PIGGERY SLURRY - AEROBIC TREATMENT

WITH HEAT RECOVERY

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by

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2. SUMMARY

The objectives of the study were to evaluate a mathematical model, derived from empirical data obtained from laboratory experiments, for the prediction of the characteristics of aerobically-treated piggery slurry in a large-scale reactor operating under practical conditions. This model was extrapolated for use in the prediction of extractable heat and heat losses from the process and written as a computer program "Farm Waste Management". Predicted heat values from this program were then compared with observed experimental data.

The $23m^3$ reactor, insulated for heat conservation, was built together with a commercial piggery for fattening and weaning pigs. The reactor was fitted with an aerator and a water to water heat exchanger. Energy recovered from the reactor was measured and used in the weaner house.

The slurry collected from the piggery varied in composition and the total solids concentration ranged from 25.2g/l to 101.8g/l. Several of the major analytical values were correlated to enable, in the future, the calculation of a whole complex of analyses from the results of a few relatively simple analyses within the range of total solids experienced.

Aeration of slurry and operation of the treatment plant met with some technical difficulties in the early stages, but after four months the plant was commissioned

and an experimental program initiated.

The effects of treatment time, temperature and dissolved oxygen concentration on the quality of the treated slurry were determined and the characteristics of the treated slurries were compared with the predicted values from the model and computer program. Differences between the observed experimental results and the predicted values are discussed and possible explanations offered. Some changes in the model would improve the accuracy of the predictions although variations in some of the experimental data may be due to the inability to control operating conditions in the large scale reactor. Incomplete mixing in particular caused sedimentation, with resultant anoxic or anaerobic zones.

The highest quality effluent slurry in terms of pollution potential was produced by treatment at mesophilic temperatures during which nitrification occurred. In general, the performance equalled or exceeded that predicted by the model except for the BOD_5 of the supernatant effluent.

Shorter treatment times and low dissolved oxygen concentrations prevented nitrification and the results of treatment were similar to those predicted except again for the BOD_5 of the supernatant.

Thermophilic treatments at $50^{o}C$ and $55^{o}C$ were compared. Treatment at $55^{o}C$ was much less effective than at $50^{o}C$ and resulted in treated slurry characteristics

which were much higher than those predicted by the model. At 50°C the results were closer to those predicted but not as close as those obtained at mesophilic temperatures.

The model equations derived from laboratory results at mesophilic temperatures predicted values closer to the observed values in the experiments at 55°C than did those calculated from the 50°C equations. The experimental values all fell within the range of 10% difference from predicted values.

The composition of the slurry was not standardised in a majority of the experiments and the effect of variations of the input slurry on the characteristics of the treated slurry are discussed. The effects were minimised at long treatment times during which biodegradation smoothed out variations in the concentrations of residual parameters which followed increasing or decreasing trends.

The quantity of heat extracted to control the operating temperatures of treatment decreased as the temperature of treatment increased. Thus, the electrical energy input was 52% of the extracted heat during mesophilic treatment and 240% of the extracted heat at 55°C. Total heat losses also rose from 53% of the extracted heat at mesophilic temperature to 592% during treatment at 55°C. Observed heat losses in the effluent were in excellent agreement with those predicted by

the Farm Waste Management Program, but the surface losses were up to 227% underestimated by the model and losses in the exhaust gas were overestimated by up to 63%. Metabolic heat varied from 1.9 to 4.5 kWh/kgO_2.

The oxygen efficiency of the aerator was measured at different depths of tap water in the reactor and varied from 0.34 to 1.14kgO_2/kWh.

3. INTRODUCTION

Animal excreta and urine were traditionally collected as farm yard manure. The bedding, mainly straw, wood shavings, peat etc. provided some biodegradable carbon and allowed, due to its structure, penetration of air into the stored farm yard manure (FYM). Natural composting occurred, decreasing malodours and enhancing the handling qualities of the manure.

After the second world war, the intensification of livestock started and waste management had to change towards a more economic use of labour. The use of bedding was more and more restricted and finally the excreta were collected, usually diluted with wash water or spillage, as a slurry.

The steep rise in animal numbers in the UK after 1950 (Kornberg, 1979) put in imbalance the area of farm land available for slurry application and the quantity of slurry available (Gasser, 1984). This is shown in Table 1.

Table 1. Holdings in Britain with more animals than available land for the utilisation of effluent (After Gasser, 1984).

Animal	Type of farm	No. of holdings	% of total stock
Dairy cows	Grass and cereals	219	0.2
Beef cattle	Grass and cereals	258	0.4
Layers	Grass and cereals	1,738	42.7
Broilers	Grass and cereals	713	83.0
All pigs	Mixed arable	3,505	24.2

If application rates of slurry were controlled by optimum utilisation of applied nitrogen, potassium and phosphorus, then countries such as the Netherlands, Denmark and Belgium possess insufficient available land for the amount of slurry produced (Williams, 1988).

Overapplication of basic nutrients N, P, and K is not the only form of pollution originating from slurries. Farming and farm neighbouring communities suffer from malodour emanated from slurries stored or spread on the fields. That this "country smell" is not always appreciated is reflected by the number of complaints registered by local authorities in Scotland, England and Wales (Tables 2 and 3). Unlike in Scotland, where in the Public Health (Scotland) Act 1897 (which is now being revised), the odour from livestock wastes cannot give rise to a public prosecution, in England and Wales the Environmental Protection Act 1990 gives the Magistrates' Court the power of implementing fines of up to £ 20,000 for persistent pollution of air by smells arising from any premises or activities.

Table 2. Number of public complaints of odours from livestock farming in Scotland, 1983-1985 (Hissett,1991).

Source	1983/84	1984/85
Livestock buildings	6	10
Manure spreading - Cattle	11	9
- Pig	21	14
- Poultry	9	6
Manure storage	9	12
Silage	7	2
Feed preparation	3	1

Table 3. Number of public complaints for odours from livestock farming in England and Wales, 1986-9 (Hissett, 1991).

Cause	1986/7	1987/8	1988/9
Cattle - Buildings	28	32	29
Slurry/manure storage	75	70	70
Slurry/manure spreading	99	120	130
Pigs - Buildings	115	116	136
Slurry/manure storage	119	119	119
Slurry/manure spreading	292	348	314
Feed products	54	142	24
Poultry - Buildings	164	133	170
Slurry/manure storage	59	46	51
Slurry/manure spreading	118	84	131
Feed production	18	5	1

The impact on the environment from malodour pollution, always unaesthetic or even offensive, is minute compared to the damage related to the penetration of wastes into watercourses. The number of these incidents, recorded by River Purification Boards in Scotland and Water Authorities in England and Wales (Table 4 and 5) do not sufficiently stress the importance of the required change in animal wastes management.

Table 4. Water pollution incidents arising from livestock farming in Scotland 1991, 1992 (Virtue, 1993).

