physical monitoring was drastically reduced.

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The results obtained by this method could, however, be accurately reproduced by running the plant on a continual oxygen feed and "fine-tuning" the system. The automatic operation was dogged by unreliability of dissolved oxygen measuring equipment throughout the test programme.

9.10 The digested sludge produced by the system proved to be odour free but did attract flies if left lying in the open for any period of time.

9.11 The digested sludge produced by the system exhibited some very poor settling properties and was capable of undergoing further anaerobic digestion.

9.12 Costs of the process, based on the pilot plant study, varied between R46 per dry ton treated and R109 per dry ton treated. (See Appendix 1.)

9.13 The process could be economical if it was possible to use a combination of air and pure oxygen or air alone as the major cost source at present is that of oxygen.

9.14 The process should not be considered for "stand-alone" use but could well be included as the first step in an aerobic/anaerobic dual digestion process.

10. FURTHER RESEARCH

The high degree of pathogenic bacteria destruction achieved by the autothermal aerobic digestion process at retention times of the order of one day could offer an efficient means of ensuring pasteurisation of the influent sludge to an anaerobic digester if the process were used as the first stage in a combined aerobic/anaerobic digestion system. The heat available would also largely negate the need to heat the anaerobic stage.

Investigations already carried out along these lines, including the EPA demonstration project at Hagerstown, have shown this system to be feasible and in fact the performance of the anaerobic stage improved to the point where the retention times could be reduced to the order of eight days, whilst gas yields were of the same order as those of a normal mesophilic anaerobic digestion system.

One of the major considerations which would have to be taken into account if a dual digestion system were to be considered is the cost of the aerobic phase of treatment. The major contributor to the fairly high cost of this form of treatment is the need to use pure oxygen as a feed gas. If the system could be run efficiently on a mixture of pure oxygen and air or on air alone there would be a drastic reduction in the operational costs and this together with the reduction in physical size, and hence capital costs, of the anaerobic stage could make the process more viable.

Although these problems are at present being investigated in some depth both in the United Kingdom and the U.S.A. it is considered that further research should be undertaken in the following areas:-

1. Investigations into the use of air or a mixture of oxygen and air as a feed gas to an autothermal aerobic digester at retention times as low as one day if this is possible.

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2. Investigations into the dual digestion process on an large enough scale for the results to be meaningful. (Most experiments into dual digestion carried out to date have relied on the use of available equipment and plant such as existing anaerobic digesters. This has either led to inefficient use of the anaerobic phase due to the small capacity of the aerobic phase or scaling up of the aerobic phase to uneconomic proportions). This will probably necessitate the construction of a fairly large pilot plant where the aerobic and anaerobic stages are properly matched so as to get the optimum results.

3. In conjunction with (2) above, an investigation into the stability of the final product from a dual digestion system and possible methods for final disposal thereof.
e.g. soil conditioner.

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FIGURE N°. 1

AUTOTHERMAL AEROBIC DIGESTION PILOT PLANT
SECTIONAL VIEW

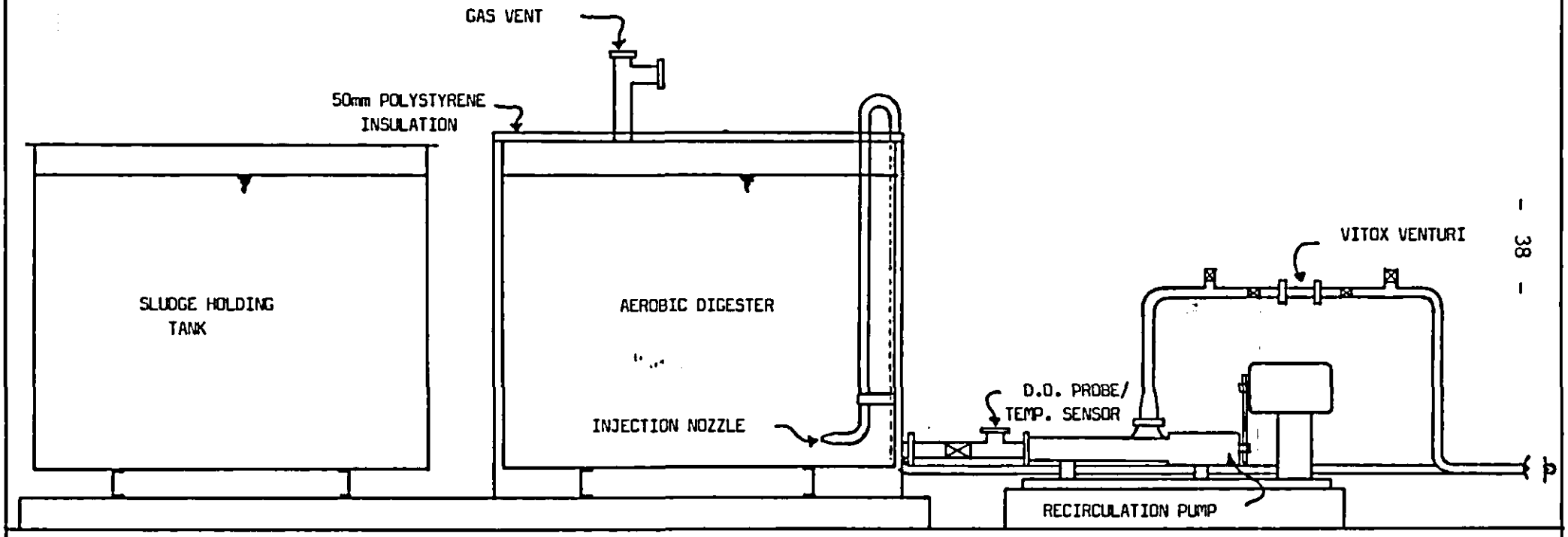
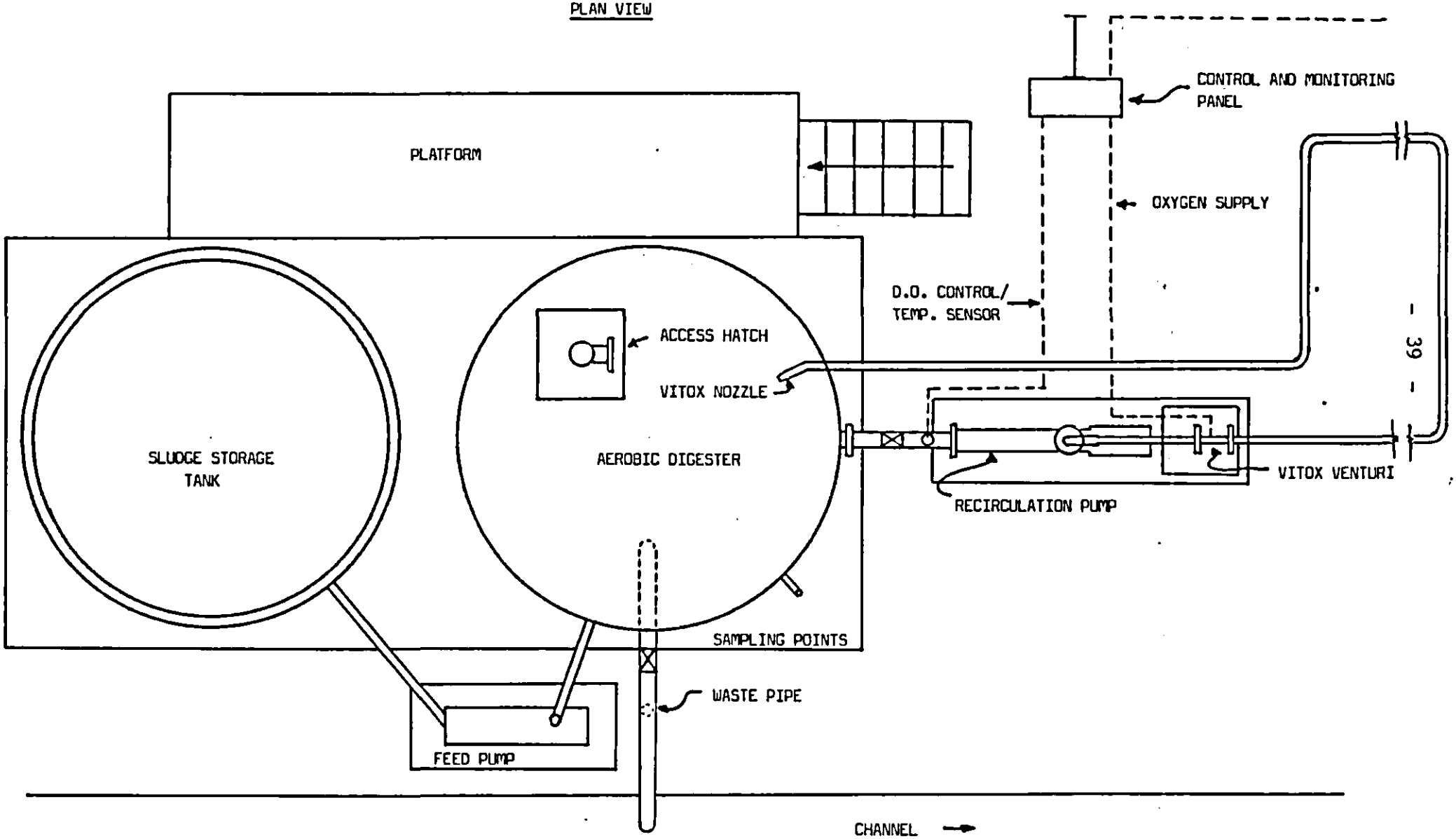


FIGURE N°. 2

AUTOTHERMAL AEROBIC DIGESTION PILOT PLANT

PLAN VIEW



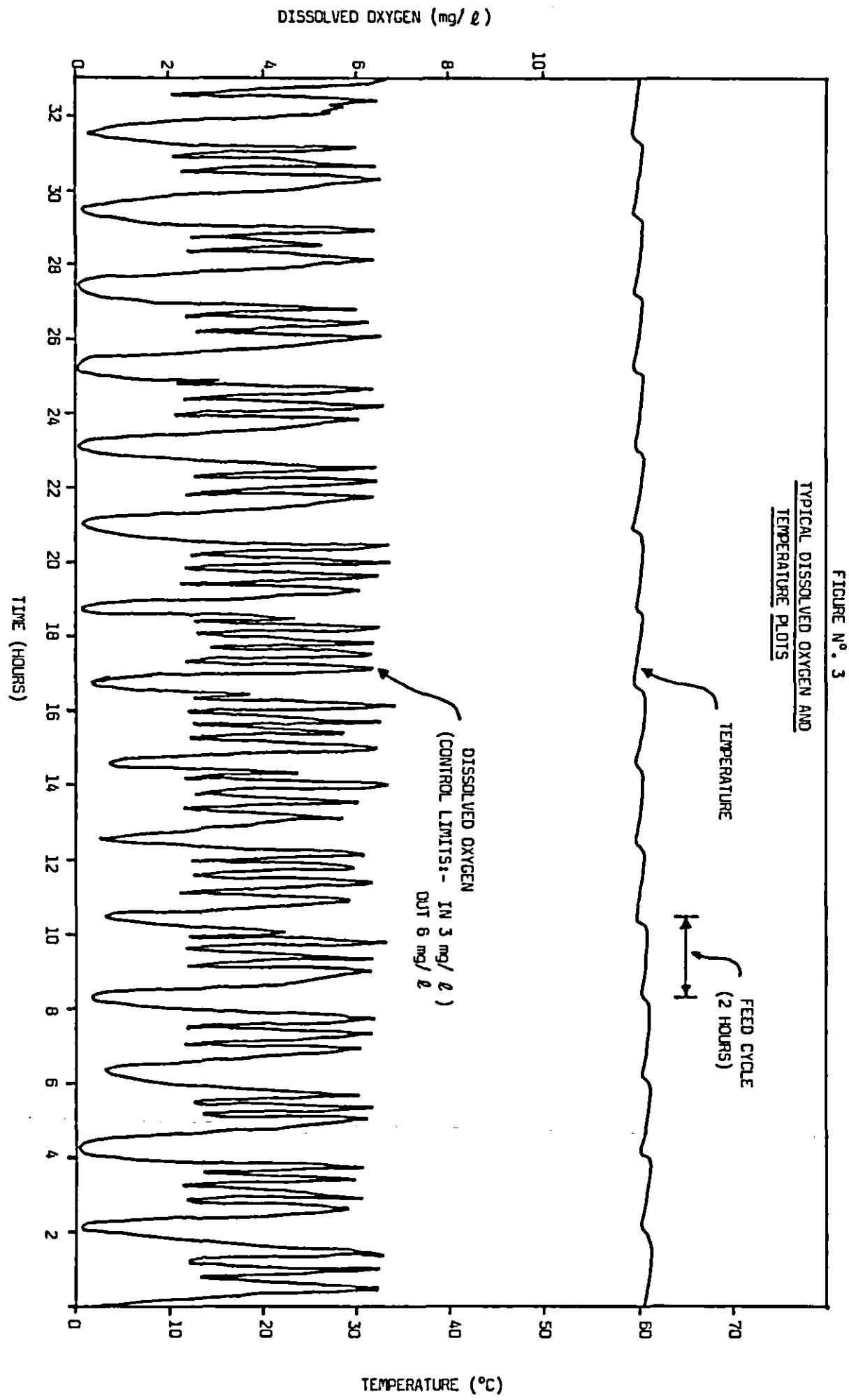


FIGURE N°. 3

TYPICAL DISSOLVED OXYGEN AND TEMPERATURE PLOTS

FIGURE 4. TYPICAL TEMPERATURES ACHIEVED DURING SYSTEM START-UP.

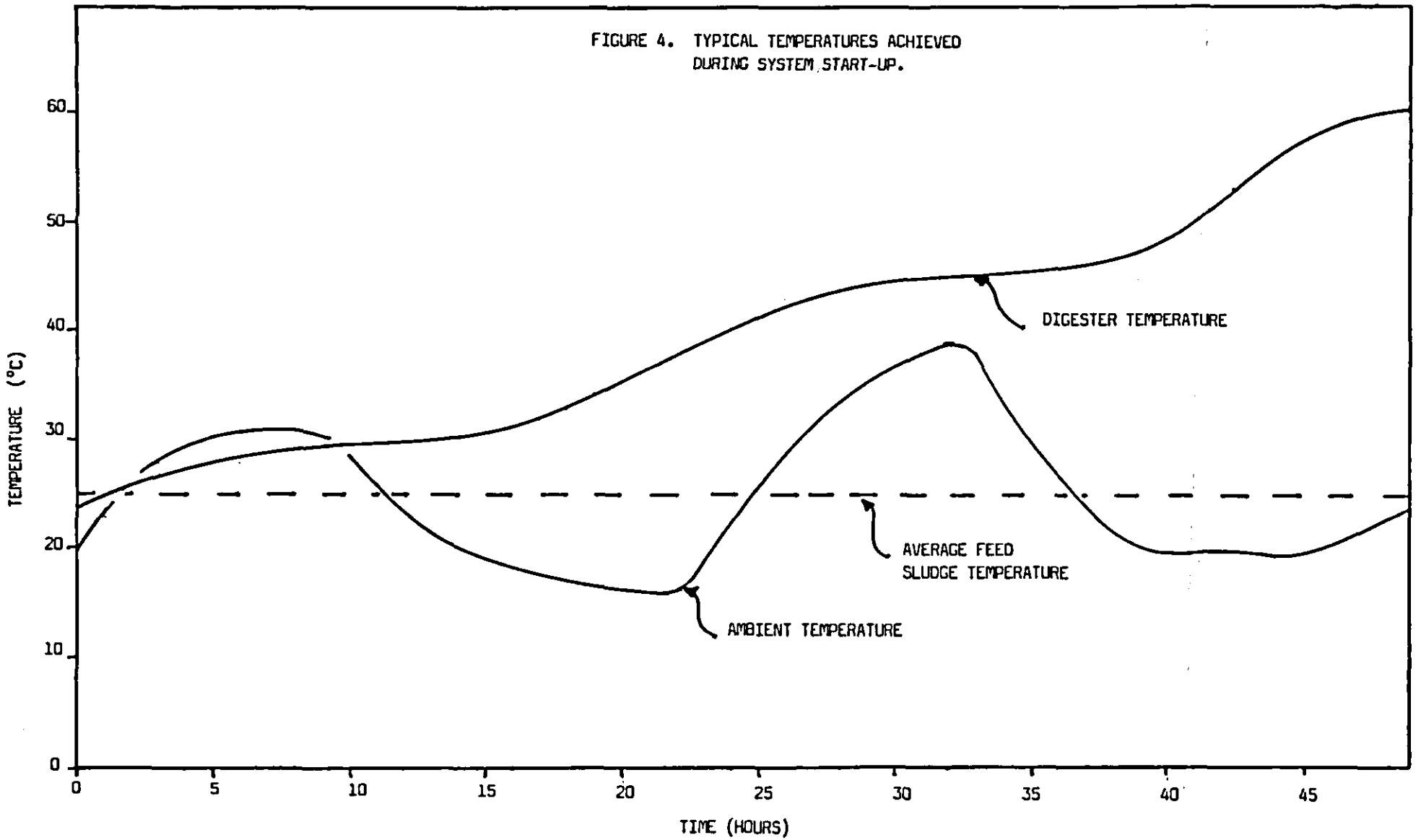
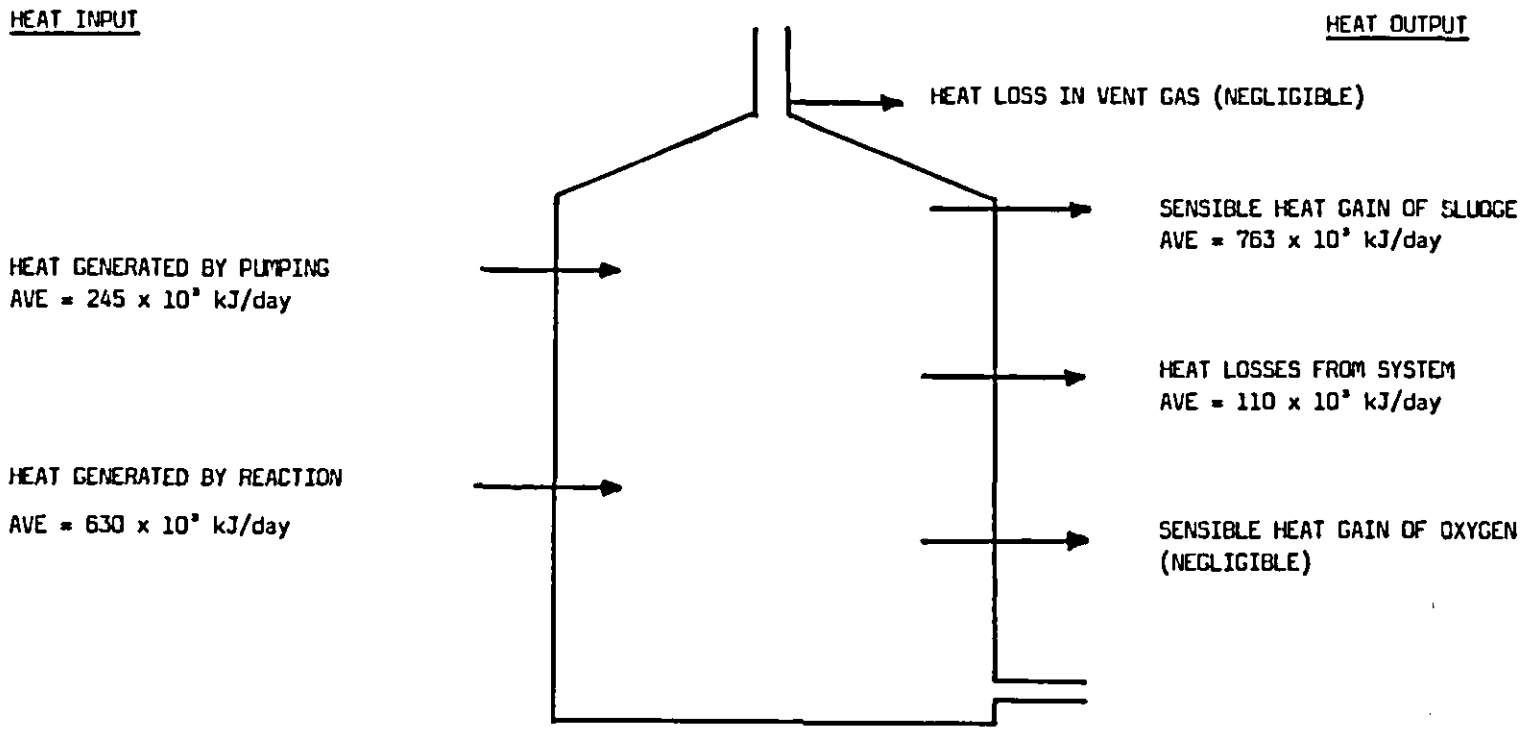


FIGURE 5. TYPICAL HEAT BALANCE (AVERAGE VALUES)



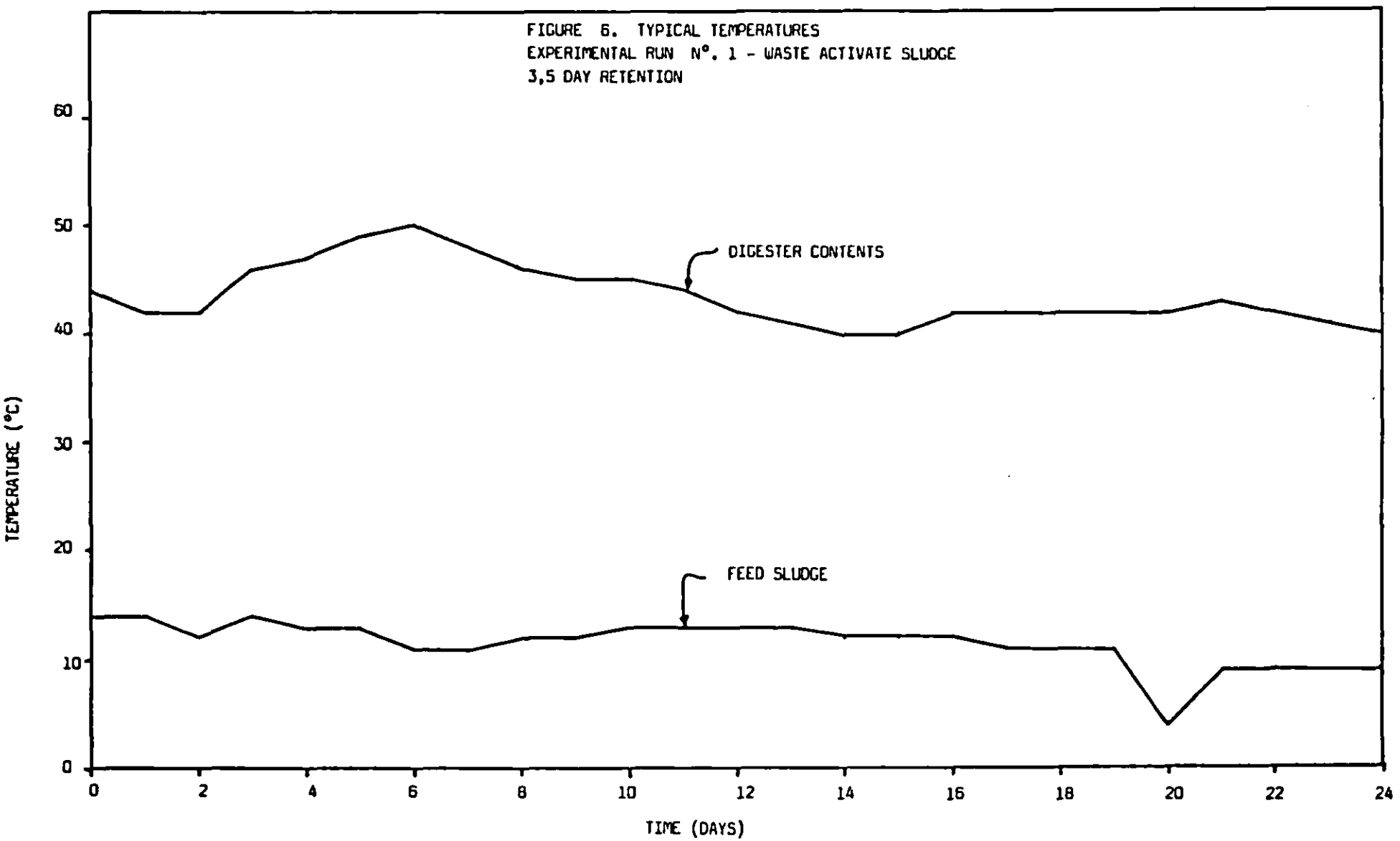


FIGURE 6. TYPICAL TEMPERATURES
EXPERIMENTAL RUN N°. 1 - WASTE ACTIVATE SLUDGE
3,5 DAY RETENTION
DIGESTER CONTENTS
FEED SLUDGE
TEMPERATURE (°C)
TIME (DAYS)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
22
24