Source	1991	1992
Cattle housing and yard	30	31
Piggery and yard	5	13
Slurry store	41	39
Dungstead	15	39
Dairy premises	34	16
Silage effluent	270	138

Table 5. Water pollution incidents arising from livestock farming in England and Wales 1988, 1989 (NRA 1990).

Source	1988	1989
Cattle		
Slurry stores	801	589
Solid manure stores	194	121
Yard/parlour washings	836	578
Treatment system failure	96	65
Land run-off	345	380
Pigs		
Slurry stores	231	169
Yard washings	59	64
Treatment system failure	20	19
Land run-off	89	92
Poultry	64	70
Silage liquor	815	245
Sheep dip	18	13

The recommended slurry application rates (Scottish and English Codes of Good Agricultural Practice, 1991) should not be higher than $50m^3$/ha at one time and are designed to safeguard water courses from pollution caused by slurry utilisation or disposal in relation to plant nutrients. However these rates cannot prevent the spread of offensive odour or decrease the biochemical oxygen demand (BOD) of the liquid phase of slurries which can still penetrate through the soil into a watercourse (Evans *et al.*, 1979a).

The most effective method for decreasing the pollution potential of livestock slurry is aerobic treatment.

3.1. Treatment systems

Aerobic methods used for treating effluents polluted with organic matter, typically municipal sewages, cannot be effectively applied to the treatment of concentrated slurries without some adaptation.

The treatment of sewage by activated sludge, biofilters or rotating contactors is based on highly diluted wastes. Attempts to dilute slurry and to apply the above methods have been made but proved to be impractical due to the huge increase in volume compared with the original waste and to the production of treated effluents which could not be safely discharged to water courses (Pontin and Baxter, 1968).

Aerobic treatment of organic wastes, typically municipal sewage (Chudoba *et al.*, 1991; Novotny (Ed.), 1989; Horan, 1986) was used for the treatment of livestock slurries mainly in oxidation ditches originally (Day *et al.*, 1975; Robertson, 1977; Loehr 1984). Laboratory experiments with pig wastes were confined to the use of diluted excreta in batch systems (Irgens and Day, 1966), semicontinuous (Converse *et al.*, 1975) or continuous aeration of the liquid fraction of separated slurries (Robinson *et al.*, 1971). To overcome the difficulties of dosing the fibrous whole slurries containing up to 2% of total suspended solids, an apparatus was designed by Owens and Evans (1972).

Irgens and Day (1966) experimented with settled piggery slurry further diluted to an average chemical

oxygen demand (COD) and a 5-day biochemical oxygen demand (BOD_5) of 4.74g/l and 2.25g/l respectively.

Converse *et al.* (1975) used pig slurry diluted 2.5 to 5 times in 15 litre fermenters. After a week of batch aeration, the offensive odour disappeared and 95% of BOD_5 was removed. Further aeration up to 40 days showed only small changes. In another experiment, a semicontinuous treatment (feeding twice a week and later once daily) was found to be preferable to the batch system giving a nitrified effluent with a supernatant BOD_5 of 25mg/l.

Systems for treating large volumes of diluted slurries were developed to their near maximum potential for large piggery units in Poland (Oleszkiewicz and Kozianski, 1981; Kutera and Kutera 1981), Czechoslovakia (Podstavek, 1986, 1988) and USSR (Gray *et al.*, 1991). The piggeries, sited too far from the land available for the practical application and disposal of slurry, produce large volumes of diluted wastes ranging from 200 to 1000m^3 daily. Because of these difficulties, treatment systems were designed with the objective of achieving the quality of final effluent suitable for disposal to the water recipient. These systems are known under the names Vidus (Hungarian system), Emona (Yugoslavian), Gi-Gi (Italian) and Wostochnyi (USSR). They are complicated plants with primary screening, lagooning, preaeration, flocculation and settling

followed by activated sludge treatment and, in some cases, disinfection of the final effluent. These systems produce excessive volumes of sludge, up to 50% of the waste water volume, there are high running costs and unstable performance, mainly of the activated sludge stage. Though the well-managed plants can produce a final liquid effluent of 500mgCOD/l and 50mgBOD_5/l, sludge disposal remains a major problem and the high costs of electrical energy and chemicals make these systems uneconomical.

Unlike these uneconomical systems, the treatment of piggery waste in Holland is economical, although as complex as the plants in central Europe and Russia. The major manufactured systems are Promes and MeMon each processing approximately 5Mm^3 of slurry annually. By 1984, construction of other plants with a capacity of up to 6Mm^3 per year is planned. These processes include screening, anaerobic digestion of slurry (10% dry matter) with a consequent centrifugation of the digested slurry. The fugate is aerobically treated to oxidise nitrogen and then concentrated to 25% dry matter. The condensate is then safely discharged to the water course and the cake from the centrifugation and the concentrate is used as fertiliser.

A comparatively recent development in treating diluted piggery slurry uses a "sequencing batch reactor" (SBR) (Wong and Choi 1989; Lo *et al.*, 1990). This

method is based on an activated sludge system. Reactors work in a cycle which usually lasts from 8 to 24 hours and consists of a sequence of filling, reacting (aeration), settling and withdrawal of supernatant. Nitrification during aeration and denitrification during the anoxic period of settling decreases considerably the total nitrogen and the effluent supernatant has a BOD_5 of less than 50mg/l.

A complete slurry treatment process for the slurry from about 400 pigs (Osborne *et al.*, 1976; Osborne and Mundy, 1977) included separation, high rate biological filtration and sludge dewatering using aluminium chlorohydrate and flocculants. The system produced a liquid effluent of 30% of the original volume with very little smell and BOD and COD reduced by 71.4% and 82.6% respectively, in addition to the separated and flocculated sludges with minimal dilution.

Slurries with minimal dilution by spillages or excess of drinking water are not suitable for methods such as the activated sludge process, biofiltration, rotating biological contactors which are designed for low solid content wastes. The complex systems used in Europe and run as a commercial enterprise cannot be used on farms where, especially on smaller farms, it would mean a very substantial increase of technology and add to the farm complexity. There would be a further requirement for highly-skilled personnel. Therefore,

simplified systems based on sludge stabilisation methods with a relatively low requirement of technical knowledge for operation were investigated.

A primary requirement was the determination of the major physical and chemical characteristics of slurries. These were largely dependent on the animal species and their food intake and had been described by Owens *et al.* (1973); O'Callaghan *et al.* (1971); Evans *et al.* (1978, 1980) and are described in detail in Chapter 4.1.

3.2. Carbonaceous compounds reduction

Hissett *et al.* (1975) assessed the biodegradability of various components of the wastes. A respirometric technique was used and showed that the rate of aerobic degradation of coarse and fine particles, colloids and solutes in fattening pig and laying hen excreta was inversely proportional to the particle size.

Laboratory scale experiments entailing batch and semicontinuous treatments of settled and diluted piggery slurry with BOD_5 of 2.25g/l were conducted by Irgens and Day (1966). The results suggested that preference should be given to semicontinuous treatment since it produced nitrified effluent of better quality with BOD_5 of 25mg/l.

Batch culture experiments (Hissett *et al.*, 1982) with piggery slurry treated at temperatures from 5 to 50^{o}C showed that the oxygen demand peaked in the first 6 to 24 hours of aeration. This indicated that the oxygen

supply would be difficult to control in order to satisfy the oxygen demand of microorganisms at any one time. A continuous culture system would be controlled more easily since the oxygen demand fluctuation is minimal and a culture of microorganisms well adapted to the concentration of substrate and DO is developed.

A laboratory apparatus initially designed for dosing whole slurry (Owens and Evans 1972) had subsequently undergone continuous development and modifications. Aerobic reactors of 1 to 15l were fed at 5 to 15 minutes intervals (to approximate to a continuous culture system) with either pig, cattle or poultry slurry of about 29g/l of total solids (TS). This system, where treatment time, temperature, DO concentration and redox potential were all controlled, worked on the principle of a chemostat (Owens *et al.*, 1973).

Results of experiments with pig slurry treated at residence times from 0.5 to 8 days and temperatures from 15 to 50^{o}C in steps of 5^{o}C with DO in the reactor maintained in excess of 20 percent, were expressed in the form of equations (Evans *et al.*, 1979, 1983). These equations described the effect of treatment time on a selection of chemical and biochemical characteristics of treated slurries, in particular Total Solids (TS), Total Suspended Solids (TSS), Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD). The effect of

treatment on degradation of carbonaceous matter showed a marked increase across the measured temperature range of 15 to 50°C, although it was recognised that for the description of the changes in TS, TSS and COD only three sets of equations were needed. Within the mesophilic range 25 to 45°C there was a considerable overlap of data thus enabling correlation in one set of equations. Another two sets of equations were calculated for temperatures 15 and 50°C.

In the thermophilic range at 50°C there was increased cellulolytic activity resulting in greater reductions in COD. These equations are listed below in Fig. 1.

Fig. 1. Equations for calculations of residual TS, TSS, COD and BOD_5 (g/l) of treated piggery slurry. R is the mean treatment time (day) and TS_f, TSS_f, COD_f and BOD_f are concentrations of fresh piggery slurry.

Treatment temperature 15°C

$$TS = [0.318/(1+0.14R) + 0.707]\ TS_f \quad (1)$$
$$TSS = [0.542/(1+0.14R) + 0.526]\ TSS_f \quad (2)$$
$$COD = [0.547/(1+0.14R) + 0.379]\ COD_f \quad (3)$$
$$BOD_5 = 2.969/R + 0.202BOD_f \quad (4)$$

Treatment temperature 25 - 45°C

$$TS = [0.262/(1+0.4R) + 0.744]\ TS_f \quad (5)$$
$$TSS = [0.282/(1+0.4R) + 0.696]\ TSS_f \quad (6)$$
$$COD = [0.333/(1+0.4R) + 0.535]\ COD_f \quad (7)$$
$$BOD_5 = 1.568/R + 0.152BOD_f \quad (8)$$

Treatment temperature 50°C

$$TS = [0.450/(1+0.7R) + 0.579]\ TS_f \quad (9)$$
$$TSS = [0.405/(1+0.7R) + 0.563]\ TSS_f \quad (10)$$
$$COD = [0.429/(1+0.7R) + 0.445]\ COD_f \quad (11)$$
$$BOD_5 = 1.567/R + 0.152BOD_f \quad (12)$$

The BOD_5 of the residual supernatant of the treated slurry (BOD_{5s}) was described by a single equation for temperatures from 15 to 45°C as:

$$BOD_{5s} = 0.110/R \qquad (13)$$

and for 50°C as:

$$BOD_{5s} = 0.0427/R + 0.007BOD_f \qquad (14)$$

Peak respiration rates of the more readily degradable components were recorded between 35°C and 40°C and decreased at 50°C. This decrease was attributed by Hissett *et al.* (1982) to the presence of a less diverse microbial population which was unable to degrade those organic constituents degraded at lower (mesophilic) temperatures. This was further confirmed by Evans *et al.* (1983), who observed a higher residual BOD of the supernatant in thermophilically-treated piggery slurry.

Provided the dissolved oxygen concentration in the slurry is maintained above 1% of air saturation the oxygen flux to the microflora is sufficient to maintain aerobic activity and the breakdown of carbonaceous compounds is mainly controlled by residence time and reactor temperature (Williams *et al.*, 1989). However below this concentration, which was measured indirectly using redox potential from 0 to -500mV E_{cal}, the BOD_{5s} and TOA (Total Organic Acids) exponentially increased

from values of around 50mg/l to 2g/l and from 100mg/l to 2g/l respectively. The BOD_5 increased by up to 8g/l over the value expected in slurry treated at DO concentrations over 1% of saturation.

These differences clearly indicate the requirement for the control of DO concentration if a treatment system is to be efficient and maximum treatment effects are to be realised.

Equations for the determination of COD and BOD_{5s} are of extreme importance. A calculation of residual COD enables the accurate assessment of the oxygen demand for treatment and thus the required size of the aerator. The value of residual BOD_{5s} indicates the potential of the slurry for polluting drainage water and hence water courses.

The first indication that these laboratory results could be used for prediction of treated slurry characteristics on a larger scale was reported by Sneath (1978). Experiments with a continuous culture treatment of separated piggery slurry took place in an uninsulated reactor of $19m^3$ volume aerated with a plunging jet aerator. At treatment temperatures up to 37^oC the reductions of COD and TSS were similar or larger than those predicted by the laboratory data at 15^oC. At that time the predictive values were known only for 15^oC, therefore the lower final values of COD and TSS were attributed to the higher operating temperature. This

increase of biodegradation with increased temperature was later documented by Evans *et al.* (1983). The predictive equations were further tested on a commercial farm with 11000 pigs fed on a whey diet (Evans *et al.*, 1979), where the slurry was causing malodour and pollution of a stream which was the recipient of the drainage water. After installation of a two-stage aeration unit, designed on the basis of COD reduction, the malodour was eliminated and the BOD_{5s} was reduced by 98%.

Williams *et al.* (1986, 1989) reported the results of aerobic treatment of separated piggery slurry in a pilot-scale reactor of 550 litres. The treatments with 1 to 4 days residence time, high and low DO concentration and temperatures around 33 and 50°C showed that the treated slurry characteristics were in a good agreement with equations from Evans *et al.* (1983) for prediction of TS, COD and BOD_5. However, when the DO concentration during the treatment was undetectable with a DO probe but was controlled by a redox potential probe around -200mvE_{cal} the constants in the BOD_5 equations at 25-45°C and 50°C had to be changed from 1.57 and 0.15 to 1.3 and 0.23 respectively to fit the experimental data.