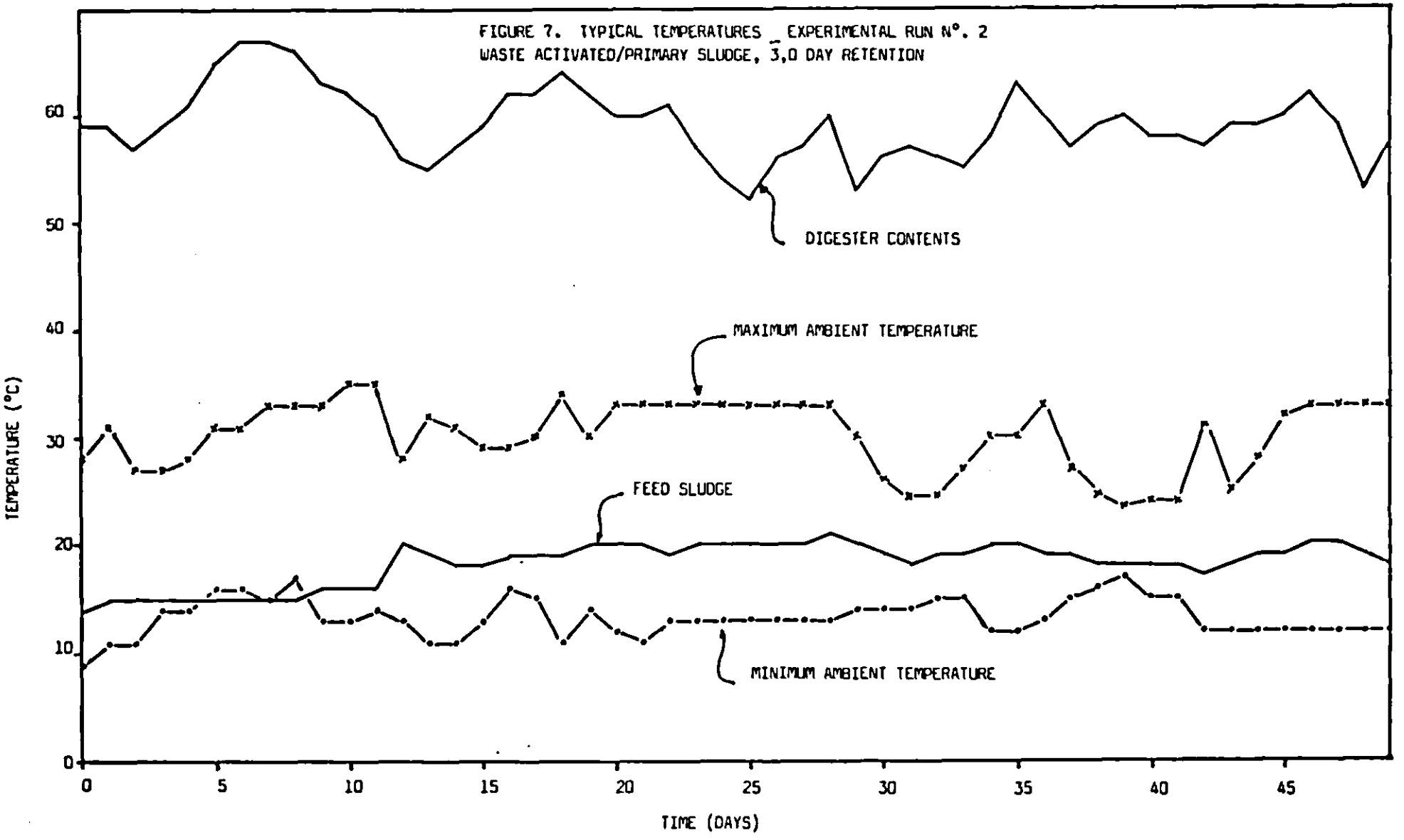


FIGURE 7. TYPICAL TEMPERATURES _ EXPERIMENTAL RUN N°. 2
WASTE ACTIVATED/PRIMARY SLUDGE, 3,0 DAY RETENTION
DIGESTER CONTENTS
MAXIMUM AMBIENT TEMPERATURE
FEED SLUDGE
MINIMUM AMBIENT TEMPERATURE
TEMPERATURE (°C)
TIME (DAYS)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45

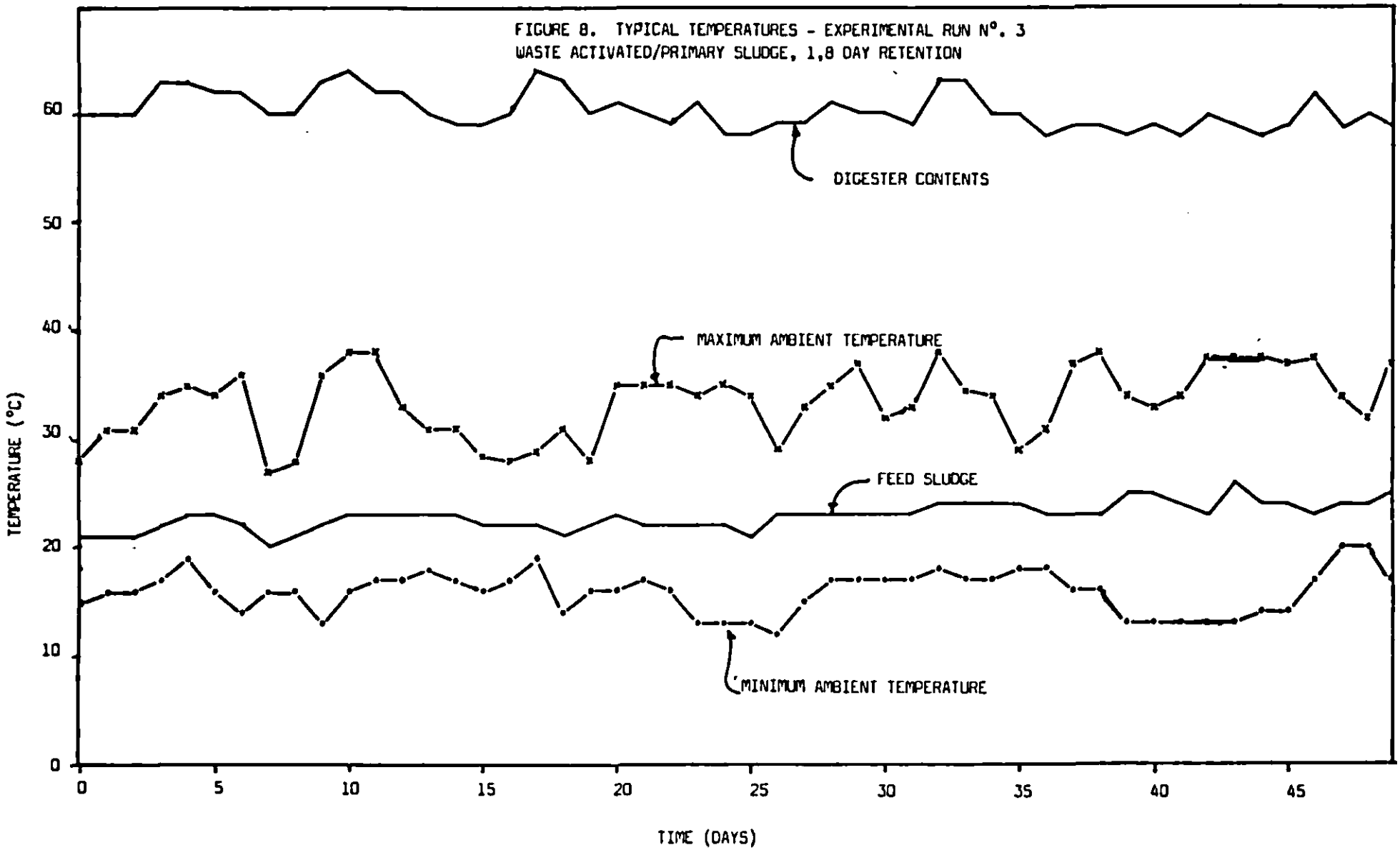


FIGURE 8. TYPICAL TEMPERATURES - EXPERIMENTAL RUN N°. 3
WASTE ACTIVATED/PRIMARY SLUDGE, 1,8 DAY RETENTION
DIGESTER CONTENTS
MAXIMUM AMBIENT TEMPERATURE
FEED SLUDGE
MINIMUM AMBIENT TEMPERATURE
TEMPERATURE (°C)
TIME (DAYS)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45

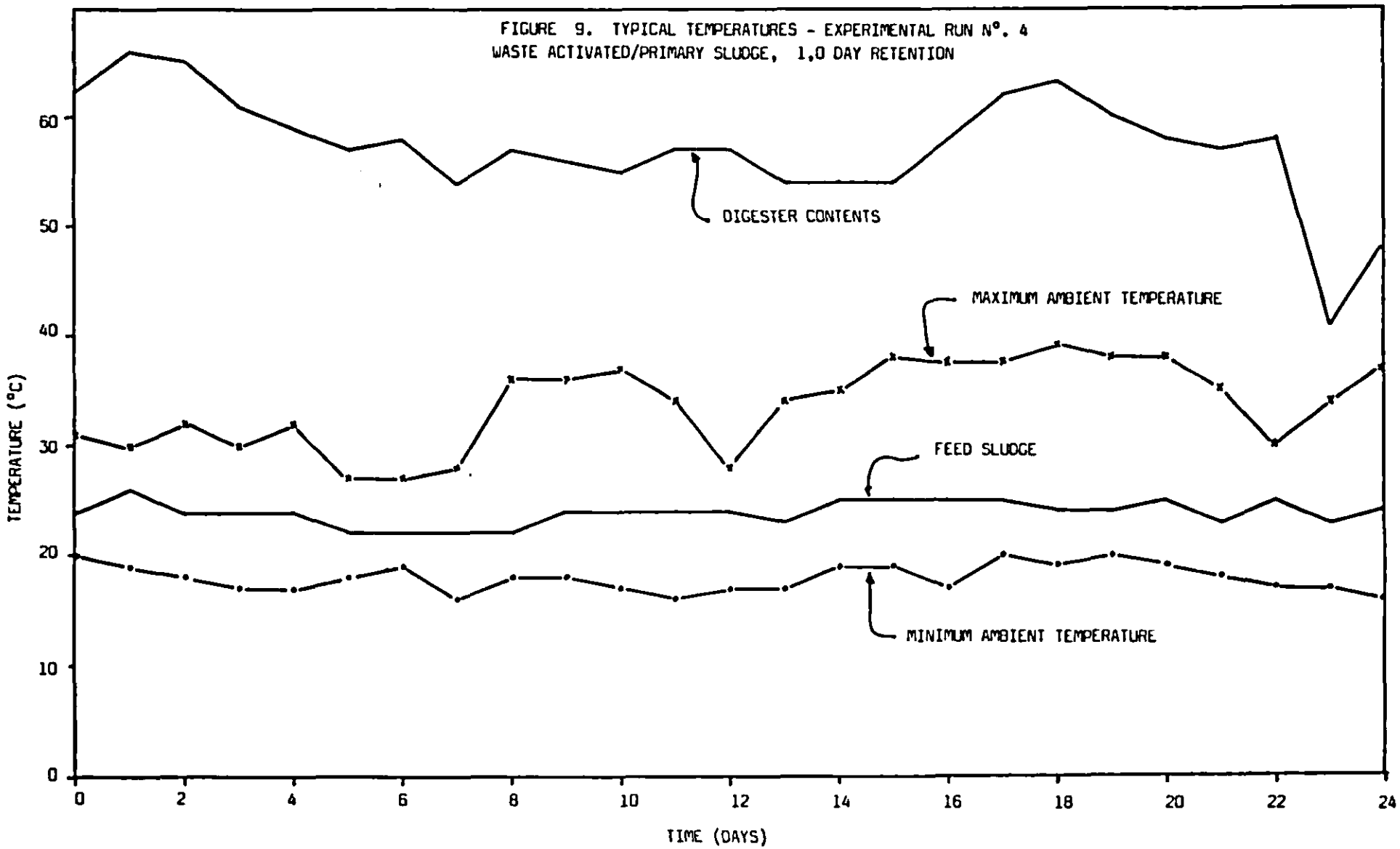


FIGURE 9. TYPICAL TEMPERATURES - EXPERIMENTAL RUN N°. 4
WASTE ACTIVATED/PRIMARY SLUDGE, 1.0 DAY RETENTION
DIGESTER CONTENTS
MAXIMUM AMBIENT TEMPERATURE
FEED SLUDGE
MINIMUM AMBIENT TEMPERATURE
TEMPERATURE (°C)
TIME (DAYS)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
22
24

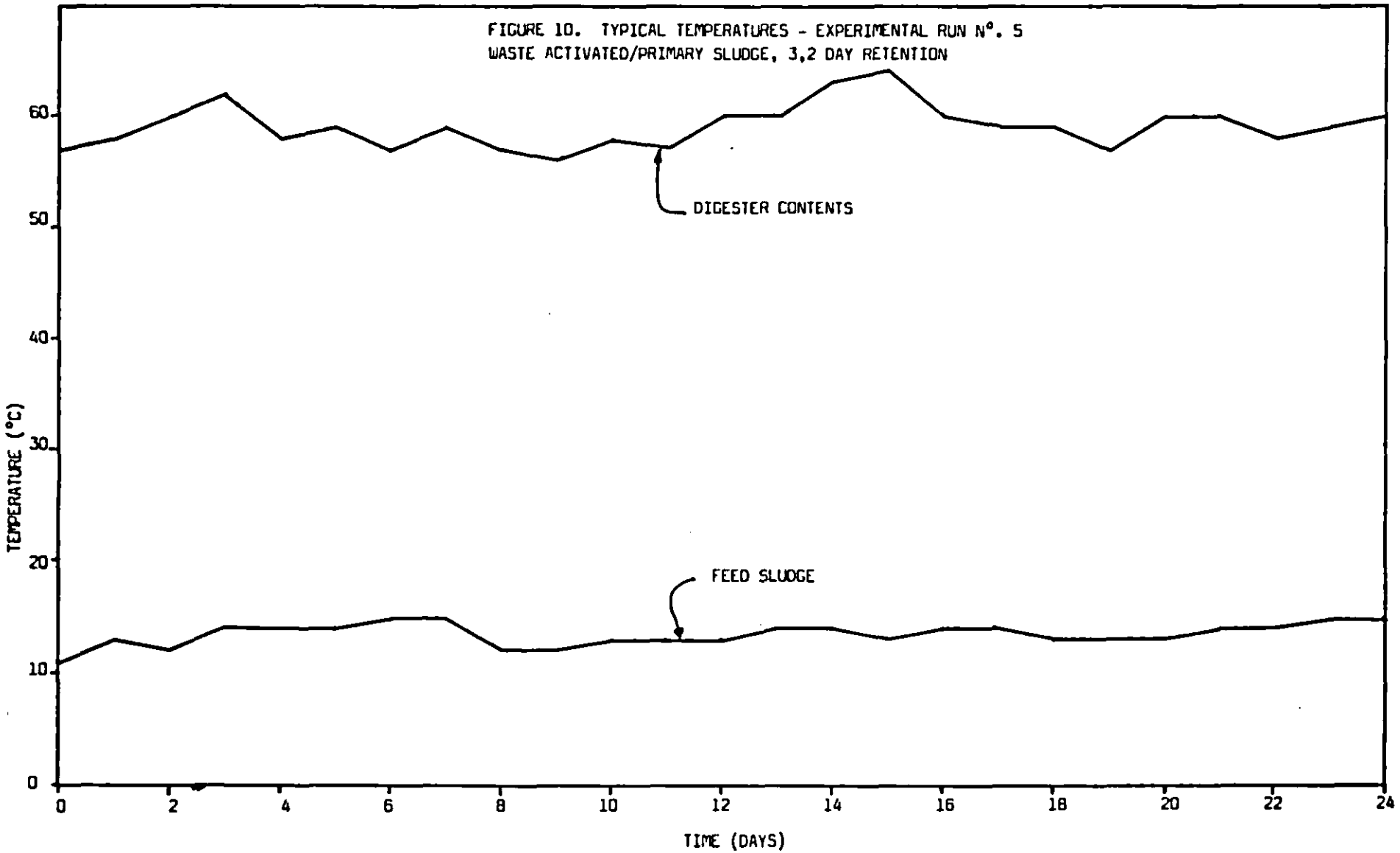


FIGURE 10. TYPICAL TEMPERATURES - EXPERIMENTAL RUN N°. 5
WASTE ACTIVATED/PRIMARY SLUDGE, 3,2 DAY RETENTION
DIGESTER CONTENTS
FEED SLUDGE
TEMPERATURE (°C)
TIME (DAYS)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
22
24

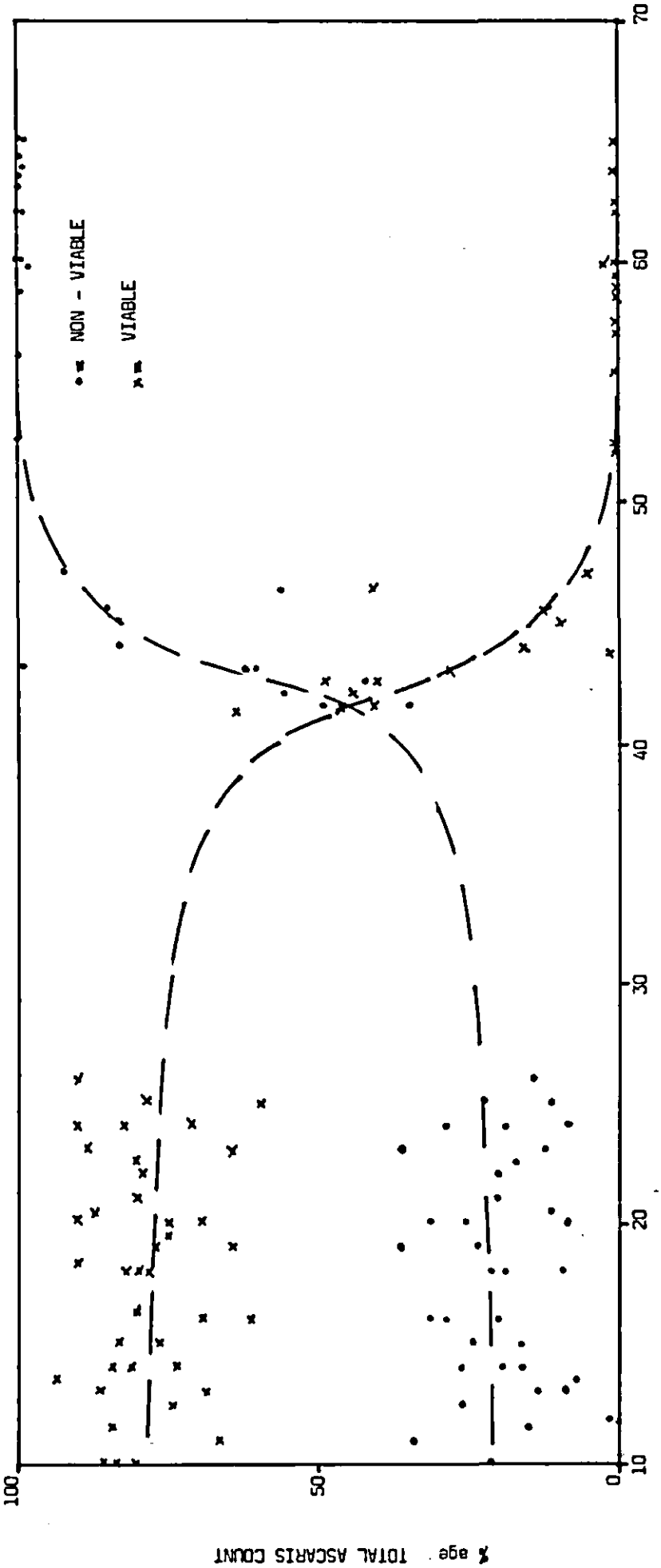


FIGURE 11. DESTRUCTION OF ASCARIS OVA

TABLE 1 - SLUDGE CHARACTERISTICS

EXPERIMENTAL RUN	RETENTION TIME (DAYS) THEORETICAL/ ACTUAL	FEED SLUDGE TYPE	SAMPLE	% TOTAL SOLIDS		% VOLATILE SOLIDS		pH	
				AVERAGE	RANGE	AVERAGE	RANGE	AVERAGE	RANGE
1	4/3,5	THICKENED WASTE	FEED	3,7	5,1 - 3,3	75,0	77,7 - 73,5	6,2	6,5- 5,9
		ACTIVATED	DIGESTER	2,8	3,5 - 2,7	71,6	72,4 - 70,7	7,0	7,2 - 6,9
2	4/3	PRIMARY + WASTE	FEED	4,2	4,7 - 3,4	70,8	72,8 - 68,2	5,6	5,8 - 5,5
		ACTIVATED	DIGESTER	3,0	3,6 - 2,4	71,2	72,8 - 69,8	7,2	8,1 - 6,8
3	2/1,8	PRIMARY + WASTE	FEED	3,9	5,3 - 3,0	69,3	71,3 - 64,6	5,6	5,8 - 5,5
		ACTIVATED	DIGESTER	3,3	3,3 - 2,7	69,1	71,3 - 66,4	7,2	8,4 - 7,0
4	1/1	PRIMARY + WASTE	FEED	3,4	4,4 - 2,4	71,1	82,0 - 68,0	5,6	6,2 - 5,3
		ACTIVATED	DIGESTER	2,6	2,8 - 2,0	71,3	79,0 - 68,4	7,4	7,9 - 7,2
5	4/3,2	PRIMARY + WASTE	FEED	4,0	4,7 - 3,4	75,0	76,4 - 74,4	6,0	6,2 - 5,8
		ACTIVATED	DIGESTER	3,0	3,2 - 2,8	72,0	73,4 - 70,4	7,3	7,8 - 7,1

TABLE 2 - SLUDGE ANALYSIS (AVERAGE)

EXPERIMENTAL RUN	FEED SLUDGE TYPE	SAMPLE	% DRY SOLIDS	% VOLATILE SOLIDS	% VOL SOLIDS DESTROYED	COD (mg/ ℓ)	% COD REDUCED	AMMONIA (mg/ℓ)	TKN (mg/ℓ)	PHOSPHORUS (mg/ ℓ)	
										TOTAL P	ORTHO P
1	THICKENED WAS	FEED	3,7	75,0	28,0	39790	21,0	90	2267	840	169
		DIGESTER	2,8	71,6		31360		454	2056	814	146
2	WAS / PRIMARY	FEED	4,2	70,8	28,0	48350	35,0	426	1656	585	181
		DIGESTER	3,0	71,2		31690		610	1600	576	100
3	WAS/ PRIMARY	FEED	3,9	69,3	23,0	46070	32,5	444	1679	578	191
		DIGESTER	3,0	69,1		31100		484	1600	528	68
4	WAS/ PRIMARY	FEED	3,4	71,1	21,0	39130	30,5	291	1375	452	185
		DIGESTER	2,6	71,3		28460		357	1285	405	56
5	WAS/ PRIMARY	FEED	4,0	75,0	28,0	46660	38,0	345	1695	644	149
		DIGESTER	3,0	72,0		29100		708	1638	590	87

TABLE 3 - SLUDGE LOADINGS

EXPERIMENTAL RUN	kg/day DRY SOLIDS IN	kg/day VOL. SOLIDS IN	kg/day VOL. SOLIDS OUT	kg/day VOL. SOLIDS DESTROYED	% VOL. SOLIDS DESTROYED	LOADING RATE kg VS/m³/day
1	87,5	65,6	47,2	18,4	28,0	8,2
2	111,9	79,2	55,9	23,3	28,0	9,9
3	181,0	124,9	93,3	31,6	23,0	15,6
4	266,8	189,7	150,5	39,2	21,0	23,7
5	100,3	75,2	54,2	21,0	28,0	9,4

TABLE 4. SYSTEM OPERATING CONDITIONS

EXPERIMENTAL RUN	ACTUAL RETENTION TIME (days)	FEED SLUDGE TYPE	AVERAGE TEMPERATURE (°C)		POWER USED (kWh/day)	OXYGEN SUPPLIED (kg/day)	% O_2 IN VENT GAS	% CO_2 IN VENT GAS	% O_2 UTILISED	OXYGEN TO WASTE (kg/day)	OXYGEN USED (kg/day)
			FEED	DIGESTER							
1	3,5	WAS	12	44	96,2	68,4	-	-	-	-	-
2	3,0	WAS/ PRIMARY	16	58	96,2	64,0	14	86	86	9,0	55,0
3	1,8	WAS/ PRIMARY	22	60	96,1	95,8	10	90	90	9,6	86,2
4	1,0	WAS/ PRIMARY	24	58	96,5	99,2	14	86	86	13,9	85,3
5	3,2	WAS/ PRIMARY	13	59	96,2	60,0	14	86	86	8,4	51,6

TABLE 5. OXYGEN AND POWER UTILISATION

EXPERIMENTAL RUN	kg O_2 SUPPLIED/ kg VS DESTROYED	kg O_2 USED/ kg VS DESTROYED	kg O_2 SUPPLIED/ kg COD DESTROYED	kg O_2 USED/ kg COD DESTROYED	kWh/kg VS DESTROYED	kWh/kg COD DESTROYED
1	3,7	-	4,0	-	5,2	5,6
2	2,8	2,4	1,4	1,2	4,1	2,1
3	3,0	2,7	1,4	1,3	3,0	1,4
4	2,5	2,2	1,2	1,0	2,5	1,1
5	2,9	2,5	1,4	1,2	4,6	2,2

TABLE 6 - POLYMER ADDITION TO AEROBICALLY DIGESTER SLUDGE

POLYMER SOLUTION (mℓs 0,05% solution/100mℓ sample)	3,2 DAY RETENTION TIME *		1,82 DAY RETENTION TIME *	
	POLY DOSE (kg/ton dry solids)	CST (secs)	POLY DOSE (kg/ton dry solids)	CST (secs)
NIL	NIL	200 000	NIL	200 000
30	5,3	1082	5,3	798
50	8,9	40	-	-
60	10,7	25	-	-
70	-	-	12,5	14
80	14,3	15	-	-
mℓs 0,5% solution added to 100mℓ sample				
7	-	-	12,5	1799
10	-	-	18,0	324

* SOLIDS CONTENT OF SLUDGE SAMPLE: 3,2 DAYS = 2,8 m/v
1,8 DAYS = 2,7 m/v

TABLE 7 - SYSTEM HEAT BALANCE

NOMINAL RETENTION TIME (DAYS)	HEAT LOST TO SURROUNDINGS H_L kJ x10³/day	HEAT GAIN BY SLUDGE H_S kJ x10³/day	HEAT INPUT BY PUMPS H_P kJ x10³/day	BIOLOGICAL REACTION HEAT $H_B = H_L + H_S - H_P$ kJ x10³/day	HEAT OF REACTION H_B/ VS kJ x10³/kg VS DESTROYED	kJ x10³/ kg O_2 USED
1	110	1120	245	985	25	10
2	110	700	244	566	18	6
3	110	470	244	336	15	5

TABLE 8. BIOLOGICAL FERMENTABILITY OF AEROBICALLY DIGESTED SLUDGE

NOMINAL RETENTION TIME (days)	VOLATILE ACIDS PRODUCED (mg/ℓ)	
	SAMPLE + 10 % DIGESTED SLUDGE	SAMPLE + 10 % ACID SLUDGE
3	780	1250
2	190	1900

TABLE 9. PROCESS COSTS *

NOMINAL RETENTION TIME (days)	COST PER DRY TON SOLIDS (R/ton)		COST PER TON VOLATILE SOLIDS DESTROYED (R/ton)	
	O_2	TOTAL	O_2	TOTAL
1	33	46	230	315
2	55	77	270	375
3	69	109	250	396

*NOTE: 1. COST OF OXYGEN TAKEN AS R0,09/kg
2. COST OF ELECTRICITY TAKEN AS R0,035/kWhr
3. COSTS RELATE TO PILOT PLANT TESTS

TABLE 10. ASCARIS OVA COUNTS AND SALMONELLA DETECTION EXPERIMENTAL RUN N°. 1
THICKENED WASTE ACTIVATED SLUDGE.
3,5 DAY RETENTION TIME.