Sneath *et al.* (1990) proved the validity of the equations of Evans *et al.*(1979) for TS and COD. But once more only separated piggery slurry was used and continuously aerated in an uninsulated pilot-scale

reactor ($18m^3$) with a working volume of $12.6m^3$ at residence times between 1.1 and 4.1 days and temperatures of 21 to 27.4°C.

Whole piggery slurry containing TS up to 52.5g/l was aerated continuously in an insulated reactor ($24m^3$) at around 36°C with treatment time from 8.6 to 11.7 days (Svoboda and Evans, 1987; Svoboda and Fallowfield, 1989). The high DO concentration promoted nitrification and the TS, TSS, COD and BOD_5 of effluents from the four experiments was in a very good agreement with the predictive equations described above. Only BOD_{5s} showed inferior quality to that predicted varying from 0.04 to 0.12 instead of being 0.01mg/l.

3.3. Odour Control

Thacker & Evans (1985) showed a relationship between the rapidly measurable total organic acid (TOA) content of the slurry supernatant and odour offensiveness. Aerobic treatment of slurries reduced odour to acceptable levels at all residence times in excess of one day. A higher residual supernatant BOD remained after thermophilic treatment. At low dissolved oxygen concentrations (< 1%) there was a linear relationship between residual odour and redox potential (Ginnivan, 1983; Evans *et al.*, 1986a). Williams *et al.* (1989) investigated the minimum aeration requirements to remove offensive odours from slurry. At operational temperatures between 28°C and 35°C they concluded that there was no requirement to

maintain detectable dissolved oxygen in the reactor mixed liquor provided the redox potential was at or above - 220 mV E_{cal} at residence times of 1 to 4.8 days. Failure to remove all fermentable substrates may lead to the regeneration of odours during storage of treated slurry. Evans *et al.* (1986a) considered a treatment time in excess of 7 days, at a redox potential higher than -200 mV E_{cal}, necessary to avoid the rapid regeneration of odours upon storage.

Williams (1981) investigated the effect on odour offensiveness and changes in the concentration of chemicals responsible for slurry odour. He described the relationship between odour offensiveness of piggery slurry and BOD_{5s}, supernatant volatile fatty acids (VFA) and total organic acids (TOA) respectively in equations which were later upgraded by Thacker and Evans (1985). The relationship between odour offensiveness and BOD_{5s} was expressed in the equation:

$$\text{Odour offensiveness} = 1.453 \log BOD_{5s} + 2.32 \qquad (15)$$

where the odour offensiveness was rated on a proportional scale 0 to 5 as 0=Inoffensive, 1=Very faintly offensive, 2=Faintly offensive, 3=Definitely offensive, 4=Strongly offensive and 5=Very strongly offensive.

A highly significant relationship was found between total organic acids concentration (TOA) and odour offensiveness expressed in the equation:

Odour offensiveness = 2.378 Log TOA + 2.327 (16)

As a result the parameters BOD_{5s} and TOA can be used as indicators for the assessment of slurry odour without using an odour panel.

It can therefore be calculated that a two-day continuous aerobic treatment would satisfy BOD so that the treated slurry would have an odour offensiveness rating lower than one on a scale of five, that is "very faintly offensive" (Evans and Smith, 1986).

Although the offensiveness of such slurry is low, the organic content (BOD) is high. Anaerobic conditions, which develop in a matter of hours, cause a regeneration of odour and, depending on the treatment time and TS concentration, the offensive odour returns in a matter of weeks or months (Williams and Evans, 1981; Williams, 1984; Sneath, 1988; Williams *et.al.*, 1984, 1981; Sneath *et.al.*, 1991).

The effective control of malodours was demonstrated by Williams (1981). The maximum odour offensiveness of 1.9 was assessed on fields sprayed with aerated piggery slurry, whereas the spraying of untreated slurry resulted in an odour offensiveness rating of 2.6.

Pain *et al.* (1990a,b) documented the substantially lower odour threshold values of air samples collected from above the fields being treated with aerated and anaerobicaly digested slurry. The trials also showed that treatment controlled by redox potential was less

effective (106.2 units) than that with a detectable concentration of DO (19.6 units). The untreated slurry threshold value was 201.2 units.

3.4. Control of nitrogen

The nitrogen content of fresh piggery slurry is almost equally divided into the organic and inorganic (ammoniacal) fractions (Evans *et al.*, 1979, 1983) although variations with organic nitrogen concentration up to twice that of ammonia were observed (Williams and Evans, 1981; Smith and Evans, 1982). Ammoniacal nitrogen increases during anaerobic storage due to the ammonification of the organic nitrogen, most of which is urea. Williams and Evans (1981) observed an increase from an original concentration of 13% to 56%. Although this ammonia nitrogen is directly available to plants, approximately 10% was found to be volatilised in the first 7 days after land application (Pain *et al.*, 1990b) and thus contributed to atmospheric pollution.

Aerobic treatment can effectively control the nature and the quantity of nitrogen. Depending upon operating conditions, nitrogen can be conserved as ammoniacal nitrogen, lost via ammonia stripping, oxidised to nitrate and conserved, or lost via denitrification (Evans *et al.*, 1986b; Bortone and Piccinini, 1991) (Fig.2).

At low aeration rates Evans *et al.* (1986b) found that when DO was not detectable and therefore was

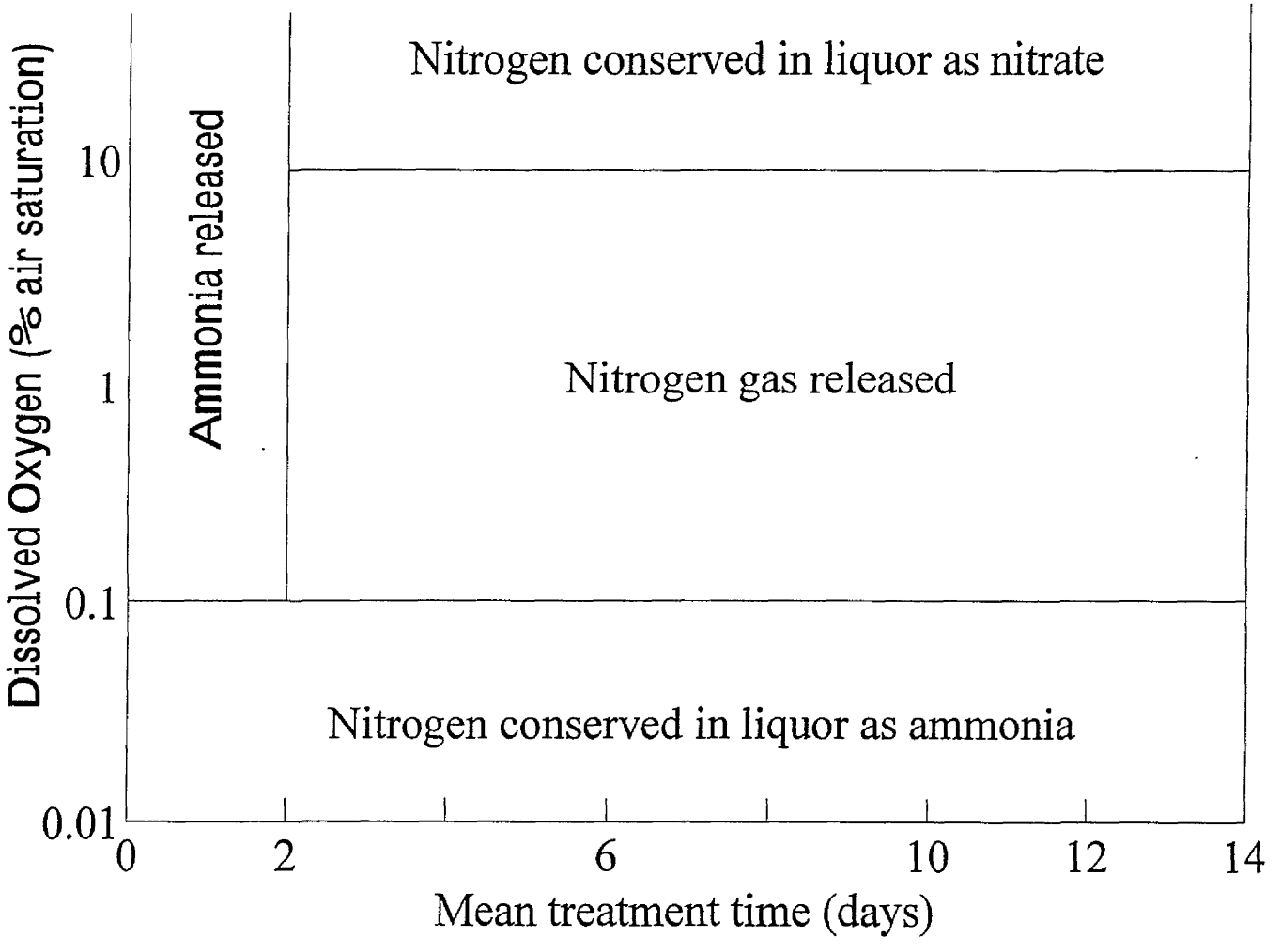

Fig.2. Effect of DO and treatment time on nitrogen speciation in treated slurry.

controlled by the redox potential, the nitrogen remained in the forms of organic nitrogen and ammonia nitrogen for all studied treatment times (0.5 to 15 days) and temperatures (15 to 50^{o}C). Rather a high proportion of organic nitrogen (up to 50%) was converted to ammonia. Nitrogen lost by ammonia stripping accounted for up to 39% of total nitrogen at 50^{o} while at 15^{o}C only 19% was lost. Similarly Williams *et al.* (1989) and Sneath *et al.* (1990) observed small losses of 4 to 24% and 0 to 21% respectively at low DO concentration and mesophilic temperature.

At aeration rates when DO can be detected, that is higher than approximately 1% of saturation, nitrification and denitrification occurred (Evans *et al.*, 1986b).

Nitrification of ammonia nitrogen can be described by a two step reaction as follows (Sharma and Ahlert, 1977):

1. $NH_4^+ + 1.5\ O_2 \rightarrow 2H^+ + H_2O + NO_2^- + 58$ to 84kcal
2. $NO_2 + 0.5O_2 \rightarrow NO_3 +$ 15.4 to 20.9kcal

In the first step the ammoniacal nitrogen is oxidised mostly by bacteria *Nitrosomonas, Nitrosococcus, Nitrospira* and *Nitrosocystis* (Painter, 1970, 1986; Focht and Verstraete, 1977; Chudoba *et al.*, 1991). In the second step the nitrite is oxidised to nitrate by *Nitrobacter* and *Nitrocystis*.

The nitrification rate in concentrated livestock wastes is affected by the following factors: DO concentration, pH value, temperature and the duration of aeration in a chemostat or continuous culture system.

3.4.1. Dissolved oxygen (DO) concentration

In completely mixed laboratory reactors, simultaneous nitrification and denitrification occurred and up to 85% of convertible nitrogen was lost as dinitrogen gas when the aeration rate was low (DO 1-15% of saturation) and with treatment times more than 3 days at 15^{o}C or 2 days at 25-35^{o}C. With DO levels higher than 15% of saturation and treatment times in excess of 3 days, ammoniacal convertible nitrogen was oxidised to nitrate and 90-100% of the total nitrogen was conserved in the treated slurry (Smith and Evans, 1982). High losses of nitrogen were also reported by Evans *et al.*, (1986b), Williams *et al.*, (1989) and Sneath *et al.*, (1990).

3.4.2. pH value

The extent of nitrogen oxidation is highly dependent on the pH value. Knowles *et al.*, (1965) described the dependence of the growth rate (m_n) of *Nitrosomonas sp.* on the pH value as follows:

$$m_n=(m_n)_{max}[1-0.833\ ^{(7.2-pH)}]$$

From the oxidation of one gram of NH_4^+-N, 0.143g of

hydrogen ions are released (Wong-Chong and Loehr, 1975; Kos, 1988; Chudoba *et al.*, 1991). This affects the acidity of treated slurry and when the pH value reaches 5.5 the nitrification rate is effectively nil (Smith and Evans, 1982). The inhibition is caused by undissociated nitrous acid (HNO_2), (Prakasam and Loehr, 1972; Anthonisen *et al.*, 1976; Alleman, 1985), the concentration of which increases with decreasing pH value and at concentrations higher than 0.3mg/l, oxidation of nitrite to nitrate effectively stops and nitrite starts accumulating in the system.

On the other side of the pH scale, when high concentrations of ammonia in the incoming feed increase the pH value so that free ammonia is present, even in concentrations as low as 0.02 mgNH_3-N/l, nitrification to nitrate ceases and an accumulation of nitrite occurs (Prakasam and Loehr, 1972).

Alleman (1985) recommended an optimum pH between 7.2 and 8.2, although some nitrification was observed at the extreme pH values of 5 and 11. A maximum reaction rate was observed at pH 7.5 (Wong-Chong and Loehr, 1975) and at pH 7.4 (Jones and Paskins, 1982).

Smith and Evans (1982) observed a fluctuation of pH during continuous aerobic treatment. A decrease of pH to 5.5 effectively stopped the nitrification but the incoming alkaline slurry caused the pH to rise and the nitrifying population regained its activity. The

continuous cycling in non-buffered systems reduced the amount of ammonia oxidised, which varied from 40% at 15°C and 40°C to 60% at 25°C (Evans *et al.*, 1986b). Similarly Williams *et al.*(1989) observed nitrification of separated piggery slurry aerated in pilot scale reactors and described the accumulation of "nitrified oxygen" (NO_2-O and NO_3-O) by a logistic growth curve.

$$\text{Nitrif O} = -0.075+\{6.10/(1+e^{[-1.40(R-3.39)]}\} \quad (kg/m^3)$$

3.4.3. Temperature

Nitrifying bacteria are more sensitive to temperature than heterotrophic organisms although they are active within a wide range of temperature from 5 to 35°C (Wong-Chong and Loehr, 1975). Their activity increases with temperature, obeying Arhenius' Law, with the optimum temperature for pure cultures between 28 and 32°C (Painter, 1970).