(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT/g DRY	POTENTIALLY INFECTIVE %	VIABLE %	NON-VIABLE %		
1	F	2243	93	93	7	present	13,5
	D	2679	40	44	56	present	46,3
2	F	2316	86	87	13	present	13,0
	D	2031	5	8	92	present	47,0
3	F	1686	68	91	9	absent	13,0
	D	3893	10	17	83	absent	45,0
4	F	2371	74	74	26	absent	12,5
	D	3429	16	17	83	absent	43,8
5	F	2063	84	85	15	present	11,5
	D	2323	64	65	35	present	41,5
6	F	1706	66	66	34	present	11,0
	D	2536	46.	51	49	present	41,6
7	F	1217	80	82	18	present	4,0
	D	1844	49	58	42	absent	42,5
8	F	1706	85	85	15	absent	9,0
	D	1933	28	33	67	absent	42,9
9	F	1419	79	79	21	absent	9
	D	2600	43	45	55	absent	41,8

TABLE 11. ASCARIS OVA COUNTS AND SALMONELLA DETECTION
EXPERIMENTAL RUN N°. 2 - WASTE ACTIVATED SLUDGE/PRIMARY SLUDGE. 3,5 DAY RETENTION.
(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT/g DRY	POTENTIALLY VIABLE %	VIABLE %	NON-VIABLE %		
1	F	1490	83	84	16	absent	15,0
	D	1912	0	0	100	present	57,4
2	F	950	76	76	24	absent	15,0
	D	2310	0	0	100	absent	58,5
3	F	1952	69	69	31	absent	16,0
	D	1107	0	0	100	absent	63,4
4	F	2529	71	71	29	absent	16,0
	D	1107	0	0	100	absent	62,0
5	F	1465	80	80	20	absent	16,0
	D	931	0	0	100	absent	62,0
6	F	2079	63	64	36	absent	19,0
	D	767	0	0	100	absent	62,2
7	F	1969	77	77	23	present	19,0
	D	1828	1	1	99	absent	63,5
8	F	2489	75	75	25	absent	20,0
	D	1800	1	1	99	absent	43,6
9	F	2250	69	69	31	present	20,0
	D	2423	0	0	100	absent	52,1

TABLE 11. (CONT'D). ASCARIS OVA COUNTS AND SALMONELLA DETERMINATIONS EXPERIMENTAL RUN N° 2- WASTE ACTIVATED SLUDGE/ PRIMARY SLUDGE. 3,5 DAY RETENTION
(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERTURE (°C)
		COUNT/g DAY	POTENTIALLY VIABLE %	VIABLE %	NON-VIABLE %		
10	F	972	90	92	8	present	18,0
	D	2444	0	0	100	absent	56,8
11	F	2079	79	79	21	absent	18,0
	D	966	0	0	100	absent	58,9
12	F	1806	79	79	21	present	18,0
	D	1586	0	0	100	absent	60,0
13	F	1262	75	75	25	absent	19,5
	D	1563	1	1	99	absent	59,9

TABLE 12. ASCARIS OVA COUNTS AND SALMONELLA DETECTION
EXPERIMENTAL RUN N° 3 - WASTE ACTIVATED
SLUDGE/PRIMARY SLUDGE . 1,8 DAY RETENTION
(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT/g DRY	POTENTIALLY VIABLE %	VIABLE %	NON-VIABLE %		
1	F	1395	87	89	11	absent	20,5
	D	1267	1	1	99	absent	60,3
2	F	2486	90	92	8	absent	20,0
	D	1531	0	0	100	absent	60,0
3	F	2595	79	80	20	absent	21,0
	D	1186	0	0	100	absent	60,2
4	F	1057	88	88	12	absent	23,0
	D	1516	0	0	100	absent	59,3
5	F	2848	82	83	17	absent	22,5
	D	1432	0	1	99	absent	58,7
6	F	2853	71	71	29	absent	24,0
	D	1636	0	0	100	absent	59,6
7	F	2230	64	64	36	absent	23,0
	D	2400	2	2	98	absent	59,8
8	F	2828	78	78	22	absent	25,0
	D	4240	1	1	99	absent	61,8

TABLE 13. ASCARIS OVA COUNTS AND SALMONELLA DETERMINATION EXPERIMENTAL RUN N° 4 - WASTE ACTIVATED SLUDGE/PRIMARY SLUDGE. 1,0 DAY RETENTION .
(F = FEED D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT/ g DRY	POTENTIALLY VIABLE %	VIABLE %	NON-VIABLE %		
1	F	2690	90	86	14	absent	26,0
	D	2036	1	1	99	absent	65.6
2	F	4138	90	92	8	absent	24,0
	D	3792	0	0	100	absent	55.6
3	F	1500	59	59	11	absent	25,0
	D	1760	0	0	100	absent	57,7
4	F	2222	82	82	18	absent	24,0
	D	2667	12	15	85	absent	45,5
5	F	1150	89	90	10	absent	22,0
	D	1600	40	40	60	absent	42,8

TABLE 14. ASCARIS OVA COUNTS AND SALMONELLA DETERMINATIONS EXPERIMENTAL RUN N°. 5
WASTE ACTIVATED SLUDGE/ PRIMARY SLUDGE.
3,2 DAY RETENTION.
(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT /g DRY	POTENTIALLY VIABLE %	VIABLE %	NON-VIABLE %		
1	F	2390	81	81	19	absent	18
	D	2785	0	0	100	absent	52,4
2	F	1772	84	84	16	absent	14,0
	D	1896	0	0	100	absent	59,0
3	F	2196	81	81	19	absent	14,0
	D	2344	0	0	100	absent	60,0
4	F	1037	73	74	26	absent	14,0
	D	2137	0	0	100	absent	60,0

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APPENDIX N°. 1

PROCESS CONPARISONS

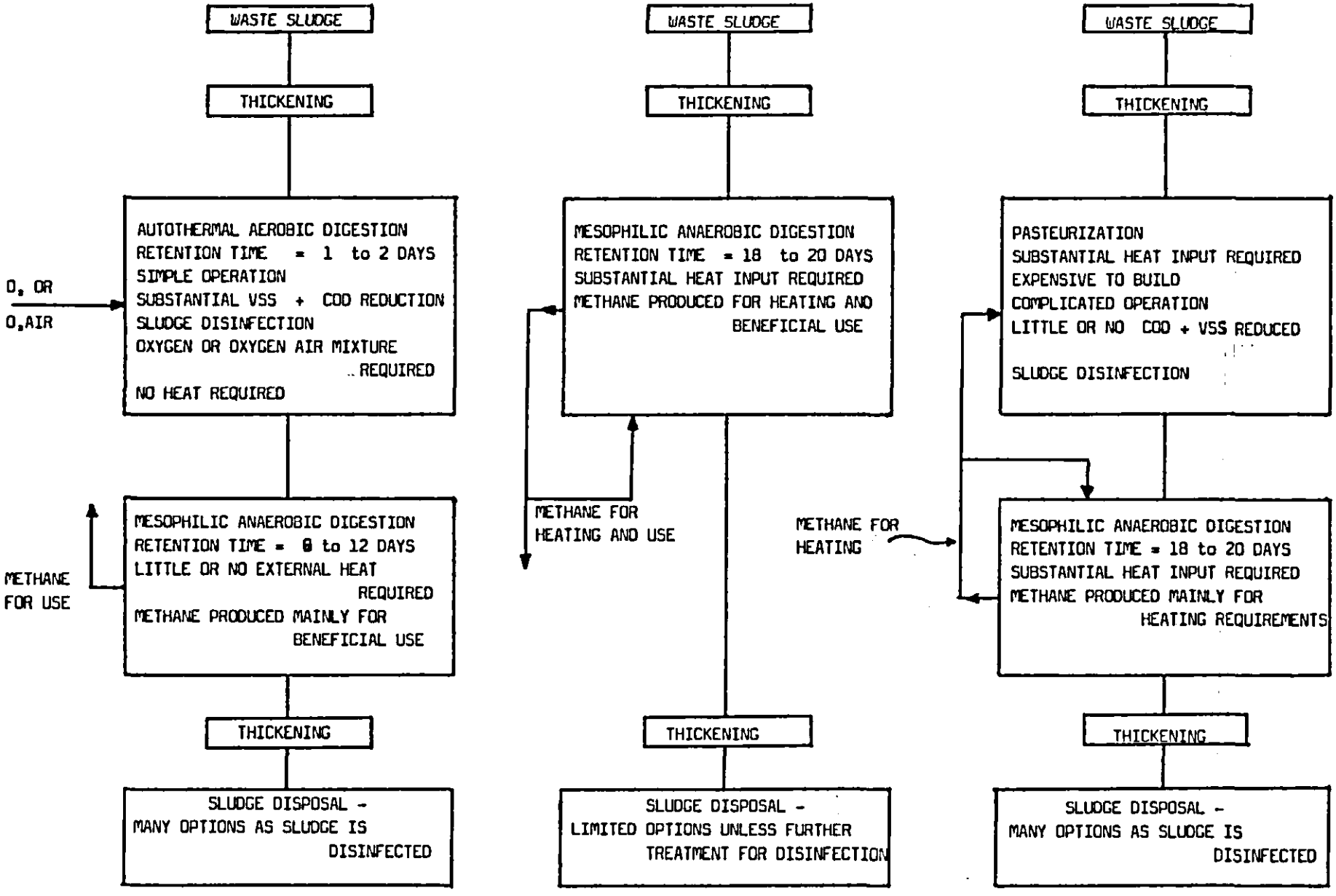
The costs given in the body of the report and in Table 9 are only indicative of the cost of the treatment phase of the autothermal aerobic digestion process at pilot scale and should not be used as the basis for comparision with other sludge treatment processes.

In order to arrive at a realistic cost for treatment by means of the autothermal process further work at larger scale including a properly sized anaerobic second stage and the optimization of oxygen or a mixture of oxygen and air would be necessary. Full scale plants of this type are presently being commissioned in the U.S.A. and as such more realistic data should be available in the near future.

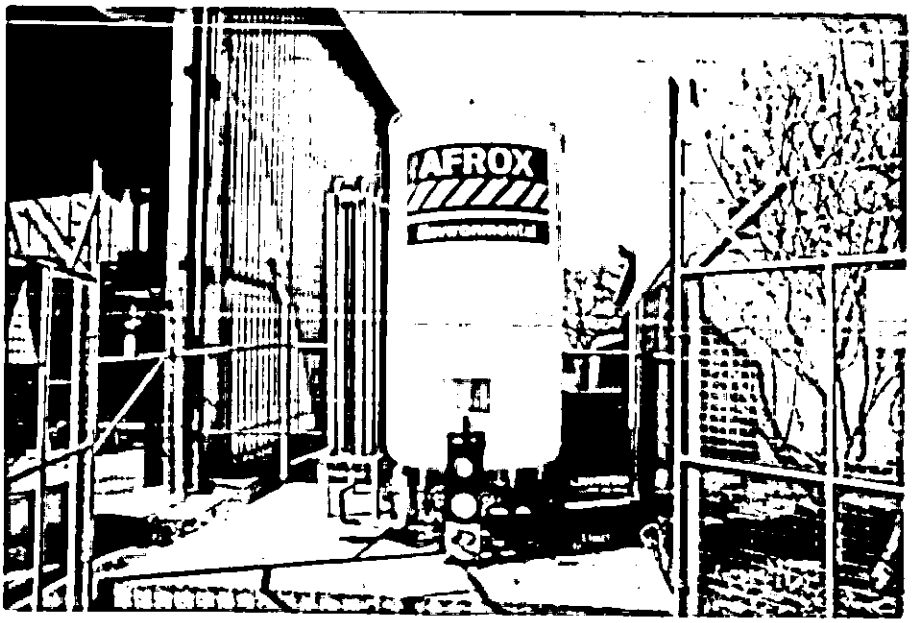
As mentioned above the costs given in the report relate only to the treatment phase and do not include capital costs which would obviously depend on such factors as the size of the plant, the materials used in its construction, the amount of standby equipment included and the degree of automation required. These figures cannot be acquired from a pilot plant operation such as the one under discussion.

In comparing the overall cost of a sludge treatment system, which includes the autothermal aerobic digestion phase, with other forms of sludge treatment there are many important considerations which must be taken into account in addition to the cost factors mentioned above. The first of these is the fact that there is a substantial reduction of both COD and VSS at retention times of the order of one to two days. Secondly, the amount of heat produced would probably be sufficient to supply the heating requirements of the second stage anaerobic process. In addition, the sludge produced by the process is pathogen free thus allowing many more disposal options than are available for anaerobically digested sludge.

The following diagram presents the salient features of three treatment processes; namely, autothermal aerobic digestion followed by mesophilic anaerobic digestion, standard mesophilic anaerobic digestion and the former in conjunction with a pasteurization stage, without trying to apportion costs related to any particular stage. It is felt that this is the most reasonable comparison that can be made based on the state of development of the autothermal digestion process to date.

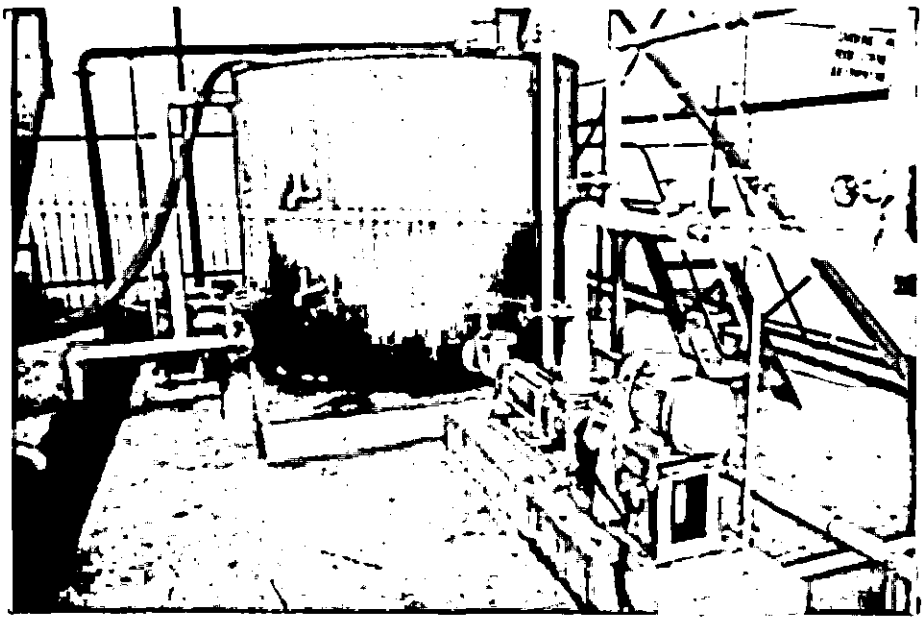


PROCESS COMPARISONS

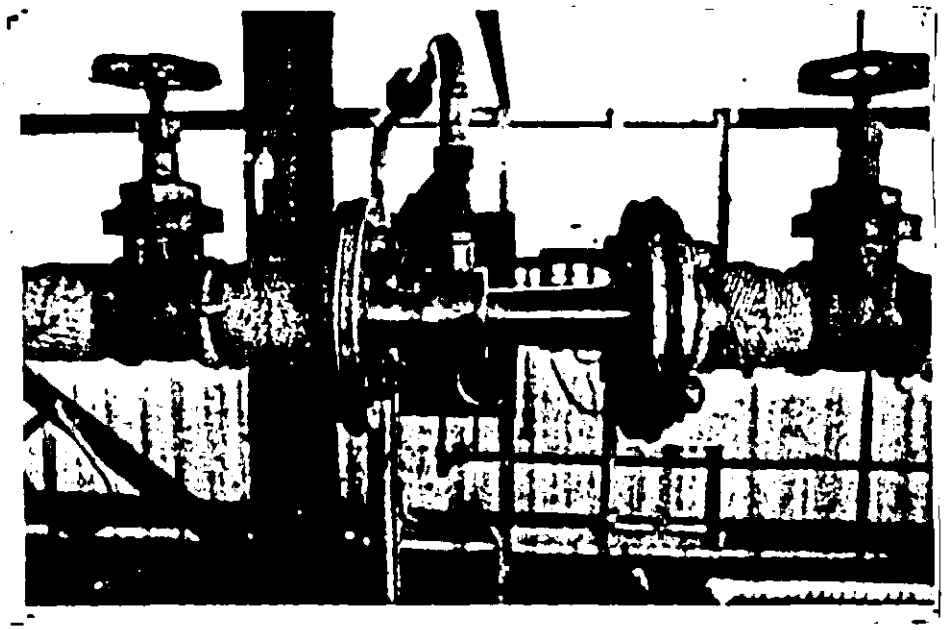


APPENDIX 2 -

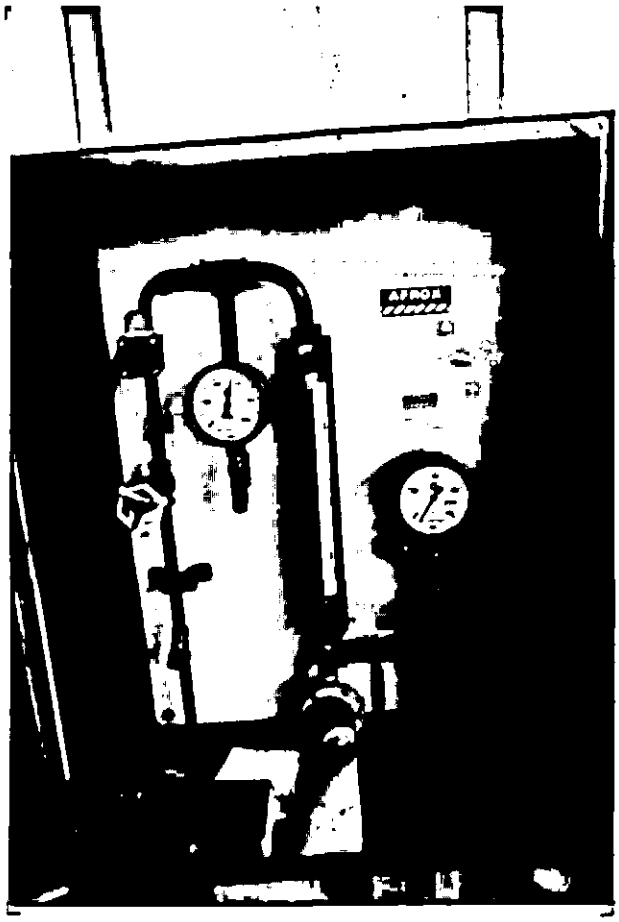
PHOTOGRAPHS



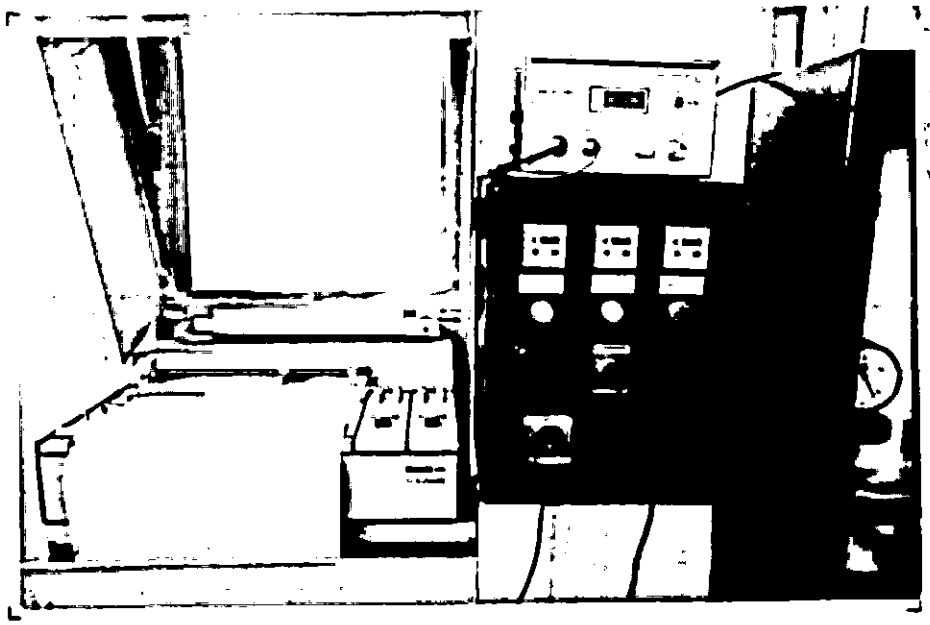
GENERAL VIEW OF PILOT DIGESTER SHOWING SAMPLING POINTS AT 1/3 AND 2/3 DEPTH. TANK FULLY INSULATED WITH 50mm POLYSTYRENE. IN FOREGROUND IS RECIRCULATION PUMP AND PIPEWORK INCLUDING VENTURI.



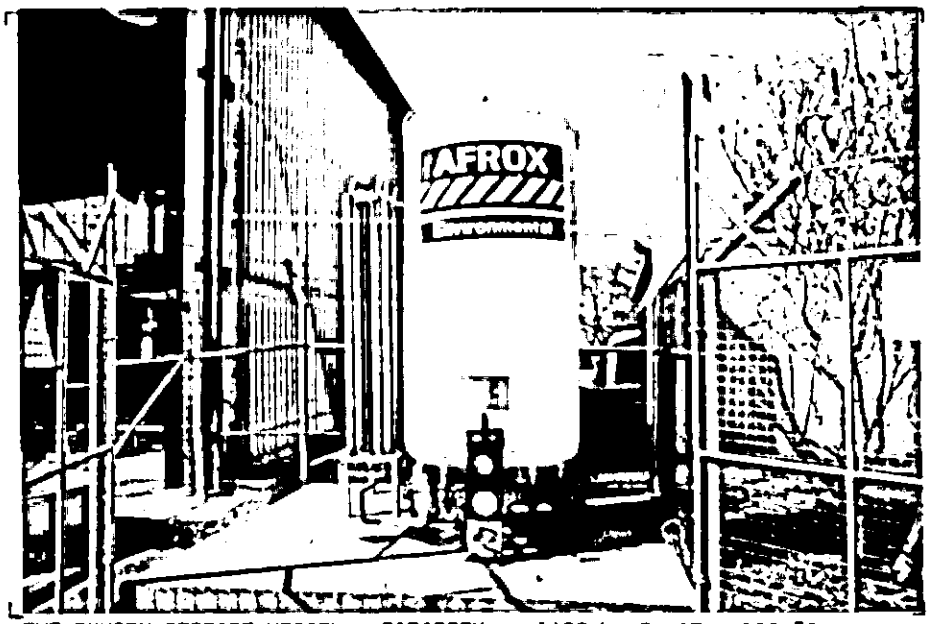
THE VITOX VENTURI WITH OXYGEN FEED PIPE AND MONITORS. THE RECYCLED SLUDGE PIPE SIZE IS 50mm DIAMETER TO AVOID BLOCKAGES AT THE VENTURI.



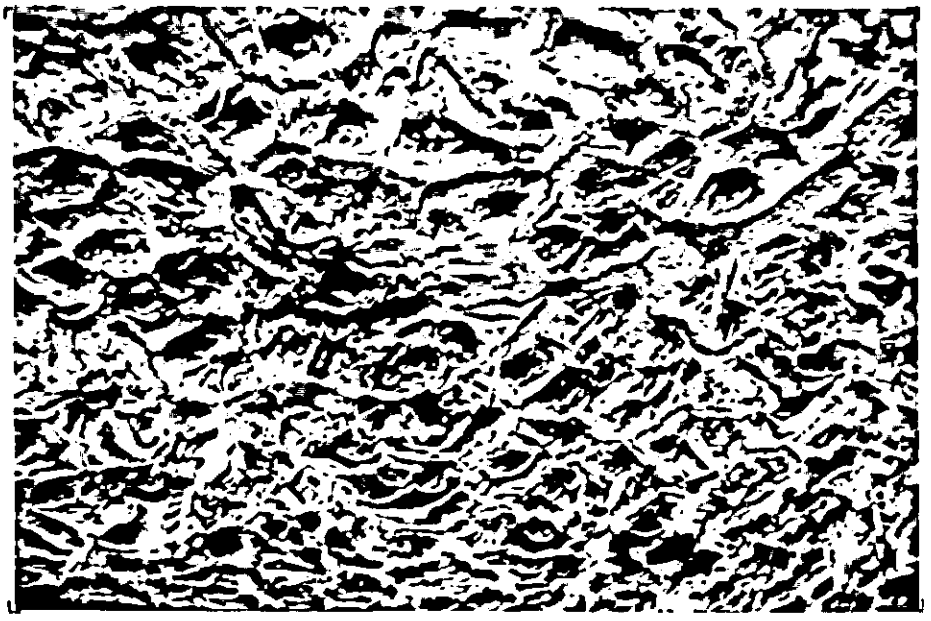
THE OXYGEN MONITORING AND CONTROL PANEL SHOWING PRESSURE AND FLOW CONTROL VALVES, SOLENOID SAFETY VALVE. OXYGEN PRESSURE GAUGE (550kPa) OXYGEN FLOW ROTAMETER AND SYSTEM PRESSURE GAUGE (170kPa)



ORBISPHERE D.O. METER (TOP) WITH CONTROLS FOR FEED PUMP RECYCLE PUMP AND OXYGEN FEED (BELOW). ON RIGHT IS TWO-PEN RECORDER FOR RECORDING D.O. AND TEMPERATURE.



THE OXYGEN STORAGE VESSEL. CAPACITY = 1400 kg O_2 AT -186 °C.
VAPOURIZER UNIT IS SITUATED AT LEFT OF VESSEL



TYPICAL SLUDGE COMPOSITION AFTER STANDING FOR APPROXIMATELY SEVEN DAYS

SLUDGE STABILISATION AND DISINFECTION BY MEANS OF AUTOTHERMAL AEROBIC DIGESTION USING OXYGEN

FINAL REPORT

by

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CITY ENGINEER'S DEPARTMENT
P.O. BOX 4323
JOHANNESBURG
2000

APRIL 1984

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ABSTRACT

The handling and disposal of sewage sludges are major problems in South Africa. In order to assist with the problems of local authorities in this field the Water Research Commission has embarked upon a programme of national research in this field including the project undertaken in conjunction with the City Council of Johannesburg which involved research into the effectiveness of the autothermal aerobic digestion process in terms of inactivation/destruction of selected pathogenic micro-organisms present in sewage sludges.

Research at pilot scale was undertaken into autothermal aerobic digestion of sludge using oxygen to demonstrate that sufficiently high temperatures could be achieved to ensure the degree of disinfection that would satisfy the health authorities. The ova of the helminth Ascaris lumbricoides was used in the disinfection studies and the dissolved oxygen level in the sludge was used as a means of controlling oxygen consumption.

The results achieved indicated that the process was very robust and rapidly attained a stable temperature of the order of 60°C which could be easily maintained and which effectively ensured disinfection of the sludge at retention periods of as low as one day. It was found that the aerobically treated sludge would not settle and was very difficult to dewater. In addition, the treated sludge was found to readily ferment anaerobically thus indicating the need for further treatment prior to final disposal.

ACKNOWLEDGEMENTS

This research project was financed by the Water Research Commission on a partnership basis with the City Council of Johannesburg. AFROX LIMITED provided considerable financial support to the project by way of providing the VITOX oxygen injection and control equipment as well as the total oxygen requirements of the research programme.

The author would also like to express sincere appreciation of the efforts of the following persons:

- Messrs. W.J. ENGELBRECHT, A.P. FISH, B.G. WEBB and other members of the staff of the Olifantsvlei Sewage Purification Works for their unstinting efforts during the research programme.
- MR. S.L.V. VENTER and staff for carrying out all the chemical analyses.
- MRS. L. MELMED and staff for carrying out all the micro biological analyses.
- MESSRS. M. WHITE and R.D. FORREST of AFROX LIMITED as well as J.E. McGLASHAN and A.R. PITMAN for their enthusiasm, encouragement and suggestions.
- The Steering Committee, as detailed below, for their able guidance and support throughout the research period.

STEERING COMMITTEE:

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1. INTRODUCTION:

Throughout the world today considerable attention is being given to the treatment and disposal of sludge resulting from the purification of domestic wastewaters. In South Africa there is no doubt that this question has become one of the major problems facing local authorities.

Sewage sludge contains inert particulate matter, oxidisable organic matter (particulate and dissolved), nutrients, trace elements, a variety of persistant substances and a range of pathogenic and non-pathogenic micro-organisms. The organic matter in sewage sludge is a valuable soil improver and in addition the sludge contains substantial amounts of nitrogen, phosphorus, calcium and magnesium and trace elements which are of value to agriculture. However, its universal use in agriculture and horticulture carries with it certain risks to public health. Oberholster (1983) states that South Africa does not differ from any other part of the world in its concern about the health aspects of the disposal and use of sewage sludge and its consequent control and that due to our agrarian way of life, the incidence of ascariasis in the population is high.

As the ova of Ascaris lumbricoides appear to be highly resistant, their presence may be a useful indicator of the hygienic quality of treated sewage sludge under South African conditions.

Not all countries have adopted the strict guidelines implemented by South Africa where sludge is disposed of to land. In the United Kingdom, for example, where the pathogen position is different to that in South Africa, Coker (1983), reports that sludge has regularly been used for market gardening and vegetable growing. Disposal policy in the United Kingdom is, however, steering sludge utilisation away from these outlets towards grain crops and land where any possible health hazard due to pathogens is remote. In the Federal Republic of Germany, on the other hand, Strauch (1983), reports that it is expected that in the near future sludge which is not disinfected will no longer be permitted on pastures and on arable land used for the production of forage.

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The guidelines for the utilization of sludge in South Africa, presented by Oberholster (1983), do not permit the use of raw sludge in agriculture. Secondary sludge (eg. digested sludge) may not be used on tuberous, bulb-type or low growing vegetables exposed to contamination or on lawns (except at planting), forage for animals, sports fields or public parks. Use is permitted for crops not eaten raw by humans, (eg. sugar cane), and for parks and sports fields during development only. Tertiary sludge (i.e. secondary sludge having been matured on drying beds for more than 90 days; raw, primary or secondary sludge that has been composted at 50°C to 65°C, according to accepted criteria or sludge pasteurised at less than 80°C), may be used on vegetables only if pathogen free i.e. no E.Coli, Ascaris lumbricoides ova or pathogenic viruses in 100g of sludge. Its use is unrestricted for other crops if well mixed with the soil, but it is not permitted as a top dressing such as on lawns. Sludge which has received advanced treatment (i.e. irradiation or high temperature treatment (150°C to 230°C)), may be used without restriction.

These guidelines give a clear indication of the degree of treatment required before sludge may be used in agriculture or horticulture and are particularly severe in regard to the presence of the very resistant ova of the parasitic roundworm Ascaris lumbricoides. The guidelines do not take into account the potential health hazards due to heavy metals and other toxic substances and relate principally to the hygienic quality of the sludge.

Due to the stringent health requirements and the lack of suitable disposal options, many of the municipalities are forced to dispose of sludge on the site of the sewage treatment works. Generally land is available for such disposal but the rates of sludge application are far in excess of those normally accepted for agricultural use. Large areas are therefore used for disposal and in the long term will be rendered unsuitable for further agricultural use. These measures are temporary solutions to the immediate problems being experienced but will undoubtedly feature for some time to come.

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In order to assist with the problems of local authorities in this field the Water Research Commission embarked upon a programme of national research in this field. One of the research projects undertaken with the City Council of Johannesburg involved research into the effectiveness of autothermal aerobic digestion in terms of the inactivation/destruction of selected micro-organisms.

2. DESCRIPTION OF THE PROCESS:

Aerobic digestion is a process which involves the direct oxidation of biodegradable matter by the biologically active mass of organisms and the oxidation of microbial cellular material. Unlike anaerobic digestion, it is a process where sludge (primary, waste activated or mixtures of sludges) is aerated in an open tank.

The main objectives of aerobic digestion are to reduce the solids content of the sludge and produce a stable end product. Claimed advantages of the process include a more stable process than conventional anaerobic digestion, a volatile solids reduction approximately equal to that obtained anaerobically, good quality supernatant liquor and the production of a humus-like, odourless,stable end product with good dewatering properties.

Autothermal or thermophilic aerobic digestion means operation in the thermophilic temperature range of 45°C to 55°C (or greater). The digestion process takes place in a well insulated, fully enclosed tank where the heat generated by the biologically active micro-organisms in the degradation of the organic material is utilized to overcome the system heat losses in such a manner that the process will be self-heating (autothermal) and will reach and maintain the required thermophilic temperatures. In most instances pure oxygen is used to supply the dissolved oxygen requirements of the process in order to reduce the large heat losses related to the quantities of air that would otherwise be required.

The basic reactions involved in autothermal aerobic digestion as summarised by Booth and Tramontini (1983) are as follows:

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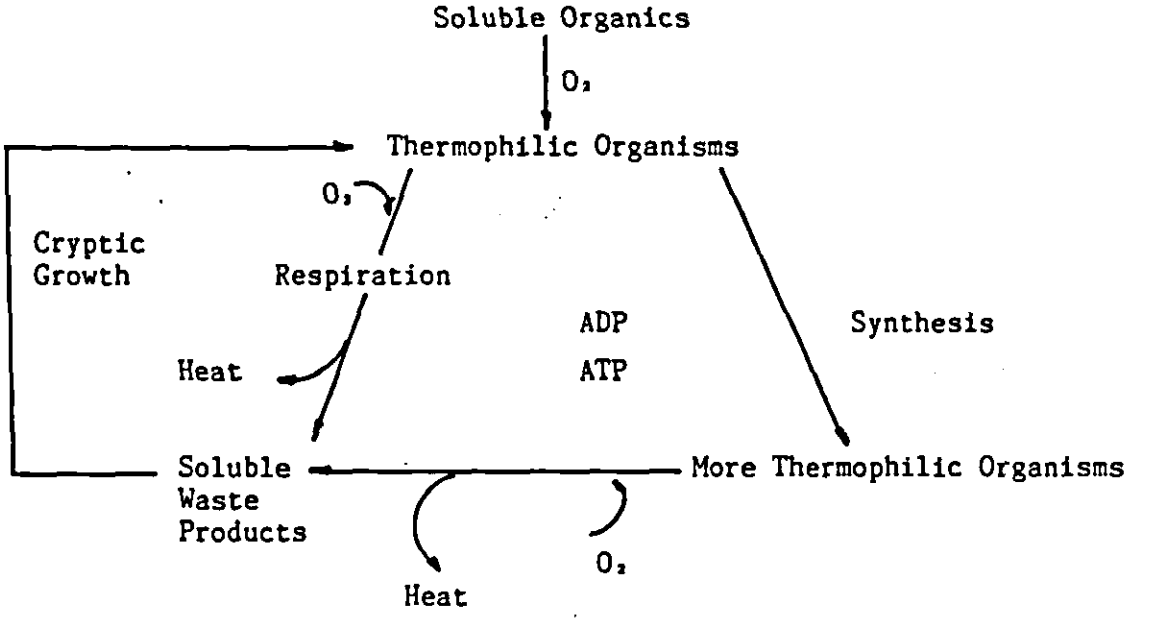
1. Solubilisation of organic matter (substrate) in order to pass through cell membranes. This is achieved by the excretion of extracellular enzymes or intracellular enzymes released by cell lysis. The rate of solubilisation increases with temperature as many organic compounds, e.g. lipids, are more soluble at higher temperatures.

2. Oxidation of soluble organic matter. The oxidation process can be represented schematically as follows:-



The oxidation of matter to CO_2 and water during respiration yields energy, some of which is stored in ATP. As micro-organisms are not 100% efficient a proportion of this energy is released as heat energy. Some of this energy is used for the maintenance of existing cells but as the micro-organisms decay the cell matter is solubilised and used for endogenous respiration thus producing more heat. At higher temperatures, such as those found in autothermal digestion, the decay rates are faster so there is more cryptic growth where micro-organisms grow on the products of decay.

The oxidation reaction can be summarised as follows:-

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Total organic solids + oxygen $\xrightarrow[\text{Nutrients}]{\text{Micro-organisms}}$ non-biodegradable organics- and $CO_2 + H_2O + NO_7$

Assuming that the formula $C_5 H_7 NO_2$ is representative of sludge organic matter, then the above equation can be expressed as:

$$C_5H_7NO_2 + 5O_2 \longrightarrow 5CO_2 + 2H_2O + NH_3 \qquad (1)$$

From this equation it can be calculated that the theoretical oxygen demand is 1,42 kg O_2/kg organic matter oxidised. In practice this figure has been found to be in the region of 2,0kg O_2/kg organic matter and above (Gould and Drnevich (1978), Water Research Centre (1983), Booth and Tramontini (1983)). As nitrification is totally inhibited at temperatures above 40°C it is very unlikely that there would be any enhanced oxygen demand from this source.

A stated advantage of the autothermal aerobic digestion process is that the potential for inactivation or destruction of pathogenic micro-organisms is so much greater than can be achieved through mesophilic digestion processes. In addition, the rate of reaction of the process is substantially faster, thus allowing shorter retention times and subsequent reductions in capital costs. Two disadvantages of the process are that it is fairly energy intensive and does not produce a useful by-product such as methane gas which is produced in the anaerobic digestion process.

Recent studies, including the EPA demonstration project at Hagerstown, have shown that a combination of autothermal aerobic and conventional anearobic digestion processes would appear to result in a system which incorporates the advantages of each of the processes while minimising their drawbacks. This study, however, deals exclusively with the aerobic treatment phase.

3. AIMS AND OBJECTIVES:

In general terms, the aim of the three year research programme into pilot scale autothermal aerobic digestion of sludge using pure oxygen, was to demonstrate that the process can be used successfully to disinfect sewage sludges.

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More specifically, the objectives were to:

- Investigate the effectiveness of autothermal aerobic digection in terms of the inactivation/ destruction of selected mirco-organisms (Ascaris ova, Salmonella)

- Investigate, where possible, the mode of destruction and factors which contribute towards the shielding of the organisms from the hostile environment.

- Maintain a close check by means of regular sampling and analysis on such parameters as pH, temperature, loading rates, COD, retention period, total solids, volatile solids, alkalinity, nutrients and toxic materials and measure solids breakdown, gas flow and composition with a view to the evaluation of the process for sludge stabilisation and sludge mass reduction efficiency.

- Assess the effect of varying such parameters as solids loading rate and retention period.

- Assess the significance of such operational problems as odour release from the treated sludge, supernatant quality, temperature control and adequate mixing.

- Assess as far as possible the economic implications of operating at thermophilic temperatures utilising pure oxygen, including any benefits due to lower retention periods.

- Assess the effects that the process has on the dewatering properties of the treated sludge.

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- Assess the potential, in the light of initial results, of the combination of autothermal aerobic and anaerobic digestion with a view to motivating further work in this field should the combined system appear attractive, especially from the point of view of cost-effective stabilisation combined with pathogen inactivation.

- Optimise the performance of the autothermal aerobic digestion plant with respect to pathogen inactivation/ destruction and economic considerations.

4. REVIEW OF RECENT STUDIES:

During the past 14 to 15 years there has been ever increasing interest in the autothermal aerobic digestion process, both as a stand-alone process and as the first stage of a two stage aerobic-anaerobic digestion process. Numerous studies, both at pilot plant and large scale, have been carried out in the United Kingdom, U.S.A. and Europe. Most of these studies were aimed at proving the process itself while investigations into the potential of the process for inactivation or destruction of pathogenic micro-organisms, although being recognised and noted in most cases, were not normally considered as one of the major goals of the experimental programme.

It is accepted by many authors that Andrews and Kambhu (1970), first developed a steady state model to investigate the parameters affecting the process. Although much of the data on sludge characteristics and heat losses had to be assumed, their studies supported the basic theory that autothermal aerobic digestion could be self sustaining with respect to temperature. They suggested that pilot testing of the process be undertaken using both air and high purity oxygen in order to test the validity of their model.

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Matsch and Drnevitch (1977), investigated high purity oxygen for aerating aerobic digesters both at full scale at Speedway, Indiana and at pilot scale in the Union Carbide laboratories at Tonawanda, Indiana. They found that aerobic digesters using pure oxygen could maintain elevated temperatures in excess of 45°C and that these temperatures increased as the concentration of volatile suspended solids increased. The process was found to be self-regulating at around 60°C and readily able to recover from shock loadings caused by operator error or equipment malfunctions. The sludge produced during these experiments was found to dewater as well as any aerobically digested sludge. Their study also concluded that reduction in pathogen concentrations to below detectable limits occurred within a period of five hours at temperatures of around 50°C.

Gould and Drnevich (1978) extended the work done at the Tonawanda pilot plant to examine some of the theoretical considerations of the process. They concluded that the results obtained on the pilot plant, especially those related to heat losses, could not be compared to full scale facilities, the heat leak being of the order of twice that expected in the field. Some results obtained indicated volatile solids reductions of 30% - 40% at three to five day retentions and reductions of Salmonella to below detectable limits in seven hours at 50°C. One observation made by the authors was that the operation of the system depends largely on the purity of the feed gas and that as the feed gas purity drops (eg. use of air) the gas sensible heat losses become large and it becomes impossible to maintain thermophilic temperatures.

Jewell and Kabrick (1980) presented the first successful large-scale application of an autothermal aerobic digestion process using air-aeration on a typical municipal sludge. They proved that air-aeration was feasible at system retention times ranging between 5 and 13 days as long as the injection methods used allowed for efficient oxygen dissolution and reduced the gas sensible heat losses as far as possible. The overall performance of their plant was influenced by numerous practical operating problems, mainly relating to variable climatic

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conditions as well as mixing and aeration problems which resulted in the production of a foam layer with the texture of a thick milkshake.

Jewell and Kabrick developed a relationship for the estimation of biological heat generation as follows:

$$\Delta F = 3,5\ \Delta COD \qquad (2)$$

Where ΔF is the total heat released in kilocalories per litre and ΔCOD is the measured change in COD in grams per litre. These units are convenient in estimating liquid temperature change because the heat released, expressed as kilocalories per litre, is equal to the temperature change. This simplified equation was then modified to take into account that approximately 30% of the biological heat of oxidation was lost from the system and becomes:

$$\Delta T = 2,4\ \Delta COD \qquad (3)$$

For example, with an influent COD of 50g/ℓ and a COD reduction of 35%, the expected temperature increase is 42°C which will raise the system temperature from an influent temperature of 18°C to 60°C, a result which compares favourably with experimental findings.

Investigations carried out by the same authors into the dewaterability of autothermally digested sludge showed that this was adversely affected in their large scale reactor with substantial increases in capillary suction time, CST, over the influent sludge. This increase became larger at higher loading rates. Contrary to the above, the sludge from their long-term bench scale digester dewatered well. They reasoned that these differences could be attributed to deflocculation caused by the type of mixer used in the large scale test versus the more gentle action of the turbine aerator used in the bench scale tests.

A study into pathogen destruction was carried out by Kabrick and Jewell (1982) as part of the previous investigation. The fate of three groups of pathogenic organisms namely Salmonella sp, Pseudomonas aeruginosa and Ascaris were compared under conditions of mesophilic anaerobic

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and autothermal aerobic digestion. Their findings showed that the autothermal aerobic digester exhibited superior performance over the mesophilic anaerobic digester with respect to the inactivation of pathogenic bacteria, viruses and parasites. The aerobic system yielded complete inactivation of Salmonella sp and viruses to below detectable limits at temperatures of 40°C and above. Parasite numbers were reduced but not completely eliminated. This was considered to be indicative of the need for better control of the system to prevent short circuiting and increased reactor temperatures to around 60°C for the control of environmentally resistant parasites such as Ascaris.

An engineering and economic assessment of the previous study carried out by Camp Dresser and McKee Inc. (1981), indicated that for a small treatment plant (3,8 Mℓ/day), autothermal aerobic digestion is cheaper than anaerobic digestion for sludge treatment ($ 160/tonne versus $ 220 /tonne). As plant size increases the situation changes due to the increased energy requirements for the aerobic system. For a large treatment plant (380 Mℓ/day), anaerobic digestion becomes substantially cheaper than autothermal aerobic ($ 35/tonne versus $ 90/tonne).

Pilot plant autothermal studies undertaken by Booth and Tramontini (1983), at Palmersford in the United Kingdom revealed that volatile solids destruction of between 17,5% and 25% was possible while temperatures of up to 60°C could be maintained consistently in a 60m³ pilot plant operating at between five and 10 day retention times and using pure oxygen to supply the dissolved oxygen requirements. At the temperatures attained virtually all the pathogenic bacteria were destroyed. The sludge produced by this system was also found to exhibit very poor thickening qualities and was not odour free. Oxygen utilization ranged from 2,03 to 4,21 kg oxygen used/kg volatile solids destroyed. It was concluded by the authors that the combined use of air and oxygen was theoretically feasible and would lead to a substantial reduction in operating costs.

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A pilot scale autothermal aerobic digester is presently being successfully operated using air as a feed gas by the Water Research Centre at Palmersford. Temperatures in excess of 55°C have been achieved at retention times of three days. Further results on this experiment are still awaited.

Although this study deals exclusively with autothermal aerobic digestion it is interesting to note that considerable success has been achieved in experimentation into dual digestion. One of the most recent investigations in this field was the EPA sponsored demonstration study at Hagerstown, Maryland, U.S.A. (1981). The process, which employs a one day aerobic digestion period using oxygen, followed by eight days anaerobic digestion, produced favourable results which, unfortunately, could not be optimized due to the incompatible match of the aerobic and anaerobic phases of the plant. (The anaerobic digester had to be operated at half of its volumetric capacity). Although retention time in the anaerobic system was reduced as far as possible it was still too long to allow stressing of the anaerobic stage of the digestion process. Not withstanding this problem the fact that anaerobic digester retention times could be reduced to the order of eight days could lead to a substantial overall capital cost saving when compared to a conventional mesophilic digestion system.

5. PLANT DETAILS:

The basic details of the pilot plant are given in Figures 1 and 2.

5.1 Digestion System.

The pilot plant consisted of a 10m³ (8m³ liquid volume) closed steel tank, fully insulated with a 50mm layer of expanded polystyrene. The tank was provided with sampling points for both sludge and head gas analyses.

Sludge consisting of either a mixture of primary and thickened waste activated sludge or just the thickened waste activated sludge was obtained from the waste sludge system of the Olifantsvlei Sewage Purification Works and screened to give a maximum solids size of approximately 10mm. It was then stored in a 10m³ holding tank from

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which it was fed to the pilot digester via a MONO SH40 feed pump. This feed system could be controlled by means of the pump's variable speed gearbox and timer to provide either a continuous feed or a step feed as required. For the duration of the test programme a two-hourly step-feed was used. This system had the capacity to provide a retention time of less than one day in the pilot digester if required.

Sludge was wasted from the digester during the feed cycles via a top overflow pipe back to the purification works.

The digester contents were mixed solely by the action of the sludge recycle system which consisted of approximately 20m of 50mm galvanised steel pipe, insulated with asbestos lagging and incorporating a MONO C91M recirculation pump and an oxygen supply venturi.

Sludge was pumped continuously from the bottom of the digester through the recirculation loop at a rate of approximately 9 litres per second and then re-introduced into the digester via a nozzle approximately 0,5m from the base of the tank. The fact that the recirculation pump had to run 24 hours per day, pumping a sludge with a high grit content, necessitated fairly frequent replacement of wearing parts such as seals, rotors, stators etc. These replacements were carried out on a routine basis and apart from one major failure of the rotor drive the pump ran faultlessly for the duration of the investigation.

The mixing energy produced by this particular system would normally be sufficient for a reactor vessel of some 4 to 5 times that of the pilot digester. This requirement was related to the oxygen feed system discussed later in this section.

5.2 Temperature and Dissolved Oxygen Measurement.

The temperature and dissolved oxygen contents of the digester contents were monitored by means of an Orbisphere Model 2716 dissolved oxygen/ temperature monitoring system and the results thus obtained plotted continuously by a two pen Servogor Model 220 plotter.

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The Orbisphere unit was chosen after considerable investigation into dissolved oxygen measuring instruments available on the local market. One of the requirements of the experimental programme was to be able to control the oxygen input to the system automatically if possible and this entailed obtaining accurate dissolved oxygen readings at temperatures in excess of 60°C. The probe supplied with the abovementioned oxygen system (model 2115) was, according to the available literature, capable of highly stable, accurate, long term monitoring of dissolved oxygen in natural waters, effluents and aeration basins through a temperature range of 0°C to 70°C. All of these claims with the exception of the durability of the probe proved to be correct. Numerous detailed examinations of the probe by the local agents and the manufacturers in Switzerland indicated that the method of sealing of the delicate sensing equipment within the probe itself was not capable of withstanding the environment which existed at the high temperatures reached in the autothermal aerobic digester. It should be noted that this was the first time that this system had been used under these conditions and investigations into the continual failure of the probe are proceeding both in the Republic and in Switzerland.

5.3 Oxygen Supply

Oxygen was supplied to the system via the patented VITOX SYSTEM venturi supplied by AFROX LIMITED in conjunction with the British Oxygen Company. The method of operation of this system was to withdraw a stream of sludge from the pilot digester via the recirculation system described previously and to pressurise it to 200kPa at the venturi. Oxygen received from the 1,4 tonne capacity bulk storage tank via the evaporators was then injected into the sludge via the venturi and the mixture conveyed back to the digester at a velocity of between 4 and 5 m/sec, allowing for very turbulent conditions in the pipeline which aided dissolution of the oxygen into the sludge. The mixture was then discharged through a specially designed nozzle (supplied by AFROX LIMITED) which shattered any remaining gas bubbles and caused rapid mixing of the oxygen rich sludge and the digester contents. This nozzle was initially placed tangentially to the side of the digester but this was

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found to have adverse effects on the mixing pattern with a large "dead spot" occurring at the centre of the tank. The nozzle was subsequently re-positioned at 90° to the tank wall which effectively eliminated the mixing problem.

The VITOX system used on the pilot plant was capable of delivering a maximum oxygenation capacity in excess of 6 kg O_2 per hour which more than adequately provided for the peak oxygen demand of the pilot unit of approximately 100 kg per day at a sludge retention time of one day. The VITOX unit was rated at this level on practical grounds as a reduction in sludge recycle pipe size below the 50mm used could have led to blockages at the throat of the venturi. Apart form a few minor blockages of the venturi, which were eliminated by a routine cleaning programme, the system performed faultlessly throughout the experimental programme.

The oxygen supplied to the unit was supplied free of charge by AFROX LIMITED for the duration of the experimental programme.

5.4 Oxygen Control System

The oxygen supply control panel was supplied by AFROX LIMITED. It consisted of an oxygen flow rotameter, solenoid operated control valves and non return valves, electrically controlled dissolved oxygen set-points, oxygen hour-run meter and hour-run meters for the feed and recirculation pumps. The system could be controlled manually by setting a constant flow through the rotameter or automatically via the dissolved oxygen signal received from the Orbisphere meter and pre-determined dissolved oxygen set-points in the control system. For example, if the lower set-point was selected as 2mg/ℓ and the upper one at 4mg/ℓ then the oxygen feed to the unit would be switched on as the dissolved oxygen level decreased below 2mg/ℓ and would remain on until the dissolved oxygen level increased above 4mg/ℓ. These set-points could be varied as required. A typical plot of dissolved oxygen and temperature as achieved using automatic control is given in Figure 3.

The operation of the automatic control system was dependent on the

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reliablility of the dissolved oxygen probe. As described prevoiusly this instrument was not entirely reliable resulting in long periods where the system, had to be run on manual control. However, during periods where the probe was operational the automatic control system proved to be an effective method of supplying oxygen to the system.

6. EXPERIMENTAL PROGRAMME, METHODS AND MATERIALS

6.1 Experimental Programme

The pilot digester was operated at retention times of three, two and one day using a 50/50 mixture of primary and thickened waste activated sludges as a feed and using automatic control of the oxygen injection system.

An experimental run was also carried out using only thickened waste activated sludge as a feed to the system at a retention time of three days. Oxygen was injected into the system on a continual basis during this run due to problems with the dissolved oxygen probe as mentioned previously.

A further experimental run was carried out using the 50/50 mixture of sludges at a retention time of three days and using manual (continual) control of the oxygen injection in order to assess the benefits (if any) of automatic versus manual control of oxygen injection. (A three day retention time was chosen purely to minimise the oxygen used during the test period).

The duration of all the abovementioned experimental runs was between one and two months to ensure that the results would be representative of the system performance under the prevailing conditions.