3.4.4. Denitrification

During denitrification, the oxidised nitrogen in nitrite and nitrate is reduced to dinitrogen gas N_2 or nitrous oxide N_2O according to the following

$$NO_3^- \text{ <---> } NO_2^- \text{ ---> } N_2O \text{ ---> } N_2$$

This dissimilatory metabolism is attributed to a relatively wide range of facultatively anaerobic bacteria, e.g. *Pseudomonas spp.*, *Micrococcus spp.*, *Denitrobacillus spp.* and *Achromobacter spp.*. (Painter

1970). In the dissimilative (denitrification) process the organisms use the nitrate and nitrite nitrogen as an electron acceptor instead of molecular oxygen, and N_2O and N_2 are produced. The assimilation process uses oxidised nitrogen as a source of nitrogen for cell synthesis.

The denitrification process uses hydrogen ions so that in simultaneous nitrification and denitrification the hydrogen ions generated during nitrification are neutralised. A near neutral pH which is optimum for both processes was reached in experimental systems with a loss of up to 70% of convertible nitrogen (Smith and Evans, 1982).

The heterotrophic bacteria involved in denitrification are less sensitive to pH than the autotrophs in nitrification. The optimal pH is in the range 6 to 9 compared with a range of 7.2-8.2 for nitrification and the temperature can reach the thermophilic range (Chudoba *et al.*, 1991). A carbon source is required for denitrification and the reaction rates are much faster with an exogenous source than with an endogenous source (Chudoba *et al.*, 1991). In wastes such as livestock slurries, unless the waste is extremely diluted or it is aerobically-treated separated slurry (Williams *et.al.* 1989), the available carbon is always sufficient for denitrification. This can be exploited in the storage of treated, nitrified slurries

in order to prevent regeneration of odour (Williams *et.al.*, 1989).

Although high accumulations of oxidised nitrogen and minimal losses of total nitrogen losses were observed in the laboratory reactors (Evans *et al.*, 1986b) at DO concentrations higher than 15% of saturation, the nitrogen balance in a large reactor showed a different pattern. Despite the high average DO concentration levels of 17 to 37% of saturation with a maximum of 74% in the farm scale reactor, high nitrogen losses of 38 to 61% of the total incoming nitrogen could not be prevented (Svoboda and Evans, 1987; Svoboda and Fallowfield, 1989). One of the reasons for these losses was the fluctuation of DO levels after feeding, when the DO level varied from 0 to 8% thereby promoting a simultaneous denitrification. Other factors contributing to denitrification, were depletion of oxygen in the centre of larger flocs (Smith and Evans, 1982; Rittmann and Langeland, 1985) and in improperly mixed zones in the reactor, where settled solids accumulated. The formation of these zones would depend upon such factors as the size of the floc, the rate of surface respiration of the floc cells scavenging oxygen and the dissolved oxygen tension.

Denitrification also affects oxygen availability for COD reduction since up to 62% of the nitrate oxygen may be recycled for heterotrophic respiration

(Johnstone, 1984). The control of nitrogen speciation following treatment has environmental implications. An advantage of nitrification is that if the treated slurry has to be stored between treatment and land spreading the nitrate acts as an oxygen donor in anaerobic conditions and prevents the reformation of odours prior to land spreading (Evans *et al.*, 1986a).

The occurrence of denitrification in controlled treatment systems is highly significant for aerobic reactor operation since nitrogen can be lost to the atmosphere as harmless nitrogen gas, thus reducing the requirement for land where application rates are subject to nitrogen limitation.

3.4.5. Energy from nitrification and denitrification

The nitrifying reactions 1 and 2 (Chapter 3.4.) are believed to yield energy for autotrophic bacteria dominated by *Nitrosomonas* (reaction 1) and *Nitrobacter* (reaction 2). Nitrifying bacteria grow more slowly than heterotrophic bacteria due to their high energy requirement for growth. Approximately 80% of their energy requirement is for carbon assimilation (Horan 1990, Wood 1986). The overall reaction of the oxidation of ammonia and biomass growth is then expressed as:

$$NH_4^+ + 1.83O_2 + 1.98HCO_3^- \longrightarrow$$
$$\longrightarrow 0.021C_5H_7NO_2 + 0.98NO_3^- + 1.041H_2O + 1.88H_2CO_3$$

From reactions 1 and 2 the stoichiometric quantities of

oxygen for oxidising 1mg of ammonia nitrogen are 3.43mg and 1.14mg of O_2 respectively. Total oxygen demand is then $4.57mgO_2/mgNH_3$-N. This may be less (4.2mg) when calculated from the above equation for the overall reaction. Because of the uncertainty of the composition of the biomass the value of $4.57mgO_2$ is normally used. The free energy released from reactions 1 and 2 is between 72.4 and 104.9 kcal. The energy utilisation efficiency from nitrification for carbon assimilation is between 11 and 34% (Laudelaut *et al.*, 1968; Kiesow, 1972). The average amount of heat released from one kilogram of oxygen required for nitrification was calculated as 1.2 kWh (Evans *et al.*, 1982).

The reduction of nitrate, by denitrification, to nitrogen gas releases 62.5% of oxygen required for nitrification (Johnstone, 1984) as can be seen from the following equations.

$4NH_4^+ + 8O_2 \longrightarrow 4NO_3^- + 8H^+ + 4H_2O$ - nitrification

$4NO_3^- + 4H^+ \longrightarrow 2N_2 + 5O_2 + 2H_2O$ - denitrification

Since heterotrophic nitrate respiration is as efficient as oxygen respiration (McClintock *et al.*, 1988), only 37.5% of the energy used for aeration is wasted when nitrification and denitrification occurs during the aerobic treatment of wastes.

3.5. Control of pathogens

Aerobic treatment, particularly at elevated temperatures, has a detrimental effect on the survival of pathogenic organisms. The rapid death rate is affected by grazing, high competitiveness and activity of aerobic microorganisms, high temperature and extreme pH values accompanying free ammonia or undissociated nitrous acid.

Jones (1976) concluded that a 90% reduction in numbers of *Salmonella* occurs within 2 to 4 weeks in anaerobically-stored cattle slurry and in 2 days if the slurry is aerated.

Kabrick and Jewel (1982) found that *Salmonella* numbers were reduced to undetectable levels (at least 3x decimal reduction) in an aerobic reactor at 35^{o}C in 24 hours.