During the experimental runs, digester temperature, dissolved oxygen, sludge recirculation rate and sludge feed rate were monitored continuously. Feed sludge temperature and ambient temperature were monitored on a four hourly basis, while feed sludge and digester sludge suspended solids, volatile suspended solids and pH were monitored on

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a daily basis. Weekly monitoring of feed sludge and digester sludge was undertaken for chemical oxygen demand, total Kjeldahl nitrogen, ammonia, nitrates, phosphorus (total and soluble) and capillary suction time, and on a twice weekly basis for Ascaris and Salmonella total count and viability.

Sludge dewaterability, heat balance and head gas analyses were carried out as specific experiments and not on a regular or routine basis.

6.2 Chemical Analyses.

Determinations of suspended solids (SS), volatile suspended solids (VSS), pH, chemical oxygen demand (COD), ammonia (NH_3), nitrate (NO_3), total Kjeldahl nitrogen (TKN) and phosphorus (total and soluble) were carried out in all cases using the methods employed by the City Council of Johannesburg Laboratories, most of which were based on Standards Methods, (1965) as revised.

6.3 Physical Analyses

Ambient temperature was measured by means of a maximum - minimum thermometer while that of the feed sludge was measured by means of a Negretti and Zambra probe thermometer with the sensor positioned approximately midway in the holding tank. Measurements of the temperature of the digester contents was by means of a temperature sensor incorporated in the dissolved oxygen probe. This system provided a continual readout which was plotted by means of a chart recorder. When required, temperatures relating to the digester insulation and pipe lagging were measured using a thermocouple attached to a Fluke Multimeter model 8024 A.

Gas analyses were carried out using an ORSAT gas analysis apparatus. This apparatus measured the percentage of both oxygen and carbon dioxide present in the vent gas of the digester. Gas analyses were carried out as specific experiments and not on a regular basis as was the case with some overseas experimental studies. The results obtained are considered to be acceptable but cannot be as accurate as would

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be expected from a continual analysis. The automatic control of oxygen injection posed numerous problems in that the cutting in and out of the oxygen feed resulted in large variations in oxygen levels in the vent gas. It was finally decided to carry out vent gas analyses on the system with oxygen being injected at a constant rate equal to the average daily consumption of the system when operating with automatic oxygen feed. This procedure resulted in acceptably reproduceable results being obtained.

Sludge settling properties were examined both on laboratory scale using beaker studies and on a larger scale at the site of the pilot plant where a tray 1,5 m long, 1,0 m wide and 150 mm deep, which was divided into three compartments, was used. These compartments were filled with sludge at staggered intervals and any settlement noted over a period of days.

Sludge dewatering properties were evaluated using both the buchner funnel method with glass fibre paper (GFC) and the CST apparatus. The effects of polymer addition (ZETAG 57) asmanufactured by Allied Colloids) was also investigated.

Calculation of heat balances was carried out using generally proven theory used by the Water Research Centre (1983) and further checked by AFROX LIMITED (1983). The heat balance equation at steady state is given below:

$$H_B + H_p = H_L + H_S \qquad (4)$$

where,

H_B = Biologically produced heat
H_P = Heat produced by pump
H_L = Heat leak to surroundings
H_S = Sludge sensible heat losses.

By calculating the sludge sensible heat loss, the heat leak to the surroundings and the heat produced by the feed and recirculation pumps and feeding these into equation (4), the biologically produced heat may be deduced. From a knowledge of the amount of volatile solids concerned the biological heat of reaction can be calculated.

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The heat balance calculations were carried out using specific data as a number of the required parameters were not measured on a continual or regular basis. The results obtained are however considered to be representative of what can be expected from the autothermal aerobic digestion process.

6.4 Biological Analyses

Microscopis analyses using a light microscope and all micro biological analyses were carried out at the Council's Cydna Laboratory during the entire experimental programme.

Biological stability and fermentability analyses were carried out on samples innoculated with 10% digested sludge from the Olifantsvlei Works and 10% "acid" sludge obtained from Northern Works. The samples were incubated in anaerobic jars for seven days at 37°C and then examined for signs of anaerobic fermentation . The volatile acids concentration and pH of the samples was also monitored.

Ascaris determinations were carried out using the method developed by the Cape Town City Council, (Le Roux, 1982) as described briefly hereafter. This method was found to be quick and effective and allowed for more frequent Ascaris determinations to be made.

Method of Ascaris Determination

About 2 litres of liquid sludge was macerated in a Waring blender at low speed for about one minute. If dry sludge was to be tested an appropriate amount was suspended in about 2 litres of water, allowed to soak for a few hours and then macerated as above.

Total Count per Gram: Approximately 1 to 5 grams of sludge (depending on the moisture content) were weighed out into a small glass beaker and immediately transferred quantitatively into a Visser filter. The sludge was filtered by washing with a strong jet of tap water to which a little 1,0% Tween 80 solution had been added periodically.

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The washing water was directed onto the sludge and sides of the inner and outer filters and both the filter and the water streams were manipulated in such a way as to ensure thorough washing of the filter and sludge. After washing for 3 to 5 minutes the inner filter (95μ) was removed. The outer filter (50μ) was washed for a further 1 to 2 minutes.

The material remaining in the outer (50μ) filter was quantitatively transferred into a 1 litre glass beaker and then filtered through a 12μm Sartorius SM 12500 membrane filter. The filter was dried at 37°C on a stainless steel support which was weighed down with the correct diameter stainless steel ring to prevent curling up. After drying the filter was cut in half using a scalpel. Each half of the filter was then transferred onto a microscope slide. Microscope oil was applied and the filter allowed to clear. The slide was then examined microscopically under 100X and 250X magnification. All Ascaris ova on both halves of the membrane filter were counted and the results expressed as number of eggs per gram of dry sludge. The moisture content of the sludge was determined after drying for approximately 24 hours at 105°C.

Viability Count This was determined by weighing out approximately 100 grams of the blended sludge and filtering through the Visser filter without using Tween 80. About one third of this mixture was passed through the filter and the ova collected into a one litre erlenmeyer flask (previously marked at 250 mℓ). The inner filter was rinsed out and the second third of the sample passed through it and collected in the same flask. The inner filter was again rinsed and the last third of the sample passed through it into the flask. The filter was again rinsed and the rinsings collected into the flask. The flask was then filled to the 250mℓ mark using water. Approximately 5 mℓ of 40% formaldehyde solution was then added to the flask. The flask was plugged with cotton wool and left at a temperature of 25 - 28°C for at least a month before being examined for viability. The flask was shaken occasionally during this period. After a month the culture was examined at weekly intervals until at least four similar results

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were obtained showing that peak viability had been reached. The average of the last three results was taken as the viability count. In some instances it was necessary to examine the cultures for a further few weeks if the peak had not been reached as described above.

Slides were prepared for viability counts by pipetting 2 to 3 drops of the sediment from the viability flask onto a microscope slide, adding a drop of stain and covering with a cover slip. At least 100 eggs per sample were counted so as to obtain a reasonably accurate classification and were screened with the 10X objective and confirmed with the 40X objective.

Classificaiton: Samples were classified as follows:

1. Fully developed worm inside the egg shell (motile or quiet)
2. Partly developed egg i.e. divided egg.
3. Single cell egg, no apparent change. (Includes infertile egg).
4. Degenerate egg with or without vacuoles.

The eggs in (1) and (2) are viable and only those which at the end of the culturing period had developed into worms, i.e. (1), were classified as potentially infective. All the ova in (3) and (4) were classified as non-viable.

Stain: The stain consisted of a mixture of 10mℓ of grams iodine and 5 mℓ of a 1% aqueous solution of eosin made up to 100 mℓ by addition of distilled water.

Salmonella determinations were carried out at the same intervals as those for Ascaris using the following method:

Pre-enrichment: 10 mℓ of sludge was innoculated into 35 mℓ phosphate buffered peptone (PBP) and incubated for 24 hours at 37°C.

Selective enrichment: 10 mℓ portions of sludge were transferred into 35 mℓ Muller Kauffman Tetrathianate Broth and Selenite. The innoculated Tetrathionate was incubated at 43°C and the innoculated Selenite at 37°C for 48 hours. The samples were plated out after

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24 and 48 hours onto Brilliant Green Agar (modified) and McConkey plates. The Brilliant Green Agar plates were incubated at 43°C overnight and the McConkey plates at 37°C.

Biochemical confirmation;

1. Triple Suger Iron Agar slopes were innoculated with the culture and incubated at 37°C for 24 hours.
2. Positive reactions in the Triple Sugar Iron were confirmed by urease, lysine and B galactosidase reaction following the same pattern of identification of Salmonella used in food.

Modified Brilliant Green Agar was produced by adding one vial of Salmonella Sulpha Mandelate supplement previously dissolved in 5mℓ distilled water to 500mℓ Brilliant Green Agar.

7. RESULTS

Detailed results obtained during the experimental programme are given in Figures 1 to 10 and Table 1 to 14.

Feed sludge was either obtained from a dissolved air flotation unit or from the underflow from the primary sedimentation tanks. This sludge comprised of a mixture of raw and waste activated sludge in approximately equal proportions. Sludge characteristics for all the experimental runs are given in Table 1 and sludge analyses in Table 2.

The autothermal aerobic digestion pilot plant was initially run on thickened waste activated sludge received via a dissolved air flotation unit from the Olifantsvlei extended aeration plant. The retention time of the pilot digester averaged 3,5 days and the feed sludge had an average concentration of 3,7% (Table 1). The temperature of the influent sludge averaged 12°C and that of the digester contents 44°C (Table 4, Figure 6). Volatile solids destruction averaged 28% and COD reduction 21% (Table 2). Oxygen was fed to the system on a continual basis for the duration of this run due to problems experienced

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with fouling of the oxygen probe within the digester. Oxygen and power utilisation averaged 4kg O_2 supplied/ kg VS destroyed and 5,2 kWh/kg VS destroyed respectively (Table 5). Ascaris ova reduction was of the order 50% and complete inactivation of Salmonella was not achieved (Table 10).

Towards the end of this test period a failure of the recirculation pump forced a closedown of the plant in order that repairs could be carried out. This opportunity was used to implement the following modifications:

1. The inlet nozzle in the recirculation pipework was re-positioned at 90° to the tank wall i.e. the fluid flowed across the tank rather than tangentially as was previously the case. This modification resulted in much improved mixing characteristics within the digester.

2. The dissolved oxygen probe was moved to a position in the suction pipe to the recirculation pump thus providing a constant flow of liquid past the membrane. This modification proved to be almost totally successful from the point of view of fouling of the probe and allowed the plant to be run on automatic control with the resultant improvement in the control of oxygen usage. The only problem still experienced was the regular failure of the probe due to faulty sealing of the sensitive sensors within the probe body.

Once the above modifications had been completed the plant was re-commissioned using a mixture of approximately 50/50 waste activated and primary sludge. Several experimental runs were undertaken using this sludge mixture, retention times of 3,0; 1,8 and 1,0 days being achieved. During these runs the oxygen feed to the system was at all times controlled automatically. Initially dissolved oxygen control set-points of 2 to 4 mg/ℓ were used but it was found that the system would go anaerobic for quite lengthy periods immediately after completion of a feed cycle. The set-points were subsequently

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increased to between 3 and 6 mg/ℓ which effectively cured the problem. These set-points were maintained throughout the rest of the test period.

During these experimental runs the average feed solids concentration averaged 4,2%; 3,9% and 3,4% respectively (Table 1). Influent sludge temperatures were 16°C, 22°C and 24°C while the digester temperature in all cases was of the same order at 58°C to 60°C (Table 4 and Figures 7 to 9). Volatile solids destruction averaged 28%, 23% and 21% while COD reductions were similar with reductions averaging 35%, 32,5% and 30,5% respectively (Table 2). Volatile solids loading rates increased with decreasing retention times, average values being 9,9; 15,6 and 23,7 kg VS/m³/ day (Table 3). Oxygen usage was 2,4;2,7; and 2,2 kg O_2/kg VS destroyed while power consumption reduced with reduction in retention time, average values achieved being 4,1; 3,0 and 2,5 kWh/kg VS respectively. Complete inactivation of Ascaris ova and Salmonella was achieved during all three experimental runs (Tables 11 to 13).

An additional experimental run (N°5) was carried out at a retention time of 3,2 days using manual (continual) oxygen injection in order to compare results with the automatic injection of oxygen. The results obtained were in all cases very similar to those obtained in run N° 2 and are detailed in the various tables and figures.

Oxygen use efficiencies (Table 4) and heat balance analyses (Table 7) were carried out as specific experiments as the necessary equipment and manpower was not available for the continuous monitoring of these parameters. Average oxygen efficiency was of the order of 86% to 90% while the heat of reaction varied from 15 x 10^3 kJ/kg VS destroyed at 3 day retention time to 25 x 10^3 kJ/kgVS destroyed at 1 day retention time. (3610 kCal/kgVS to 6010 kCal/kgVS).

Samples of digested sludge were taken from the pilot digester when the system was being fed a 50/50 mixture of sludge at both 3,0 and 1,8 day retention times. These samples were examined microscopically and for biological stability and fermentability. The temperature

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of the samples ranged from 57°C to 62°C on extraction but these were allowed to cool to room temperature before any experimentation took place.

Examination of a wet preparation of the 3 day retention sludge under a light microscope revealed two solid phases. The larger solids appeared to be debris or other inert material from the feed sludge while the small solids were almost entirely dispersed bacteria. These were coccoid in shape and moved around under the slide in small rivulet type streams together with the other colloidal material. No flocculation of the biomass occurred with the solids having an extremely dispersed appearance when compared to activated sludge.

The digested sludge samples, when tested for biological stability and fermentability by addition of 10% acid sludge or 10% anaerobically digested sludge, showed signs of anaerobic fermentation after seven days incubation in anaerobic jars at 37°C. The results obtained are given in Table 8. These results indicate that the sludge product was not stable and could ferment readily to acids thus being a potential nuisance if disposed of without further treatment.

Results obtained from similar experiments on the 1,8 day retention sludge showed the same dispersed growth appearance and produced similar results to the 3 day sludge with regard to anaerobic fermentation.

Investigations into the settling and dewatering properties of the digested sludge from both the 3 day and 1,8 day retention experiments indicated that the sludge solids would not separate away from the liquid phase under gravity settling. Even after 3 to 4 days of standing no separation of the sludge layer occurred. This confirmed the dispersed colloidal nature of the sludge solids as observed under microscopic examination. Attempts to filter off a liquid phase when filtering samples on a buchner filter with glass fibre paper proved to be quite impossible and CST values of the order of days were not uncommon. The addition of polymer to various sludge samples was then investigated to try and ascertain the amount of polymer required to render the

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sludge dewaterable. The polymer used in all tests was ZETAG 57 as supplied by Allied Colloids. Typical results obtained are given in Table 6.

It is evident that about 14 kg/dry ton of polymer would be required to render this sludge dewaterable. This should be compared with the usual dose of 1,3 to 2,0 kg/dry ton usually required to dewater waste activated sludge.

Process costs were analysed at pilot plant scale using oxygen and power consumption as the main cost parameters. Overall costs on this basis ranged from R109/dry ton at 3 day retention to R46/dry ton at one day retention time (Table 9).

8. DISCUSSION

This study has shown the autothermal aerobic digestion process to be of a very robust nature and quite capable of surviving shock loads such as the doubling of the feed rate, a drastic reduction in oxygen injection rate or a complete shut-down for a number of hours for maintenance purposes without any detrimental effect on the process itself.

The process proved to be very easy to establish as is evidenced by the following example: From a cold start-up, i.e. the digester filled with a mixture of primary and waste activated sludge at ambient temperature, the contents were recirculated, fed with oxygen on automatic control and with sludge every two hours to give a nominal two day retention time. Under these conditions the digester temperature had increased from 24°C to 61°C in a matter of 50 hours after which time stable operating conditions were established. A temperature plot related to this start-up is given in Figure 4.

Temperatures of the order of 60°C were common at retention times as low as one day and although Andrews and Kambhu (1971) indicated that the process would be self limiting at about 65°C, temperatures of up to 74°C were measured at times where excess oxygen was fed to the system. Similar temperatures were recorded by Booth and Tramontini (1983) under summer operating conditions.

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As was to be expected at the temperatures achieved pathogenic bacteria, which are capable of surviving anaerobic digestion, were eliminated. This study has shown that a sludge consisting of a mixture of primary and waste activated sludge (in approximately equal proportions) can be disinfected (in terms of Ascaris ova inactivation) in the process at a system retention time of one day. Although this particular experimental run was carried out under summer conditions it is quite confidently expected that the system would perform as well at a retention time of one day under winter conditions. This is borne out by the fact that the system operated quite satisfactorily and maintained temperatures continually in excess of 55°C when run at an actual retention time of 1,8 days under winter conditions where the influent sludge temperature dropped as low as 8°C occasions.

At the temperatures achieved at a one day retention time a 100% destruction of viable Ascaris ova was achieved (Table 13) with only one instance being recorded where destruction was 99% (system operating correctly), this probably being due to short circuiting. The results achieved do not necessarily mean that a one day retention period is required for disinfection as the random method of sampling employed and the fact that the system was fed at two-hourly intervals tends to indicate that the minimum time required for complete inactivation must be less than two hours. Unfortunately these results cannot be compared with those achieved in other studies such as Gould and Drnevich,(1978); Kabrick and Jewell,(1982) or Booth and Tramontini, (1983) as the reactors in all these studies were fed on a batch basis using a once per day cycle and retention times were far longer than those achieved in this study. The results do, however, confirm the results reported by Krusé, (1977) and Brandon and Langley, (1977) that a temperature of approximately 55°C is the minimum required to ensure that there are no viable Ascaris ova in the treated sludge.

Destruction of Salmonella was also effectively achieved although the use of this pathogen as an indicator should be questioned as it was not always present even in the feed sludge. Kabrick and Jewell,(1982) indicated that complete inactivation of Salmonella was achieved at

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temperatures of 42°C - well below the digester temperatures achieved in the study. Some instances where Salmonella was found to be present in the digested sludge have been put down to re-infection of samples in the laboratory.

An experimental run undertaken at a retention time of 3,5 days using only thickened waste activated sludge from the Olifantsvlei extended aeration plant at no time achieved the required temperature for the complete inactivation of Ascaris ova. The average temperature achieved during this run was only 40°C - 46°C with a maximum of 52°C being recorded. The average viable Ascaris ova reduction at no time exceeded 50%. The failure of the system to produce the desired results was due to the limited biodegradable fraction of the feed sludge which was insufficient to support the degree of microbial reaction required to generate higher temperatures.

Inactivation of Salmonella during this run was poor and, although some of the results obtained could have been due to re-infection as mentioned previously.it is likely that the temperature achieved was not sufficient for complete inactivation. This would tend to agree with the findings of Kabrick and Jewell (1982).

One of the advantages of the autothermal aerobic digestion process is the high loading rate that can be achieved due to the increased rate of reaction. During the experimental runs tabled in this report the solids loading rates achieved ranged from 9,4 kgVS/m³/day to 23,7 kg VS/m³/day at retention times ranging from 3,2 to 1,0 days. (50/50 sludge mixture). The result achieved at 3,2 days compares favourably with that achieved at a similar retention time by Matsch and Drnevich (1977) and the five day value presented by Booth and Tramontini, (1983) while the result achieved at a one day retention time far exceeds any results reported due to the fact that no study reported achieving retention times as low as one day. If these results are compared with generally accepted figures for aerobic digestion of approximately 1,6 to 4,0 kg VS/m³/day at retention times of 15 to 20 days and those for anaerobic digestion of 1,6 to 6,4 kgVS/m³/day

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at 10 to 20 day retentions (Wastewater Engineering, 1979)it becomes evident that the autothermal digestion process is capable of accepting much higher loading rates at substantially lower retention times than either of these two well-used digestion processes.

The actual destruction of volatile solids at the loading rates achieved varied from 21% to 28% (Table 3), the lowest reduction being achieved at one day retention. These figures compare favourably with those achieved by Matsch and Drnevich, (1977); Gould and Drnevich, (1978); Jewell and Kabrick, (1980) and Booth and Tramontini, (1983). These values are lower than the generally accepted value of 40% reduction reported for the stability of anaerobically digested sludge which can be achieved at retention times of 10 to 20 days.

The results for COD reduction given in Table 1 show that the reductions achieved varied from 31% at 1,0day retention to 38% at 3,2 days. These results also compare favourably with those obtained by the authors mentioned above.

The average COD: Volatile solids ratio achieved during this study was 2,1 kg COD/kg VS. Comparison with the value for anaerobic digestion of 1,3 kg COD/kgVS given by Booth and Tramontini,(1983) indicates that a higher degree of treatment was actually being achieved in the aerobic system. A possible explanation for this discrepancy given by the same authors is that the aerobically digested sludge contains a higher oxygen ratio in its constituents than the raw sludge.

From the above results it is evident that both volatile solids destruction and COD removal decrease with a decrease in retention time. This fact would have to be taken into consideration if the process were to be used for overall sludge treatment rather than primarily for inactivation of pathogenic micro-organisms.

The formula presented by Jewell and Kabrick, (1977) relating change in temperature to change in COD i.e. $\Delta T = 2,45\ \Delta COD$ was found to predict fairly accurately the change in temperature for retention

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times in the region of 3,0 days, (which is the lowest achieved by the authors) but becomes less accurate when applied to the results achieved at a one day retention time. (Predicted final temperature at 3,0 days = 57°C (58°C) while at 1,0 day predicted temperature = 54°C (58°C)). Nevertheless, it would seem that this simple formula can be used to predict the final system temperature with a reasonable degree of accuracy, making it a useful design aid.

One of the aims of this study was to investigate the feasibility of using automatic oxygen injection to control the supply of oxygen to the digester. The system employed is described in Section 6. It was envisaged that such a system would lead to a more efficient use of oxygen in the process thus reducing one of the major cost factors When operational the system was able to accurately pace the oxygen demand of the digester and allow for efficient oxygen use within the system. However, the problems involved in monitoring dissolved oxygen concentrations at high temperatures have not yet been overcome and accordingly such a control system should not be considered on a large scale as it can lead to very inefficient oxygen utilisation during or after failure, (tends to lead to continual oxygen addition to the system).

A theoretical oxygen demand for sludge under ideal conditions was given by Matsch and Drnevich,(1977) as 1,42 kgO_2/kg VS destroyed. Actual oxygen utilisation obtained during experimental runs from 1,0 to 3,2 day retention ranged from 2,2 to 2,7 kg O_2 used/kg VS destroyed (2,5 to 3,0 kg O_2 supplied/kg VS destroyed). These figures compare favourably with those obtained by Booth and Tramontini, (1983), who employed continual oxygen injection, and the tests carried out by the Water Research Centre, (1983) where both automatic and continual injection modes were used. The higher oxygen use is in part due to unavoidable inefficiencies within the system and possible non-biological uptake of oxygen.

In order to assess the efficiency of oxygen utilisation head gas analyses were performed using an ORSAT apparatus as described in

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Section 6. With the system operating on automatic oxygen injection control it was found to be impossible to carry out these gas analyses due to the frequent cutting in and out of the oxygen feed as evidenced in Figure 3. It was thus decided to use the average daily oxygen input as calculated from the runs using automatic oxygen injection control as a continual oxygen feed to the system for the purposes of these analyses. This system worked successfully and results of between 86% and 90% oxygen utilisation were measured. These compare favourably with figures given by the Water Research Centre, (1983) and Booth and Tramontini, (1983). The Water Research Centre results were achieved under the same conditions as employed above, i.e. using a similar VITOX system and continual oxygen feed to the digester.

It is interesting to note that by using the head gas analysis results it was possible to "fine tune" the oxygen consumption of the system to a point where there was just a trace of oxygen remaining after a feed cycle (of the order of 2%) and up to 93,5% use efficiency during the remainder of the cycle prior to the following feed. This procedure produced average oxygen comsumptions of the same order as those achieved using automatic injection control (compare Table 5: Experimental runs 2 and 5) as well as almost identical performance results in other areas.

Taking into consideration the continual problems experienced with the automatic injection control system it appears that, given a reliable form of head gas analysis,which could be carried out at predetermined intervals, the system could be run very efficiently without complicated control equipment. It should be noted, however, that continual head gas analysis has been found to be just as prone to problems as automatic injection control of oxygen by the authors mentioned above.

In order to assess the affects of gross over oxygenation of the system the oxygen feed was increased to the equivalent of 3,5 kgO_2/kg VS destroyed whilst running at a retention time of 1,0 days.

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The effect was an immediate reduction in the temperature of the digester contents (Figure 9) due to the cooling effect of the oxygen. In contrast, on occasions where the imminent failure of the automatic injection system led to an increase in oxygen feed to a level slightly above the optimum, an increase in temperature was experienced, a maximum of 74°C being recorded.

Power consumption for any particular experimental run was almost constant as the major power consumer, the recirculation pump, ran continually throughout the experiment. The figures obtained (Table 5) of 2,5 to 4,6 kWh/kg VS destroyed compare well with those obtained by Booth and Tramontini, (1983), but it should be noted that as in the case of their experiment the recirculation pump used in this study was oversized. and thus the figures cannot be considered as representative of a large scale facility.

Heat balance calculations were carried out as specific experiments as mentioned previously in the report. It was found that the insulation of the digester (50mm expanded polystyrene) formed a very effective heat trap with the external temperature remaining constant at approximately 33°C through a large range of ambient temperatures. There was a substantially larger heat loss from the pipework which was only insulated with asbestos lagging. The major heat loss from the system was the sludge sensible heat gain of the influent sludge while the heat input due to the pump remained constant as it was operational for 24 hours per day. The heat of reaction as calculated from these tests (Table 7) averaged 20 000 kJ/kg VS destroyed (4760 k Cal/kg VS destroyed). This value, although not as accurate as would be expected from continual heat monitoring techniques, compares with the findings of Andrews and Kambhu, (1970); Jewell and Kabrick,(1977); Booth and Tramontini, (1983) and the Water Research Centre, (1983).

The final product produced by the autothermal aerobic digestion process exhibited some very unusual properties. Initial investigations showed that on passing through the digester the feed sludge (either waste activated or a nominal 50/50 mixture of waste activated and primary sludge) became more fluid and would not settle.

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These findings confirm the experience of Jewell and Kabrick (1980); the Water Research Centre, (1983) and Booth and Tramontini,(1983), all of whom agree that the sludge produced by this process was very difficult to deal with.

As is evident from the results the aerobically digested sludge readily ferments when seeded with 10% acid fermented sludge or anaerobically digested sludge (Table 8). Additional treatment of the sludge, such as anaerobic digestion, appears to be necessary in order to further stabilise it. Notwithstanding the above, when the sludge was decanted into a tray and left standing exposed to the elements for a long period no unpleasant odours were obvious although a large number of flies were attracted.