Aeration of pig and cattle slurry decreased substantially the time required for the decimal reduction of 5 strains of *Salmonella* (Munch *et al.*, 1987). A decimal reduction occurred in 0.3 to 1.0 week at 18 to 20^{o}C and 1.0 to 2.5 weeks at 6 to 9^{o}C in aerated slurry and in 1.0 to 3.0 weeks at 18 to 20^{o}C and 3.0 to 8.0 weeks at 6 to 9^{o}C in slurry which was not aerated.

Thermophilic aerobic treatment is an effective method for control of bacterial and viral pathogens as well as the eggs of parasites. Batch experiments

with pig slurry were carried out in a 550m^3 insulated reactor, by Bohm (1984). Infectivity of foot and mouth disease virus was completely lost 24 to 44 hours after commencement of the aeration experiment. To reach the final temperature of 50^oC from about 15^oC took about 40 hours. To inactivate the viruses of pseudorabies and swine vesicular disease Bohm (1984) recommends retention times of 50 and 48 hours respectively, during which times temperatures of 40^oC should be reached.

Hojovec (1990) reported a decrease in the total bacterial count (TBC) of piggery slurry treated by aerobic-thermophilic stabilisation. Slurry was aerated in laboratory, pilot-scale and full-scale plants at average temperatures of 60^oC for an average of 8 to 10 days. The TBC decreased from an average of 10^{11} to 10^5ml and the coliform count was reduced from 10^6 to 10^3ml to eventually nil after 24 hours of aeration.

Enteroviruses and rotaviruses can both survive for periods of several weeks or months in slurry stored at ambient temperature, but show greater death rates at elevated temperatures and when the slurry is aerated. Strauch (1986) considered aerobic-thermophilic stabilisation as a disinfection process. Sludge is virtually disinfected in a two-stage, batch and continuous treatment system with a minimum treatment time of 5 days and a treatment temperature between 55 and 60^oC.

Oechsner and Ruprich (1989) reported similar results from a two-stage, batch and continuous treatment of piggery slurry. In the second reactor, in which the temperature reached 68^{o}C, the faecal streptoccoci were eliminated in 2 days, while in the first reactor with a maximum temperature of 55^{o}C, four days were required. During continuous treatment, with 3 days residence time in each reactor, the faecal streptoccoci were always present in the first reactor, being introduced with each daily fresh slurry input, whereas they were not present in the second reactor.

3.6. Economics of aeration

Aerobic treatment of livestock slurries, a means of protecting the environment from pollution from agricultural wastes, is a process requiring capital and running costs. It is therefore usually chosen as a last option in instances where storage and spreading of slurry are causing serious pollution of air or water, which is likely to give rise to prosecution.

The cost of treating slurry is influenced by many factors which are specific to each farm and system adopted, and include number of animals, slurry dilution, pretreatment of slurry and aerator efficiency (Cumby, 1987a,b,c). The least expensive treatment would be designed for odour control which can be achieved in short treatment times (Thacker and Evans, 1985) whereas the most costly would be long-term treatment with

nitrification (Evans *et al.*, 1982; Williams *et al.*, 1989).

The number of pigs affects the overall cost of treatment per pig. Sneath (1988) found that an increase of herd size from 2000 to 8000 decreases the typical cost per pig of slurry processing by 30 to 50%. A similar but slightly lower decrease of 20% was reported by Williams *et al.* (1989).

Costs per pig produced of various treatments of slurry were estimated by Sangiorgi *et al.* (1987). The most expensive, £5.50/pig produced was total treatment producing an effluent of sufficient quality for discharge to a water recipient. Oleszkiewicz (1985) calculated an even higher cost of £10.50/pig for similar treatment.

The cost per pig for unspecified aerobic treatments were assessed by Sangiorgi *et al.* (1988) and Ritter (1990) at £3.20 and £6.10 respectively.

When slurry was pretreated by removal of solids by centrifugation and then aerated for a short period of time of 1 or 2 days, the cost of treatment varied between £1.10 to £1.40 (Sneath, 1988; Sneath *et al.*, 1990). Longer treatment times of 3 to 5 days increased the cost to between £1.70 and £4.60.

When the utilisation of heat energy recovered from aerobic treatment (Evans *et al.*, 1982) is included in the economics of treatment, the cost can be much more

attractive to the farmer. Thyselius (1982) reported that the heat energy at 50°C recovered from a piggery slurry treatment plant was up to 3.5 times more than the electrical energy used for aeration. Svoboda and Fallowfield (1989) recovered from a small, farm-scale reactor twice as much heat energy as the electrical energy used for aeration.

Hughes (1984) installed a heat recovery system into a lagoon of continuously-aerated pig slurry from which the solids had been removed. A payback period for the heat pump and the system of 3.5 years indicates an expected profit from the recovered heat.

An example of a farm (Evans *et al.*, 1979a) where, due to the installation of a treatment plant, the farmer could double his pig production without polluting the water recipient by field drainage water shows that aeration does not always have to have a negative influence on cash flow.

4. CHARACTERISTICS OF PIGGERY SLURRY AND ENERGY FROM AEROBIC METABOLISM OF ORGANIC SUBSTRATES

4.1. Piggery slurry characteristics

The properties of manures can be classified as physical, chemical and biological. The physical and chemical properties are known to be affected by the physiology of the animal, the feed ration and the environment, mainly the temperature and humidity. The live weight of the animal is perhaps the most important physiological parameter. Other parameters like sex, breed, animal activity and environmental stress influence efficiency of the feed conversion. The chemical characteristics of excreta depend on the composition of the feed, especially the protein, fibre and oil content. The volume of excreta depends on the quantity and digestibility of food eaten, and the volume of water consumed. Faeces contain nitrogen from undigested protein while the nitrogen from digested protein not used for growth is excreted in urine. Most of the phosphorus and potassium in the feed is excreted.

The use of growth promoters such as copper, zinc and, in some instances, antibiotics may be reflected in waste characteristics as will the presence of any feed gaining access from spillage and therefore undigested.

The concentrations of total solids (TS), total suspended solids (TSS), volatile solids (VS), volatile suspended solids (VSS), the viscosity, capillarity

suction time (CST) and the distribution of particle sizes are all largely dependent on the quality and quantity of feed ingested and on water consumption. The practices used in the collection and storage of slurry affects the dilution and therefore the concentration of chemical, physical and biological components. The volume of excreta depends on the digestibility of feed. Changes in digestibility over the last 40 years have resulted in lower ratios of excreta to feed quantities.

The inclusion of bedding influences further the physical characteristics of wastes but the handling and treatment of the resulting farmyard manure is excluded from the present study.

Taiganides and Hazen (1966) gave guide values for the average daily production and composition of manure by a 100lb swine, as 7lb of manure containing 16%TS of which 85% are VS and 4.5%, 2.7% and 4.3% are nitrogen, phosphate and potash respectively. These values represent, on average 75% of nitrogen, 80% of phosphate and 85% of potash present in the feed. About 30 to 40% of the organic matter in the feed is excreted. Urine, which is 30 to 40 % of the total excreted, contains between 40 and 70% of the plant nutrients.