The dewatering properties of the digested sludge (Table 6) were found to be extremely poor with capillary suction times of the order of days being measured while filtration of samples on a buchner filter proved to be impossible. As detailed in the results about 14 kg/ dry ton of polymer would be required to render the sludge dewaterable. At present day prices this equates to a polymer cost of approximately R70/ton dry solids treated. This should be compared with a cost of approximately R10/ton day solids required for the dewatering of waste activated sludge.

The above results are a decided disadvantage of the process where dewatering would be required prior to disposal. If the sludge could be disposed of directly to land or further treated by anaerobic digestion then this problem, and the additional cost involved, would be eliminated.

It is evident from the above that further treatment of the sludge would be desirable . An attractive possibility in this regard is dual digestion, the combination of a short retention period autothermal aerobic first stage followed by anaerobic digestion. Advantages of such a system would include effective disinfection, reduced net anaerobic retention period, no external heating required, stable process

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performance, methane production equivalent to conventional anaerobic digestion and simplified operation and control. Favourable results have been achieved on this process to date including those of the Hagerstown demonstration project, (1981).

The process costs were worked out on the basis of oxygen and power utilisation on the pilot plant. It must be emphasized that these costs cannot be used to compute the cost of the process on a larger scale due to the over-sizing of equipment such as the recirculation pump and VITOX system required for reliable operation. The costs given in Table 9 vary from R46 to R109 at retention times of 1 to 3 days, the major contributor in each case being the cost of oxygen. All of these values are substantially in excess of the cost of anaerobic digestion (R35-40/dry ton in Johannesburg) and in fact, as previously discussed, if the sludge were to be further treated an amount (less than that mentioned above due to reduced size, retention etc) would have to be included for anaerobic digestion or approximately R70/dry ton for sludge dewatering, making the process very expensive when compared with present disposal methods. (See Appendix 1.)

Experimental work being carried out at present at the British Water Research Centre indicated that the autothermal process can be made to operate efficiently using air as a feed gas at a retention time of three days with temperatures in excess of 55°C being achieved. If the final outcome of this experiment indicates that the system can be operated reliably using air instead of oxygen as a feed gas then one of the major cost factors is removed and the process becomes economically viable, especially when considered as the first stage in a dual digestion process.

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9. CONCLUSIONS

9.1 The autothermal aerobic digestion process can be made to operate successfully at temperatures of up to 60°C at retention times as low as one day using a mixture of primary and waste activated sludge. Thermophilic temperatures could not be achieved when using thickened waste acitvated sludge alone as a feed to the system.

9.2 The process is self-sustaining with regard to temperatures in the thermophilic range and is very resistant to changes in loading and physical abuse.

9.3 Temperature of the system can be increased by increasing oxygen input to some degree; temperatures of up to 74°C being measured. A large excess of oxygen fed to the system does however lead to cooling.

9.4 At the temperatures attained (55 - 60°C) and a retention time of 1 to 3 days virtually all pathogenic bacteria are eliminated.

9.5 The destruction of volatile solids ranged from 21% to 28% and that of COD form 30% to 38%.

9.6 Solids loading of between 9,9 and 23,7 kg VS/m³/day were achieved at retention times between 3 and 1 days.

9.7 Across the range of operating conditions oxygen utilization varied from 2,5 to 3,7 kg oxygen supplied/kg volatile solids destroyed (2,2 to 2,7 kg oxygen used/kg volatile suspended solids destroyed.)

9.8 Efficiency of oxygen utilization ranged from 86% to 90%. This efficiency could be further fine - tuned by careful monitoring of the head gases and subsequent alterations of oxygen feed, a maximum efficiency of 94% being noted.

9.9 Automatic control of oxygen input proved to be effective in that the degree of physical monitoring was drastically reduced.

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The results obtained by this method could, however, be accurately reproduced by running the plant on a continual oxygen feed and "fine-tuning" the system. The automatic operation was dogged by unreliability of dissolved oxygen measuring equipment throughout the test programme.

9.10 The digested sludge produced by the system proved to be odour free but did attract flies if left lying in the open for any period of time.

9.11 The digested sludge produced by the system exhibited some very poor settling properties and was capable of undergoing further anaerobic digestion.

9.12 Costs of the process, based on the pilot plant study, varied between R46 per dry ton treated and R109 per dry ton treated. (See Appendix 1.)

9.13 The process could be economical if it was possible to use a combination of air and pure oxygen or air alone as the major cost source at present is that of oxygen.

9.14 The process should not be considered for "stand-alone" use but could well be included as the first step in an aerobic/anaerobic dual digestion process.

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10. FURTHER RESEARCH

The high degree of pathogenic bacteria destruction achieved by the autothermal aerobic digestion process at retention times of the order of one day could offer an efficient means of ensuring pasteurisation of the influent sludge to an anaerobic digester if the process were used as the first stage in a combined aerobic/anaerobic digestion system. The heat available would also largely negate the need to heat the anaerobic stage.

Investigations already carried out along these lines, including the EPA demonstration project at Hagerstown, have shown this system to be feasible and in fact the performance of the anaerobic stage improved to the point where the retention times could be reduced to the order of eight days, whilst gas yields were of the same order as those of a normal mesophilic anaerobic digestion system.

One of the major considerations which would have to be taken into account if a dual digestion system were to be considered is the cost of the aerobic phase of treatment. The major contributor to the fairly high cost of this form of treatment is the need to use pure oxygen as a feed gas. If the system could be run efficiently on a mixture of pure oxygen and air or on air alone there would be a drastic reduction in the operational costs and this together with the reduction in physical size, and hence capital costs, of the anaerobic stage could make the process more viable.

Although these problems are at present being investigated in some depth both in the United Kingdom and the U.S.A. it is considered that further research should be undertaken in the following areas:-

1. Investigations into the use of air or a mixture of oxygen and air as a feed gas to an autothermal aerobic digester at retention times as low as one day if this is possible.

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2. Investigations into the dual digestion process on an large enough scale for the results to be meaningful. (Most experiments into dual digestion carried out to date have relied on the use of available equipment and plant such as existing anaerobic digesters. This has either led to inefficient use of the anaerobic phase due to the small capacity of the aerobic phase or scaling up of the aerobic phase to uneconomic proportions). This will probably necessitate the construction of a fairly large pilot plant where the aerobic and anaerobic stages are properly matched so as to get the optimum results.

3. In conjunction with (2) above, an investigation into the stability of the final product from a dual digestion system and possible methods for final disposal thereof.
e.g. soil conditioner.

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FIGURE N°. 1

AUTOTHERMAL AEROBIC DIGESTION PILOT PLANT
SECTIONAL VIEW

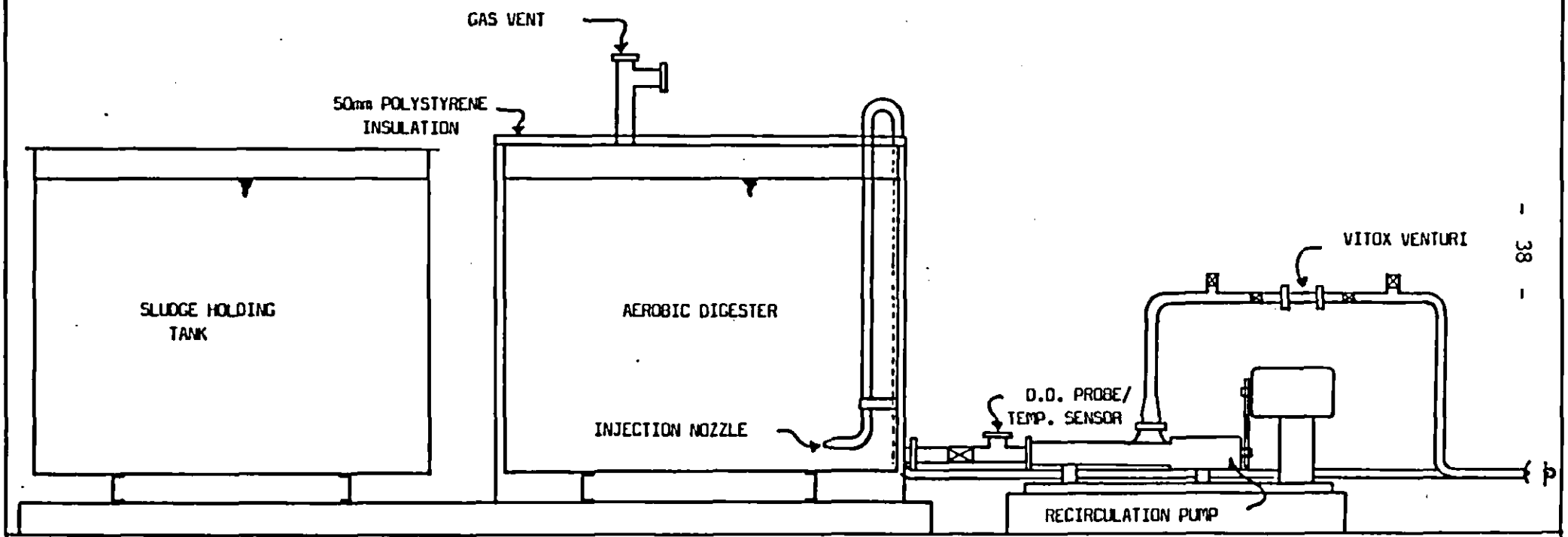
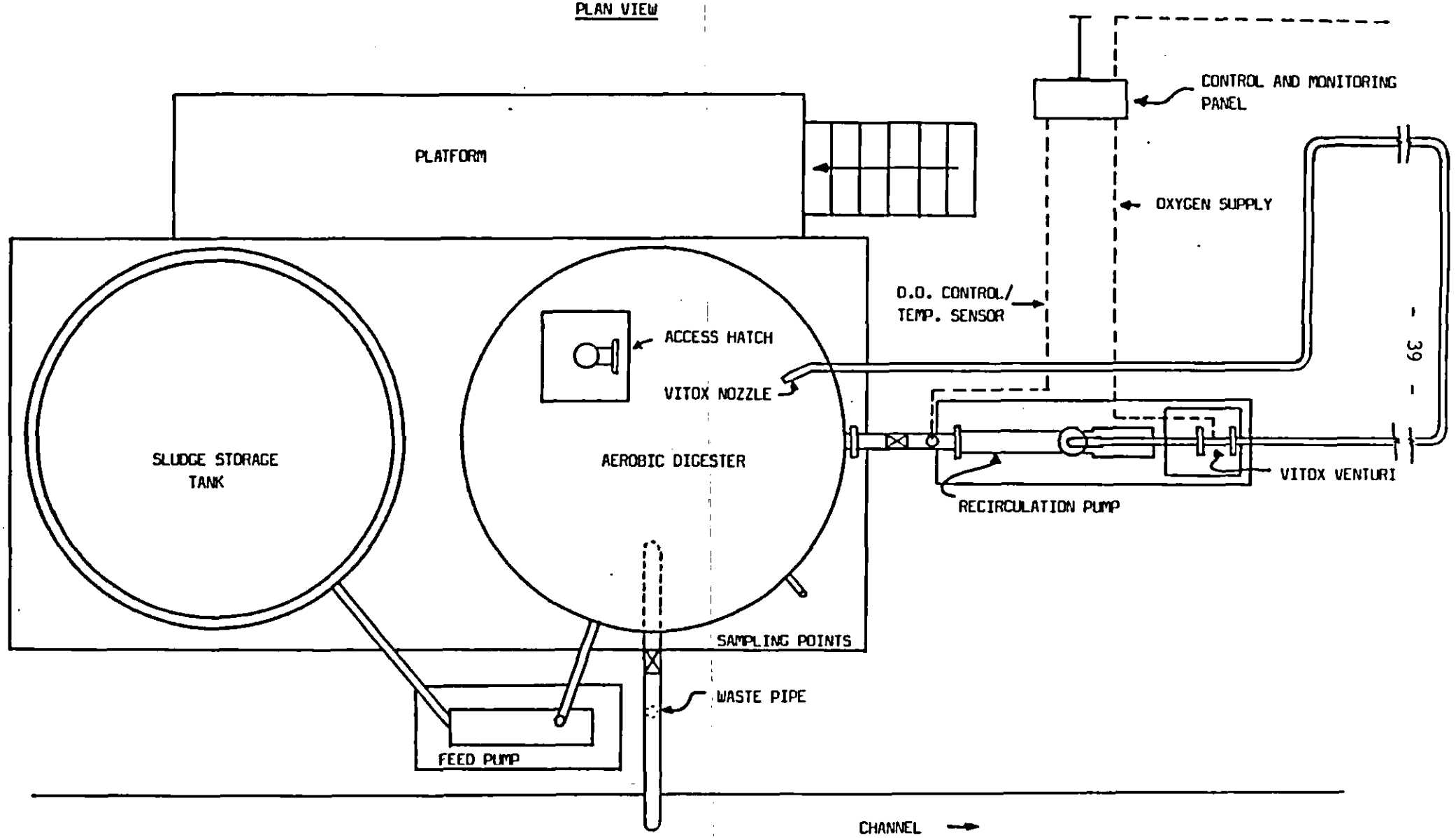


FIGURE N°. 2

AUTOTHERMAL AEROBIC DIGESTION PILOT PLANT

PLAN VIEW



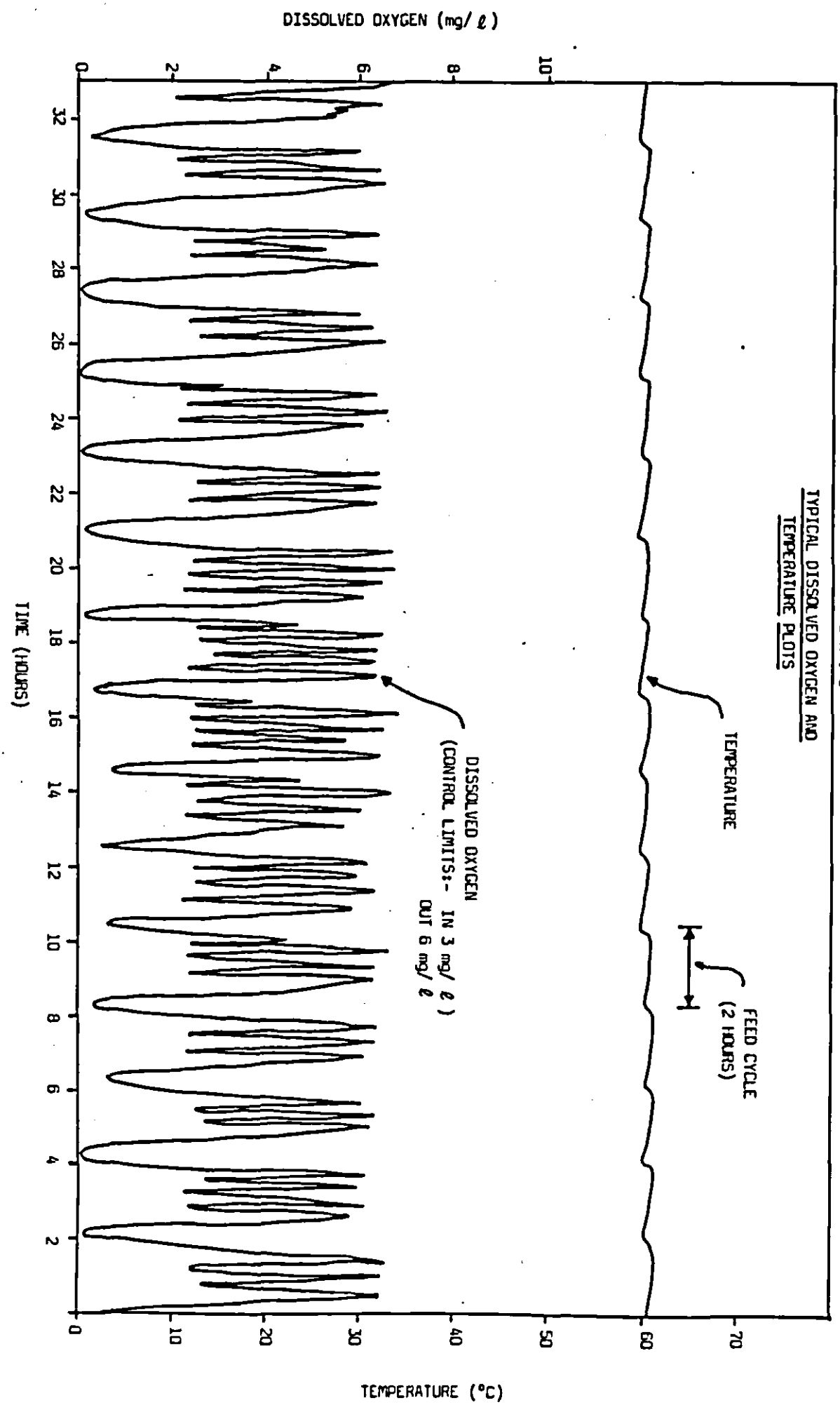


FIGURE N°. 3

TYPICAL DISSOLVED OXYGEN AND TEMPERATURE PLOTS

FIGURE 4. TYPICAL TEMPERATURES ACHIEVED DURING SYSTEM START-UP.

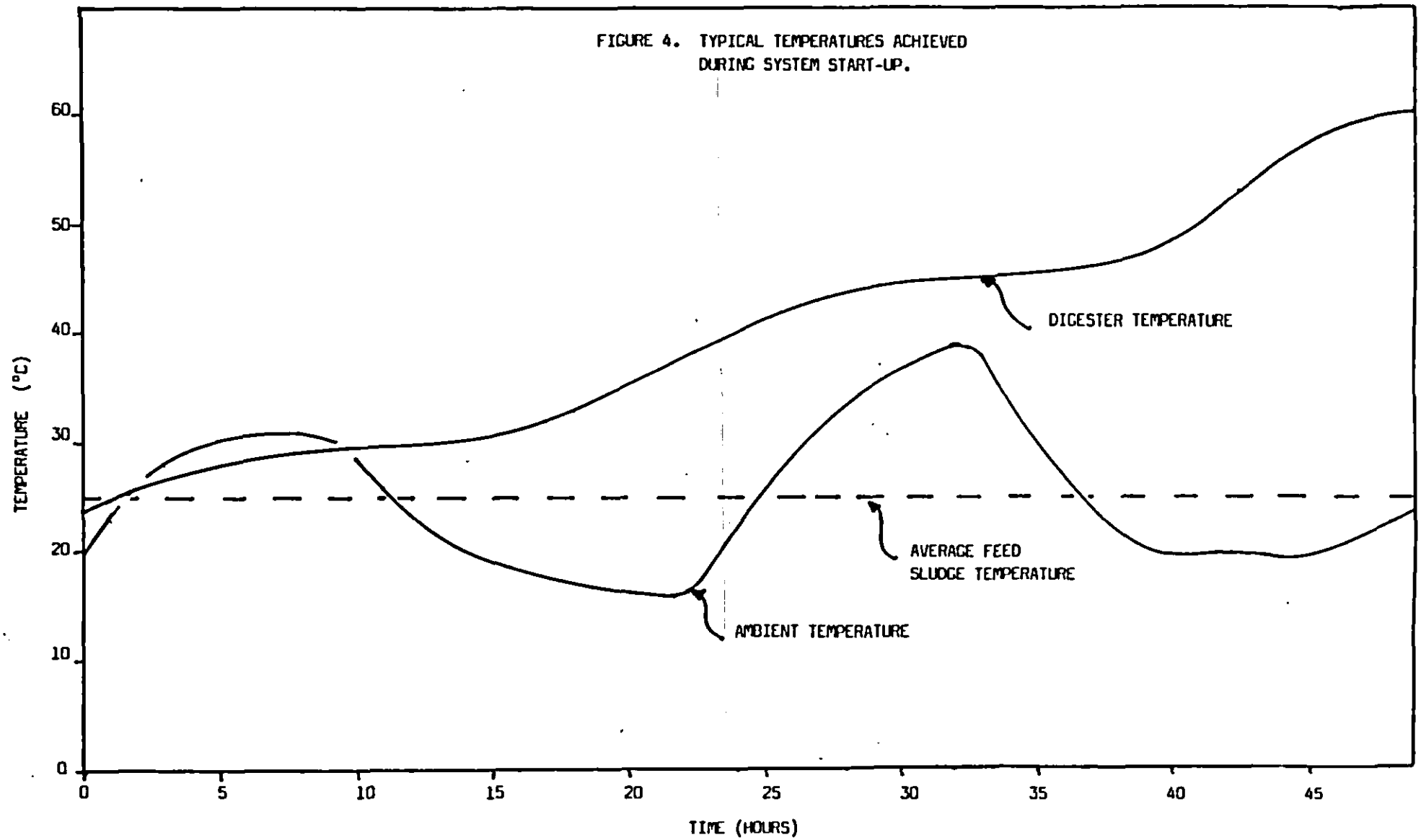
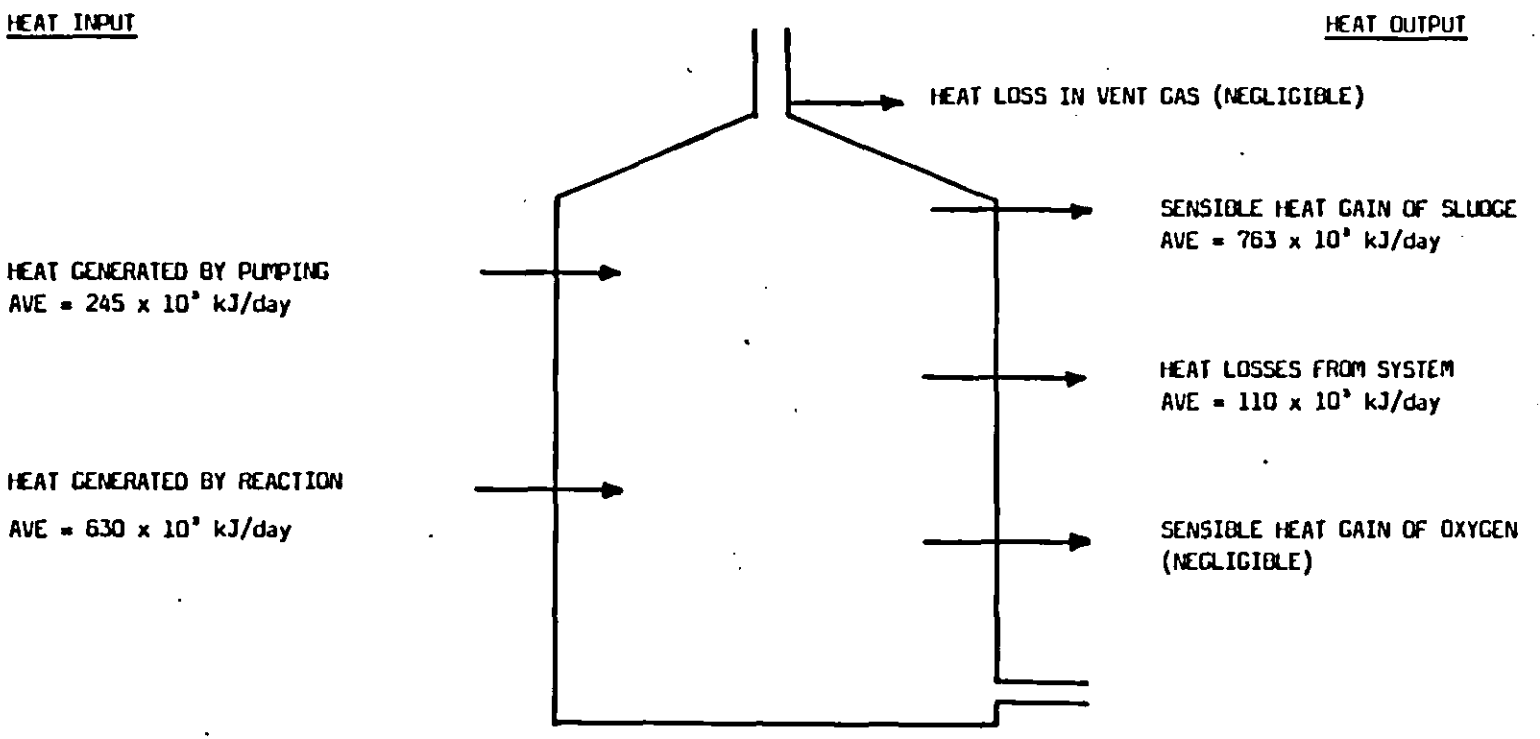


FIGURE 5. TYPICAL HEAT BALANCE (AVERAGE VALUES)



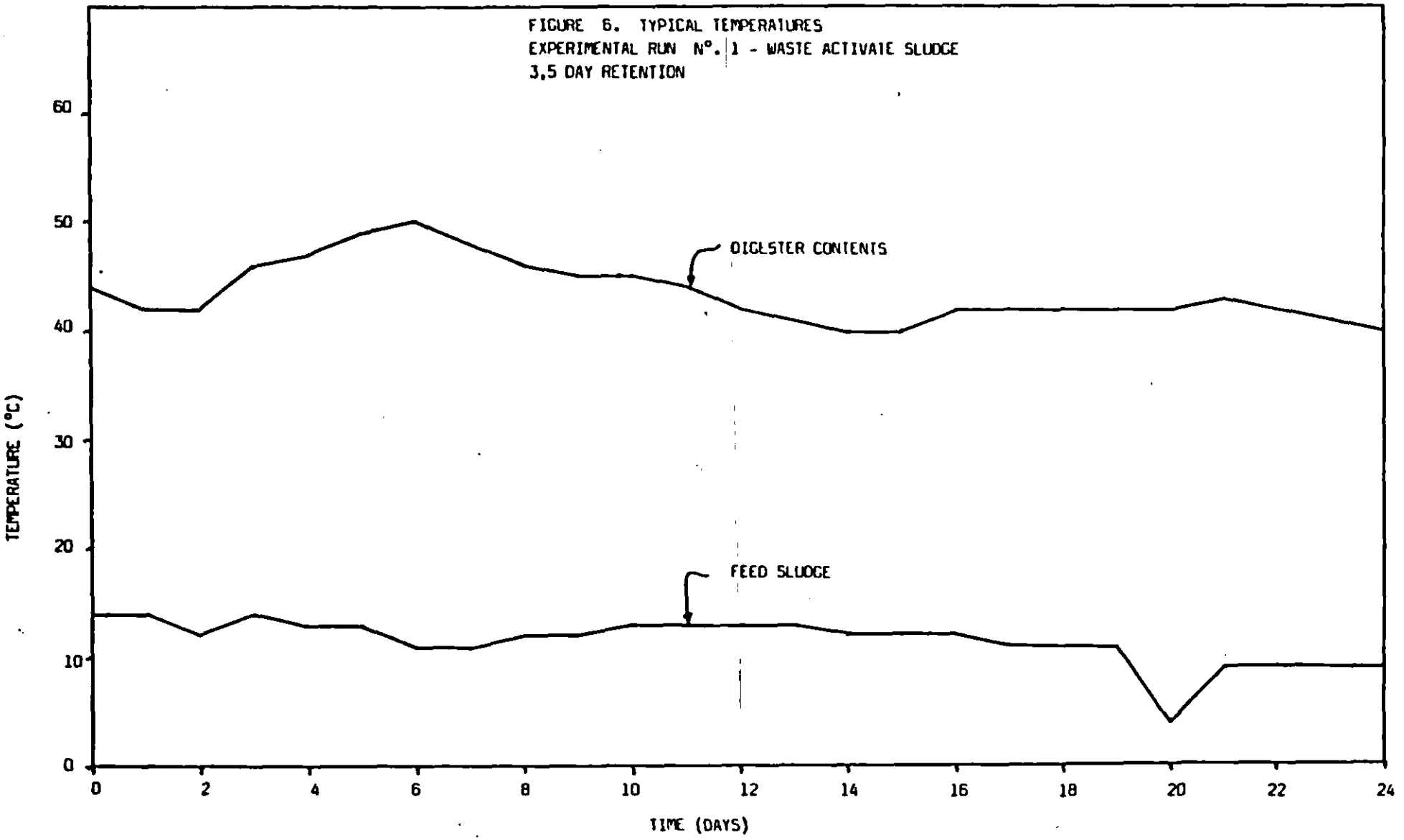


FIGURE 6. TYPICAL TEMPERATURES
EXPERIMENTAL RUN N°. 1 - WASTE ACTIVATE SLUDGE
3,5 DAY RETENTION
DIGESTER CONTENTS
FEED SLUDGE
TEMPERATURE (°C)
TIME (DAYS)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
22
24

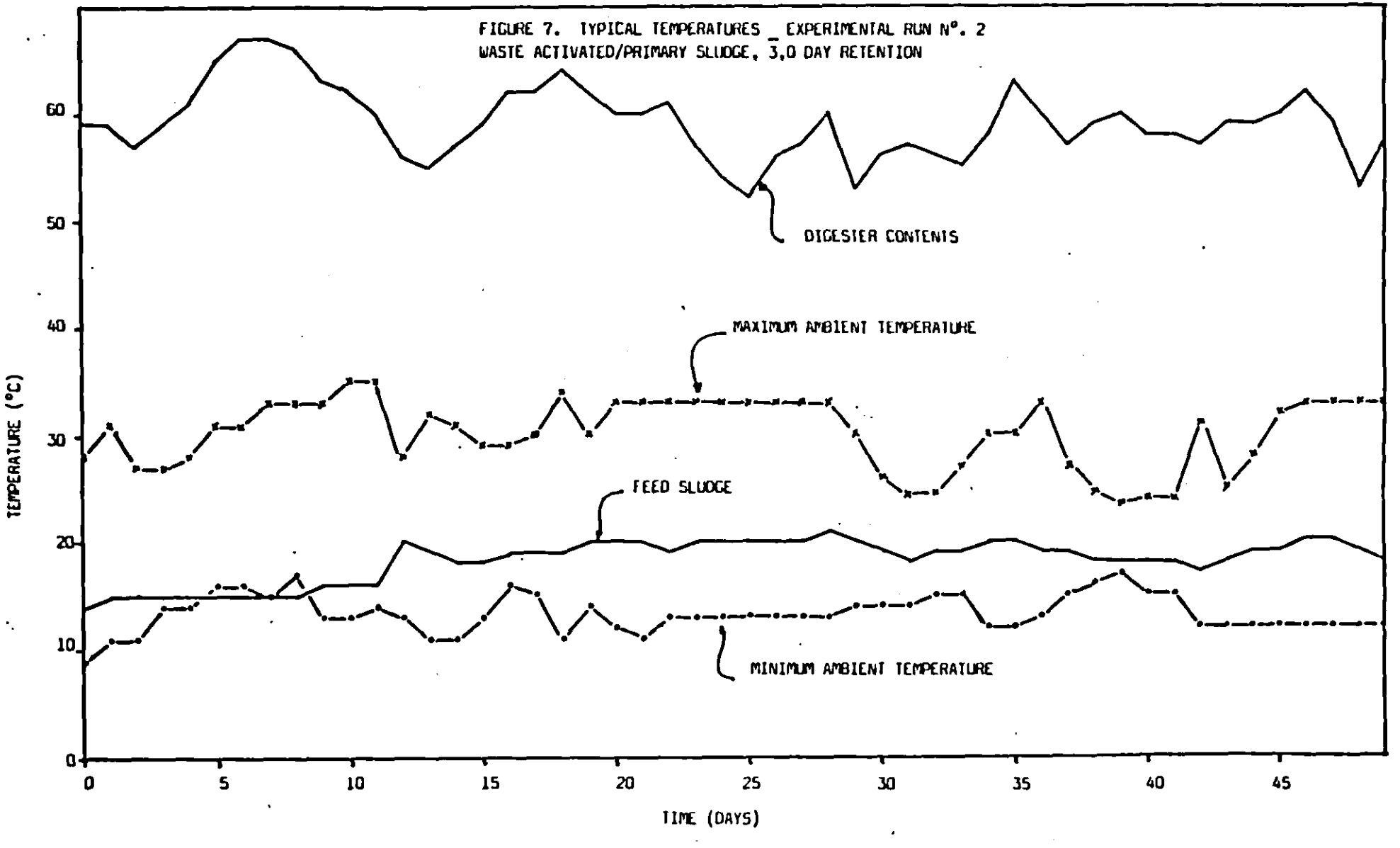


FIGURE 7. TYPICAL TEMPERATURES _ EXPERIMENTAL RUN N°. 2
WASTE ACTIVATED/PRIMARY SLUDGE, 3,0 DAY RETENTION
DIGESTER CONTENTS
MAXIMUM AMBIENT TEMPERATURE
FEED SLUDGE
MINIMUM AMBIENT TEMPERATURE
TEMPERATURE (°C)
TIME (DAYS)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45

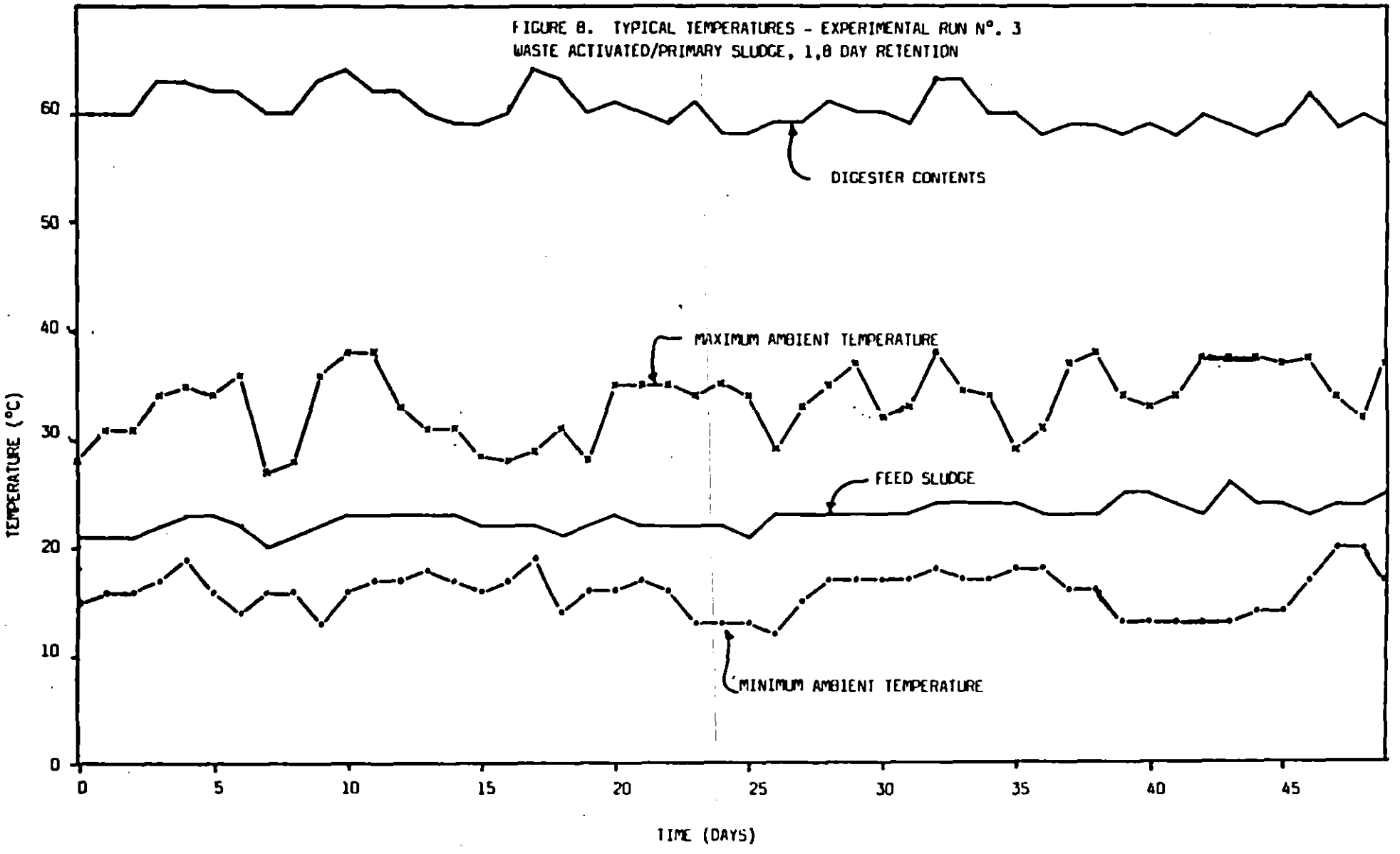


FIGURE 8. TYPICAL TEMPERATURES - EXPERIMENTAL RUN N°. 3
WASTE ACTIVATED/PRIMARY SLUDGE, 1,8 DAY RETENTION
DIGESTER CONTENTS
MAXIMUM AMBIENT TEMPERATURE
FEED SLUDGE
MINIMUM AMBIENT TEMPERATURE
TEMPERATURE (°C)
TIME (DAYS)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45

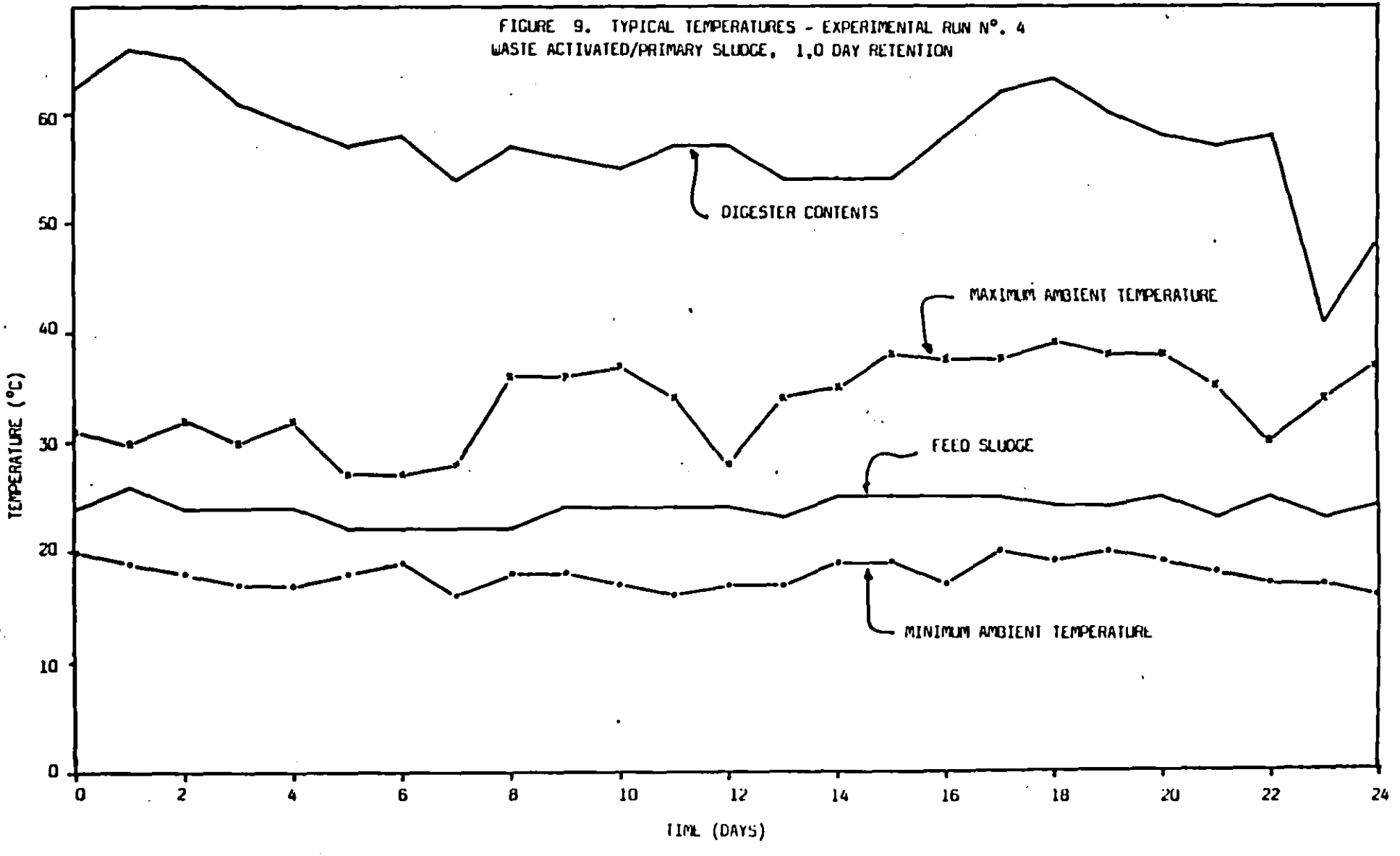


FIGURE 9. TYPICAL TEMPERATURES - EXPERIMENTAL RUN N°. 4
WASTE ACTIVATED/PRIMARY SLUDGE, 1,0 DAY RETENTION
DIGESTER CONTENTS
MAXIMUM AMBIENT TEMPERATURE
FEED SLUDGE
MINIMUM AMBIENT TEMPERATURE
TEMPERATURE (°C)
TIME (DAYS)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
22
24

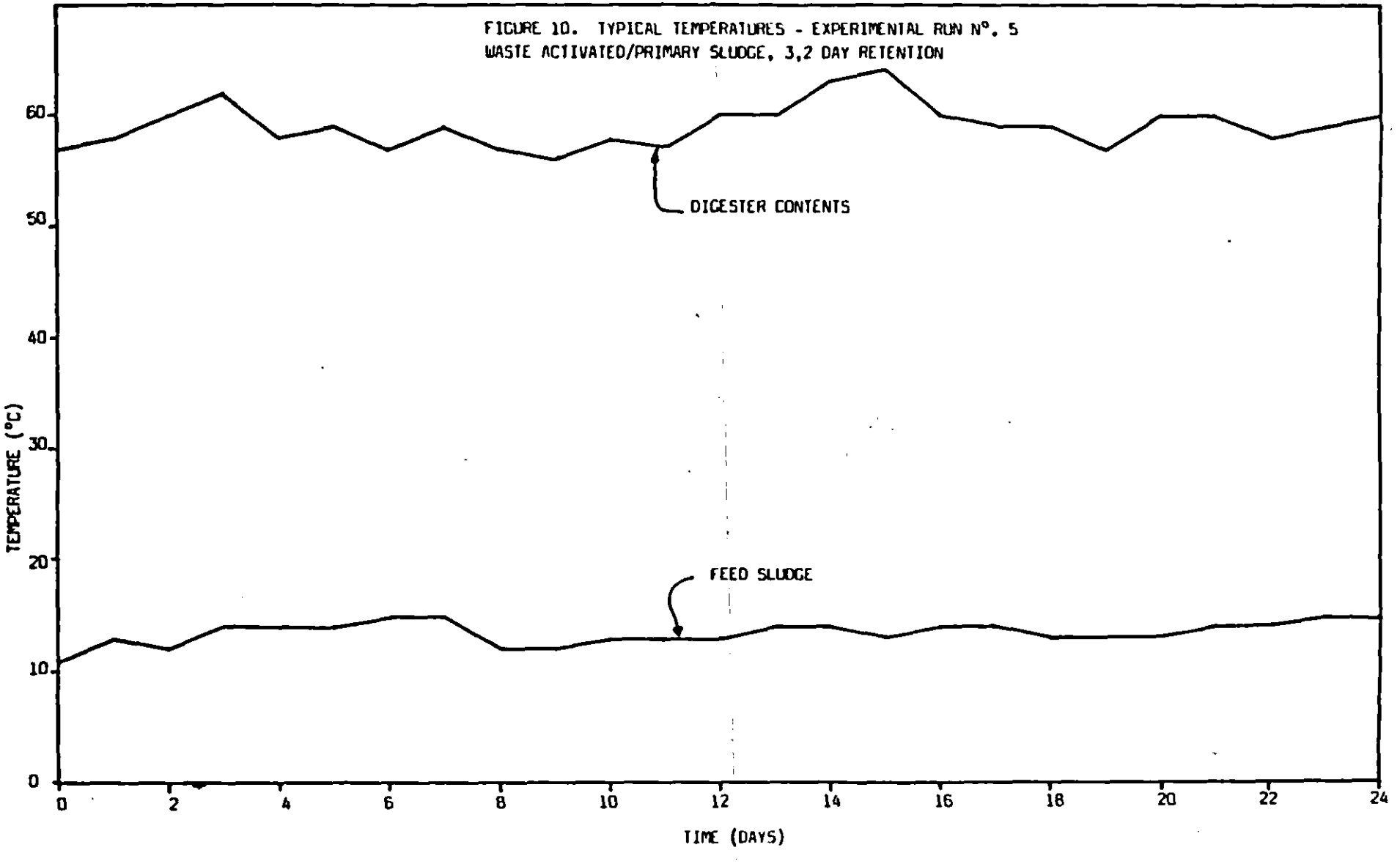


FIGURE 10. TYPICAL TEMPERATURES - EXPERIMENTAL RUN N°. 5
WASTE ACTIVATED/PRIMARY SLUDGE, 3,2 DAY RETENTION
DIGESTER CONTENTS
FEED SLUDGE
TEMPERATURE (°C)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
22
24
TIME (DAYS)

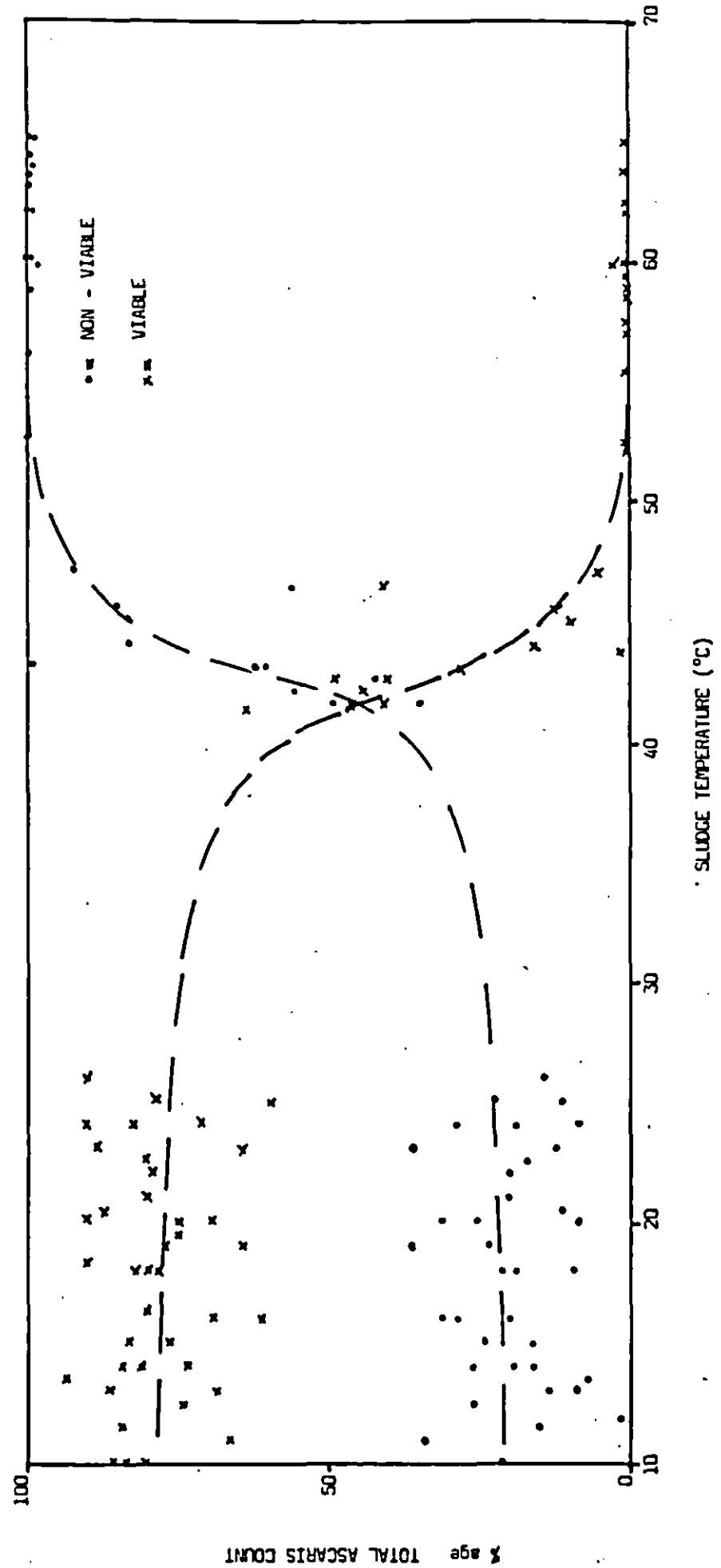


FIGURE 11. DESTRUCTION OF ASCARIS DVA

TABLE 1 - SLUDGE CHARACTERISTICS

EXPERIMENTAL RUN	RETENTION TIME (DAYS) THEORETICAL/ ACTUAL	FEED SLUDGE TYPE	SAMPLE	% TOTAL SOLIDS		% VOLATILE SOLIDS		pH	
				AVERAGE	RANGE	AVERAGE	RANGE	AVERAGE	RANGE
1	4/3,5	THICKENED WASTE ACTIVATED	FEED	3,7	5,1 - 3,3	75,0	77,7 - 73,5	6,2	6,5- 5,9
			DIGESTER	2,8	3,5 - 2,7	71,6	72,4 - 70,7	7,0	7,2 - 6,9
2	4/3	PRIMARY + WASTE ACTIVATED	FEED	4,2	4,7 - 3,4	70,8	72,8 - 68,2	5,6	5,8 - 5,5
			DIGESTER	3,0	3,6 - 2,4	71,2	72,8 - 69,8	7,2	8,1 - 6,8
3	2/1,8	PRIMARY + WASTE ACTIVATED	FEED	3,9	5,3 - 3,0	69,3	71,3 - 64,6	5,6	5,8 - 5,5
			DIGESTER	3,3	3,3 - 2,7	69,1	71,3 - 66,4	7,2	8,4 - 7,0
4	1/1	PRIMARY + WASTE ACTIVATED	FEED	3,4	4,4 - 2,4	71,1	82,0 - 68,0	5,6	6,2 - 5,3
			DIGESTER	2,6	2,8 - 2,0	71,3	79,0 - 68,4	7,4	7,9 - 7,2
5	4/3,2	PRIMARY + WASTE ACTIVATED	FEED	4,0	4,7 - 3,4	75,0	76,4 - 74,4	6,0	6,2 - 5,8
			DIGESTER	3,0	3,2 - 2,8	72,0	73,4 - 70,4	7,3	7,8 - 7,1

TABLE 2 - SLUDGE ANALYSIS (AVERAGE)

EXPERIMENTAL RUN	FEED SLUDGE TYPE	SAMPLE	% DRY SOLIDS	% VOLATILE SOLIDS	% VOL. SOLIDS DESTROYED	COD (mg/ ℓ)	% COD REDUCED	AMMONIA (mg/ℓ)	TKN (mg/ℓ)	PHOSPHORUS (mg/ ℓ)	
										TOTAL P	ORTHO P
1	THICKENED WAS	FEED	3,7	75,0	28,0	39790	21,0	90	2267	840	169
		DIGESTER	2,8	71,6		31360		454	2056	814	146
2	WAS / PRIMARY	FEED	4,2	70,8	28,0	48350	35,0	426	1656	585	181
		DIGESTER	3,0	71,2		31690		610	1600	576	100
3	WAS/ PRIMARY	FEED	3,9	69,3	23,0	46070	32,5	444	1679	578	191
		DIGESTER	3,0	69,1		31100		484	1600	528	68
4	WAS/ PRIMARY	FEED	3,4	71,1	21,0	39130	30,5	291	1375	452	185
		DIGESTER	2,6	71,3		28460		357	1285	405	56
5	WAS/ PRIMARY	FEED	4,0	75,0	28,0	46660	38,0	345	1695	644	149
		DIGESTER	3,0	72,0		29100		708	1638	590	87

TABLE 3 - SLUDGE LOADINGS

EXPERIMENTAL RUN	kg/day DRY SOLIDS IN	kg/day VOL. SOLIDS IN	kg/day VOL. SOLIDS OUT	kg/day VOL. SOLIDS DESTROYED	% VOL. SOLIDS DESTROYED	LOADING RATE kg VS/m³/day
1	87,5	65,6	47,2	18,4	28,0	8,2
2	111,9	79,2	55,9	23,3	28,0	9,9
3	181,0	124,9	93,3	31,6	23,0	15,6
4	266,8	189,7	150,5	39,2	21,0	23,7
5	100,3	75,2	54,2	21,0	28,0	9,4

TABLE 4. SYSTEM OPERATING CONDITIONS

EXPERIMENTAL RUN	ACTUAL RETENTION TIME (days)	FEED SLUDGE TYPE	AVERAGE TEMPERATURE (°C)		POWER USED (kWh/day)	OXYGEN SUPPLIED (kg/day)	% O_2 IN VENT GAS	% CO_2 IN VENT GAS	% O_2 UTILISED	OXYGEN TO WASTE (kg/day)	OXYGEN USED (kg/day)
			FEED	DIGESTER							
1	3,5	WAS	12	44	96,2	68,4	-	-	-	-	-
2	3,0	WAS/ PRIMARY	16	58	96,2	64,0	14	86	86	9,0	55,0
3	1,8	WAS/ PRIMARY	22	60	96,1	95,8	10	90	90	9,6	86,2
4	1,0	WAS/ PRIMARY	24	58	96,5	99,2	14	86	86	13,9	85,3
5	3,2	WAS/ PRIMARY	13	59	96,2	60,0	14	86	86	8,4	51,6

TABLE 5. OXYGEN AND POWER UTILISATION

EXPERIMENTAL RUN	kg O_2 SUPPLIED/ kg VS DESTROYED	kg O_2 USED/ kg VS DESTROYED	kg O_2 SUPPLIED / kg COD DESTROYED	kg O_2 USED/ kg COD DESTROYED	kWh/kg VS DESTROYED	kWh/kg COD DESTROYED
1	3,7	-	4,0	-	5,2	5,6
2	2,8	2,4	1,4	1,2	4,1	2,1
3	3,0	2,7	1,4	1,3	3,0	1,4
4	2,5	2,2	1,2	1,0	2,5	1,1
5	2,9	2,5	1,4	1,2	4,6	2,2

TABLE 6 - POLYMER ADDITION TO AERODICALLY DIGESTER SLUDGE

POLYMER SOLUTION (mℓs 0,05% solution/100mℓ sample)	3,2 DAY RETENTION TIME *		1,82 DAY RETENTION TIME *	
	POLY DOSE (kg/ton dry solids)	CST (secs)	POLY DOSE (kg/ton dry solids)	CST (secs)
NIL	NIL	200 000	NIL	200 000
30	5,3	1082	5,3	798
50	8,9	40	-	-
60	10,7	25	-	-
70	-	-	12,5	14
80	14,3	15	-	-
mℓs 0,5% solution added to 100mℓ sample				
7	-	-	12,5	1799
10	-	-	18,0	324

* SOLIDS CONTENT OF SLUDGE SAMPLE: 3,2 DAYS = 2,8 m/v
1,8 DAYS = 2,7 m/v

TABLE 7 - SYSTEM HEAT BALANCE

NOMINAL RETENTION TIME (DAYS)	HEAT LOST TO SURROUNDINGS H_L kJ x10³/day	HEAT GAIN BY SLUDGE H_S kJ x10³/day	HEAT INPUT BY PUMPS H_P kJ x10³/day	BIOLOGICAL REACTION HEAT $H_B = H_L + H_S - H_P$ kJ x10³/day	HEAT OF REACTION H_B/ VS kJ x10³/kg VS DESTROYED	kJ x10³/ kg O_2 USED
1	110	1120	245	985	25	10
2	110	700	244	566	18	6
3	110	470	244	336	15	5

TABLE 8. BIOLOGICAL FERMENTABILITY OF AEROBICALLY DIGESTED SLUDGE

NOMINAL RETENTION TIME (days)	VOLATILE ACIDS PRODUCED (mg/ℓ)	
	SAMPLE + 10 % DIGESTED SLUDGE	SAMPLE + 10 % ACID SLUDGE
3	780	1250
2	190	1900

TABLE 9. PROCESS COSTS *

NOMINAL RETENTION TIME. (days)	COST PER DRY TON SOLIDS (R/ton)		COST PER TON VOLATILE SOLIDS DESTROYED (R/ton)	
	O_2	TOTAL	O_2	TOTAL
1	33	46	230	315
2	55	77	270	375
3	69	109	250	398

*NOTE: 1. COST OF OXYGEN TAKEN AS R0,09/kg
2. COST OF ELECTRICITY TAKEN AS R0,035/kWhr
3. COSTS RELATE TO PILOT PLANT TESTS

TABLE 10. ASCARIS OVA COUNTS AND SALMONELLA DETECTION EXPERIMENTAL RUN N°. 1
THICKENED WASTE ACTIVATED SLUDGE.
3,5 DAY RETENTION TIME.

(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT/g DRY	POTENTIALLY INFECTIVE %	VIABLE %	NON-VIABLE %		
1	F	2243	93	93	7	present	13,5
	D	2679	40	44	56	present	46,3
2	F	2316	86	87	13	present	13,0
	D	2031	5	8	92	present	47,0
3	F	1686	68	91	9	absent	13,0
	D	3893	10	17	83	absent	45,0
4	F	2371	74	74	26	absent	12,5
	D	3429	16	17	83	absent	43,8
5	F	2063	84	85	15	present	11,5
	D	2323	64	65	35	present	41,5
6	F	1706	66	66	34	present	11,0
	D	2536	46	51	49	present	41,6
7	F	1217	80	82	18	present	4,0
	D	1844	49	58	42	absent	42,5
8	F	1706	85	85	15	absent	9,0
	D	1933	28	33	67	absent	42,9
9	F	1419	79	79	21	absent	9
	D	2600	43	45	55	absent	41,8

TABLE 11. ASCARIS OVA COUNTS AND SALMONELLA DETECTION
EXPERIMENTAL RUN N°. 2 - WASTE ACTIVATED
SLUDGE/PRIMARY SLUDGE. 3,5 DAY RETENTION.
(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT/g DRY	POTENT-IALLY VIABLE %	VIABLE %	NON-VIABLE %		
1	F	1490	83	84	16	absent	15,0
	D	1912	0	0	100	present	57,4
2	F	950	76	76	24	absent	15,0
	D	2310	0	0	100	absent	58,5
3	F	1952	69	69	31	absent	16,0
	D	1107	0	0	100	absent	63,4
4	F	2529	71	71	29	absent	16,0
	D	1107	0	0	100	absent	62,0
5	F	1465	80	80	20	absent	16,0
	D	931	0	0	100	absent	62,0
6	F	2079	63	64	36	absent	19,0
	D	767	0	0	100	absent	62,2
7	F	1969	77	77	23	present	19,0
	D	1828	1	1	99	absent	63,5
8	F	2489	75	75	25	absent	20,0
	D	1800	1	1	99	absent	43,6
9	F	2250	69	69	31	present	20,0
	D	2423	0	0	100	absent	52,1

TABLE 11. (CONT'D). ASCARIS OVA COUNTS AND SALMONELLA DETERMINATIONS EXPERIMENTAL RUN N° 2- WASTE ACTIVATED SLUDGE/ PRIMARY SLUDGE. 3,5 DAY RETENTION
(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERTURE (°C)
		COUNT/g DAY	POTENTIALLY VIABLE %	VIABLE %	NON-VIABLE %		
10	F	972	90	92	8	present	18,0
	D	2444	0	0	100	absent	56,8
11	F	2079	79	79	21	absent	18,0
	D	966	0	0	100	absent	58,9
12	F	1806	79	79	21	present	18,0
	D	1586	0	0	100	absent	60,0
13	F	1262	75	75	25	absent	19,5
	D	1563	1	1	99	absent	59,9

TABLE 12. ASCARIS OVA COUNTS AND SALMONELLA DETECTION
EXPERIMENTAL RUN N° 3 - WASTE ACTIVATED SLUDGE/PRIMARY SLUDGE . 1,8 DAY RETENTION
(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT/g DRY	POTENTIALLY VIABLE %	VIABLE %	NON-VIABLE %		
1	F	1395	87	89	11	absent	20,5
	D	1267	1	1	99	absent	60,3
2	F	2486	90	92	8	absent	20,0
	D	1531	0	0	100	absent	60,0
3	F	2595	79	80	20	absent	21,0
	D	1186	0	0	100	absent	60,2
4	F	1057	88	88	12	absent	23,0
	D	1516	0	0	100	absent	59,3
5	F	2848	82	83	17	absent	22,5
	D	1432	0	1	99	absent	58,7
6	F	2853	71	71	29	absent	24,0
	D	1636	0	0	100	absent	59,6
7	F	2230	64	64	36	absent	23,0
	D	2400	2	2	98	absent	59,8
8	F	2828	78	78	22	absent	25,0
	D	4240	1	1	99	absent	61,8

TABLE 13. ASCARIS OVA COUNTS AND SALMONELLA DETERMINATION EXPERIMENTAL RUN N° 4 - WASTE ACTIVATED SLUDGE/PRIMARY SLUDGE. 1,0 DAY RETENTION .
(F = FEED D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT/ g DRY	POTENTIALLY VIABLE %	VIABLE %	NON-VIABLE %		
1	F	2690	90	86	14	absent	26,0
	D	2036	1	1	99	absent	65.6
2	F	4138	90	92	8	absent	24,0
	D	3792	0	0	100	absent	55.6
3	F	1500	59	59	11	absent	25,0
	D	1760	0	0	100	absent	57,7
4	F	2222	82	82	18	absent	24,0
	D	2667	12	15	85	absent	45,5
5	F	1150	89	90	10	absent	22,0
	D	1600	40	40	60	absent	42,8

TABLE 14. ASCARIS OVA COUNTS AND SALMONELLA DETERMINATIONS EXPERIMENTAL RUN N°. 5 WASTE ACTIVATED SLUDGE/ PRIMARY SLUDGE. 3,2 DAY RETENTION.
(F = FEED SLUDGE D = DIGESTED SLUDGE)

SAMPLE NUMBER	SLUDGE SOURCE	ASCARIS OVA COUNT				SALMONELLA	SAMPLE TEMPERATURE (°C)
		COUNT /g DRY	POTENTIALLY VIABLE %	VIABLE %	NON-VIABLE %		
1	F	2390	81	81	19	absent	18
	D	2785	0	0	100	absent	52,4
2	F	1772	84	84	16	absent	14,0
	D	1896	0	0	100	absent	59,0
3	F	2196	81	81	19	absent	14,0
	D	2344	0	0	100	absent	60,0
4	F	1037	73	74	26	absent	14,0
	D	2137	0	0	100	absent	60,0

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APPENDIX N°. 1

PROCESS CONPARISONS

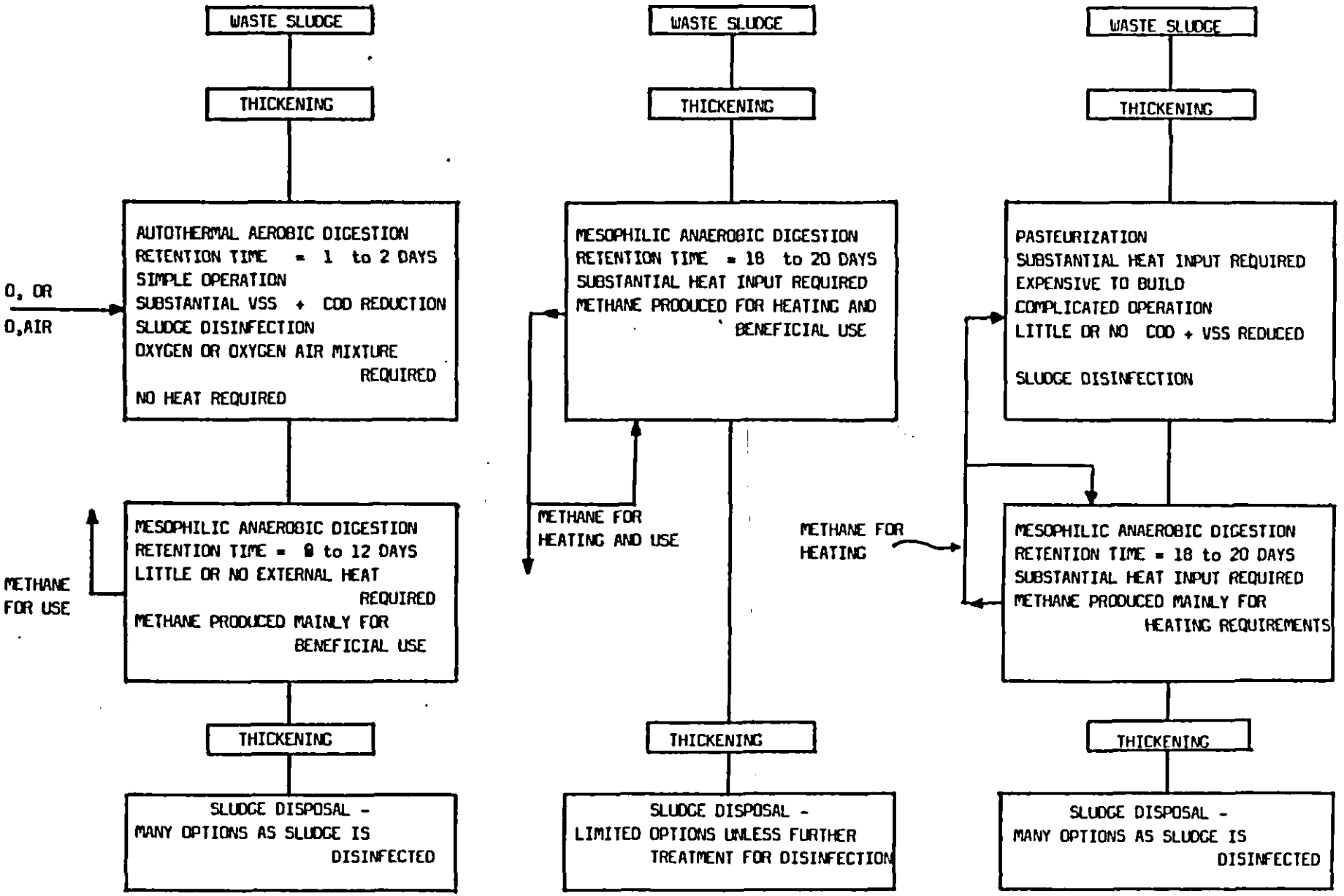
The costs given in the body of the report and in Table 9 are only indicative of the cost of the treatment phase of the autothermal aerobic digestion process at pilot scale and should not be used as the basis for comparision with other sludge treatment processes.

In order to arrive at a realistic cost for treatment by means of the autothermal process further work at larger scale including a properly sized anaerobic second stage and the optimization of oxygen or a mixture of oxygen and air would be necessary. Full scale plants of this type are presently being commissioned in the U.S.A. and as such more realistic data should be available in the near future.

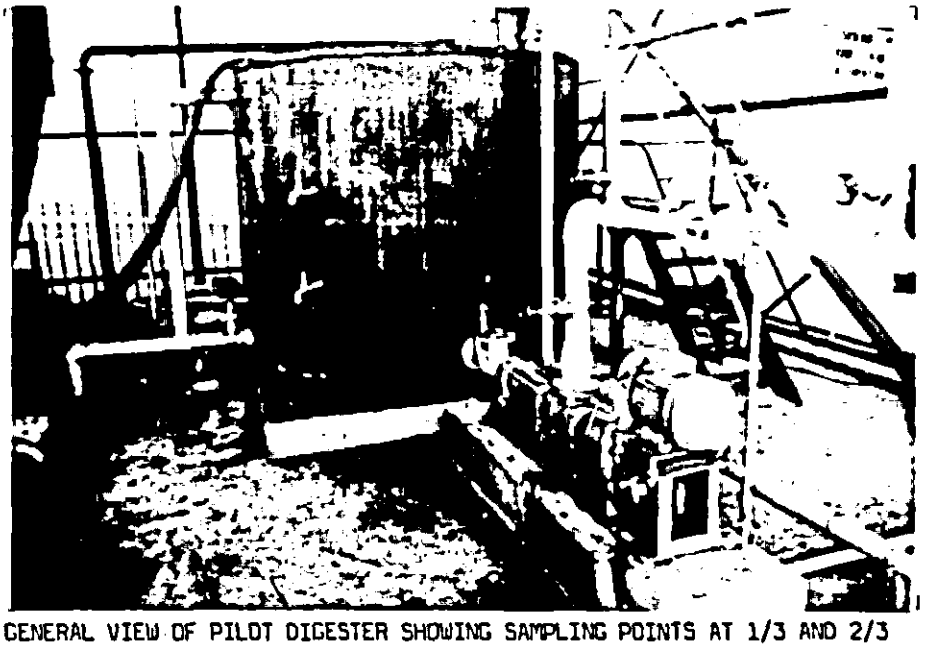
As mentioned above the costs given in the report relate only to the treatment phase and do not include capital costs which would obviously depend on such factors as the size of the plant, the materials used in its construction, the amount of standby equipment included and the degree of automation required. These figures cannot be acquired from a pilot plant operation such as the one under discussion.

In comparing the overall cost of a sludge treatment system, which includes the autothermal aerobic digestion phase, with other forms of sludge treatment there are many important considerations which must be taken into account in addition to the cost factors mentioned above. The first of these is the fact that there is a substantial reduction of both COD and VSS at retention times of the order of one to two days. Secondly, the amount of heat produced would probably be sufficient to supply the heating requirements of the second stage anaerobic process. In addition, the sludge produced by the process is pathogen free thus allowing many more disposal options than are available for anaerobically digested sludge.

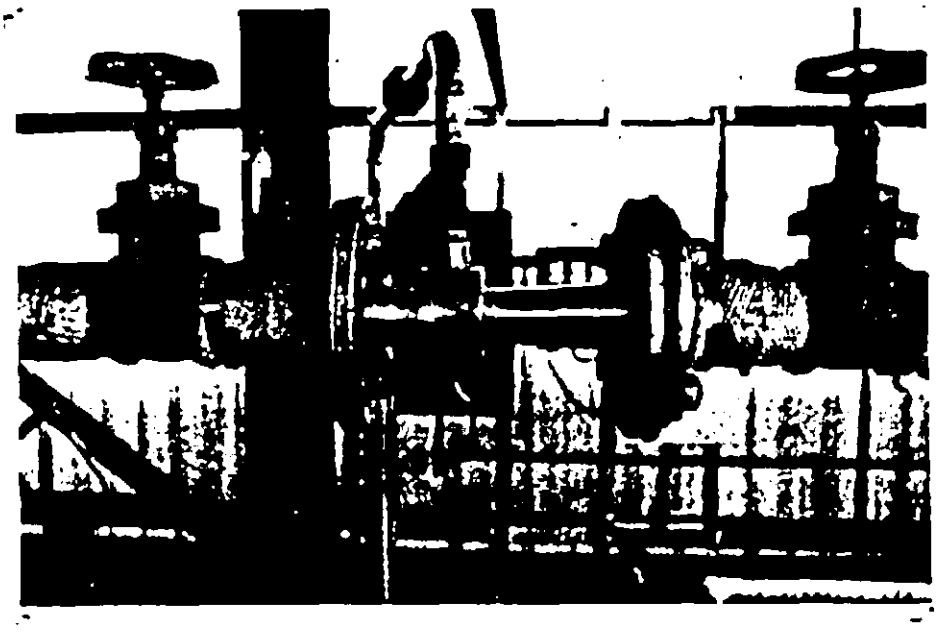
The following diagram presents the salient features of three treatment processes; namely, autothermal aerobic digestion followed by mesophilic anaerobic digestion, standard mesophilic anaerobic digestion and the former in conjunction with a pasteurization stage, without trying to apportion costs related to any particular stage. It is felt that this is the most reasonable comparison that can be made based on the state of development of the autothermal digestion process to date.



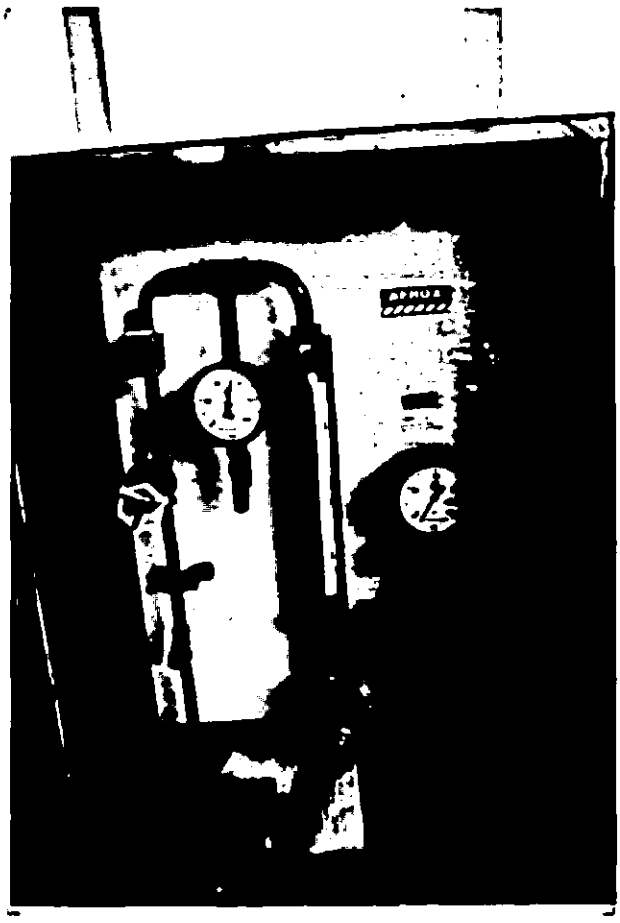
PROCESS COMPARISONS



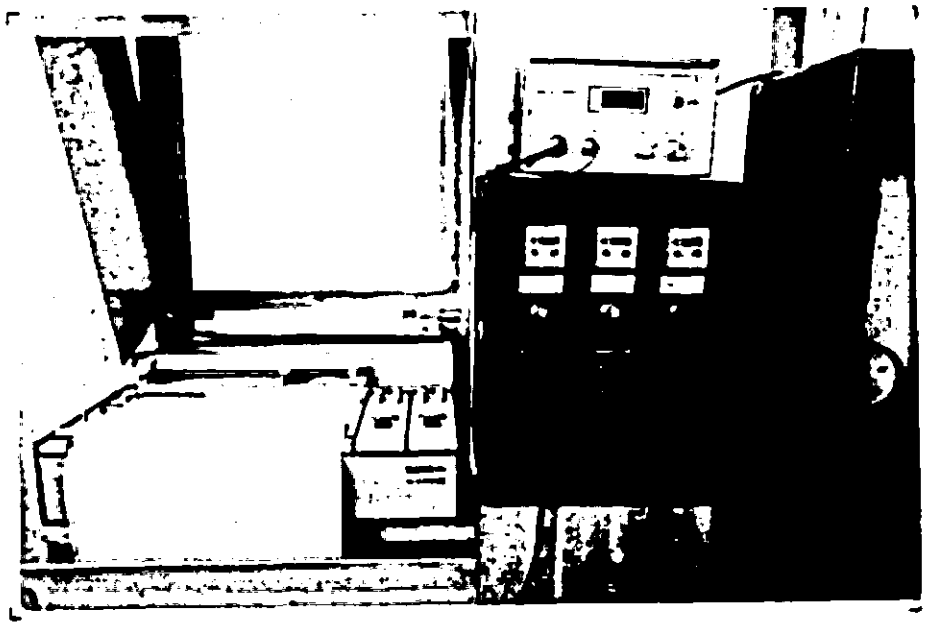
GENERAL VIEW OF PILOT DIGESTER SHOWING SAMPLING POINTS AT 1/3 AND 2/3 DEPTH. TANK FULLY INSULATED WITH 50mm POLYSTYRENE. IN FOREGROUND IS RECIRCULATION PUMP AND PIPEWORK INCLUDING VENTURI.



THE VITOX VENTURI WITH OXYGEN FEED PIPE AND MONITORS. THE RECYCLED SLUDGE PIPE SIZE IS 50mm DIAMETER TO AVOID BLOCKAGES AT THE VENTURI.

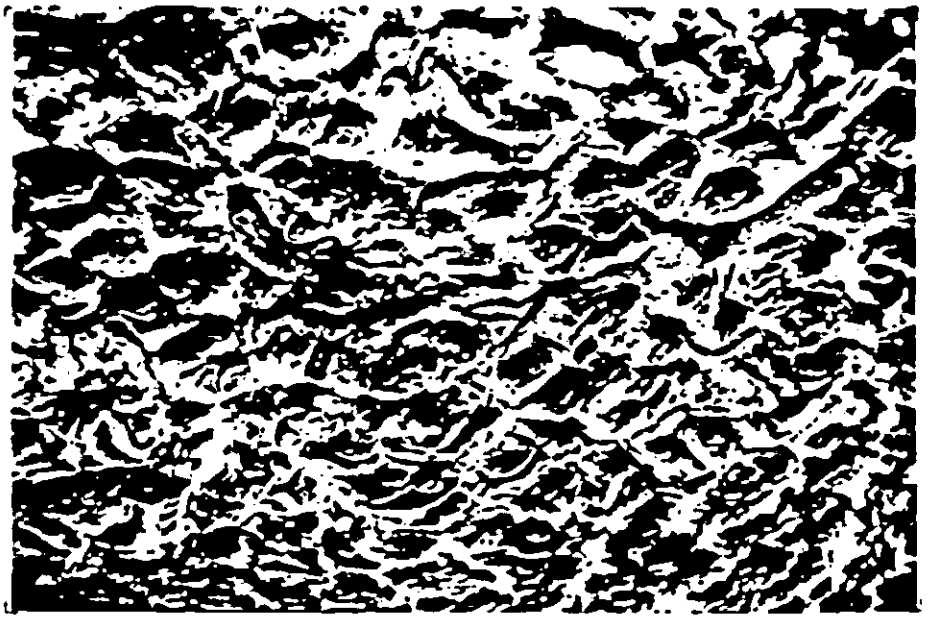


THE OXYGEN MONITORING AND CONTROL PANEL SHOWING PRESSURE AND FLOW CONTROL VALVES, SOLENOID SAFETY VALVE. OXYGEN PRESSURE GAUGE (550kPa) OXYGEN FLOW ROTAMETER AND SYSTEM PRESSURE GAUGE (170kPa)



ORBISPHERE D.O. METER (TOP) WITH CONTROLS FOR FEED PUMP RECYCLE PUMP AND OXYGEN FEED (BELOW). ON RIGHT IS TWO-PEN RECORDER FOR RECORDING D.O. AND TEMPERATURE.

THE OXYGEN STORAGE VESSEL. CAPACITY = 1400 kg O_2 AT -186 °C.
VAPOURIZER UNIT IS SITUATED AT LEFT OF VESSEL



TYPICAL SLUDGE COMPOSITION AFTER STANDING FOR APPROXIMATELY SEVEN DAYS