The manure excreted daily by a 100lb swine contained averages of 0.95lb VS, 0.34lb BOD_5 and 1.25lb COD. The ratios of BOD_5 /VS, COD/VS and BOD_5/COD

were 0.354, 1.32 and 0.268 respectively.

Some workers characterised pig slurry from long-term metabolic experiments (O'Callaghan, 1971), or commercial piggeries (Barth, 1985; Payne, 1986) but most authors describe the characteristics of slurries used in their experiments (Evans *et al.*, 1978, 1979, 1980, 1983, 1986; Fallowfield and Garrett, 1985; Williams and Evans, 1981; Williams *et al.*, 1989; Sneath *et al.*,1990). Typical characteristics of excreta from fattening pigs (20 to 100kg liveweight) are given in Table 6 (Evans *et al.*, 1978). The average volume of undiluted excreta was 4.51/d.pig and contained 100g/l of total solids.

Table 6. Concentration of main components of fattening pig slurry expressed as a percentage of TS of whole slurry (Evans *et al.*, 1978).

Component	Whole	Supernatant
Volatile solids	82	9.7
Total suspended solids	86	-
Volatile suspended solids	75	-
COD	133	17
BOD_5	35	12.5
Total-N	6.6	2.1
Organic-N	3.4	0.5
Ammoniacal-N	3.2	1.6
Phosphorus	2.0	0.5
Potassium	2.2	1.8
Copper	0.04	0.002
Zinc	0.14	0.003
Calcium	1.5	0.2
Magnesium	0.76	0.04

The biodegradability of slurry, which is very important in the design of and during operation of

treatment processes, is reflected by the BOD and COD values. Since nearly 50% of COD can be satisfied by biological oxidation during an aerobic process, more components than those expressed as BOD_5 are evidently removed. The remaining fraction of COD, approximately 53% (Williams *et al.*, 1989), is not satisfied and represents those slurry components contributing to the COD which are inert to aerobic biological activity.

Anaerobic microbial processes in the gut of the animal result in end products which impart a typical odour to slurry. More than 100 compounds (O'Neil and Phillips, 1992) which are mostly volatile fatty acids, phenols, cresols, indoles and mercaptans contribute to the odour. The concentrations of many of these compounds further increase with storage (Williams and Evans, 1981) but they can be oxidised or removed during aerobic treatment for 2 days or more (Thacker and Evans, 1986; Williams *et al.*, 1989).

4.2. Heat energy from aerobic metabolism

The first reported study of heat production from a microbial fermentation is by Dubrunfaut (1856) who conducted his experiments in a 21.4 m^3 vat.

The first real calorimetric studies were performed by Bouffard in 1895 in 1 litre cultures. From these measurements, very accurate for that time, Bouffard found the heat generated during glucose fermentation to be 26.5 kcal/mol. This value was relatively recently

confirmed and more precisely determined by Battley in 1960.

Meyerhof (1924) combined respirometric measurements with heat production and expressed, for some of the bacterial growth phases, the ratio of heat produced to quantity of oxygen used.

A differential calorimeter, developed by Hill (1912) and perfected by Bayne-Jones (1929), was used to determine heat produced by a single bacteria cell (10^{-6} cal). It showed that the heat generated varied with the bacterial growth phase. To specify these variations, more accurate calorimeters had to be developed. Such developments include a heat flux meter perfected by Calvet (Calvet and Prat 1956) and the more recent calorimeters developed by Monk and Wadso (1969), Monk (1978), Picker (1974) and Wadso (1985).

Microorganisms attain three levels of metabolic activity that can be observed during the growth of batch cultures (Forrest and Walker, 1971). Each of these levels can be maintained at steady state (Lamprecht, 1980).

The first level of metabolic activity is endogenous metabolism of the cell. The cell utilises its own energy supply during a complete lack of exogenous substrate and thus generates the minimal possible energy. It has been estimated (Belaich 1980) that the magnitude of endogenous metabolism can be about 5% of

that of exogenous metabolism.

The second level occurs when the cell is not growing or dividing, but just repairing itself from any damage caused by irradiation for example, resynthesising macromolecules and keeping the internal control mechanism active. The energy apparatus is being supplied by endogenous metabolism (Forrest 1972). This level of metabolism can be classified as maintenance (Lamprecht 1980).

The third level of metabolism occurs during growth and multiplication and is most demanding of substrate. It can be divided into six phases for a typical microbial culture (Chudoba *et al.*, 1991). The phases are: 1. Lag phase, 2. acceleration phase, 3. exponential growth rate phase, 4. deceleration phase; 5. stationary phase, 6. decline phase. Each of phases 2 to 6 can be maintained in a steady state condition in a chemostat.

Microbial growth is associated with enthalpy changes. Monk (1978) observed the heat effect of growth of *Streptococcus lactis* and divided the heat produced into three categories: 1. Enthalpy change with catabolism of the energy-supplying substrate; 2. Enthalpy change with growth; 3. Heat of ionisation and dilution of degradation products.

Mo and Cooney (1976) described three generalised exothermic reactions of cell metabolism.

1. $S+[O]_1$ ------> S_i + ATP + $[H]_1$

2. $S_i+[O]_2$ -----> $CO_2 + H_2O + ATP + [H]_{II}$

3. $S_i+ATP+NH_3$ -----> cells + H_2O + $[H]_{III}$

Where S is the carbon and energy source, S_i is an intermediate product of catabolism and an initial substrate for biosynthesis, and [H] is the amount of heat evolved.

Reaction 1 is the degradation of the carbon source and the production of adenosine triphosphate (ATP) by substrate-level phosphorylation. The ratio $[H]_I/[O]$ depends on the nature of the substrate and of the microorganism.

Reaction 2 is ATP production resulting from oxidative phosphorylation and the value of $[H]_{II}$ depends on the efficiency of the coupling of the oxidative phosphorylation reaction.

Reaction 3 represents the biosynthesis of cell mass or fermentation products and the value of $[H]_{III}$ depends on the type of biosynthetic reaction.

Oxidative phosphorylation was described by Lehninger (1971) by the equation:

$$NAD_{red}+3ADP+3P_i+2H^+ + .5O_2 = NAD_{ox}+3ATP+4H_2O$$

NAD - nicotinamide adenosine dinucleotide
ADP - adenosine diphosphate

Since 3ATP require at least 3*7.3=21.9 kcal and oxidation of NAD_{red} yields 52 kcal then 21.9/52*100=42% of the total energy is used. Thus 58% is lost as heat.

Respiration chain phosphorylation can be inhibited by certain poisons, so that electron transport is still continuous but the linked phosphorylation of ADP to ATP does not occur. Thus the energy of substrate is dissipated completely as heat and none is recovered as ATP. Such poisons are called uncoupling agents.

There are, in general, two most important energy changes during the metabolism of substrate by aerobic microorganisms. The endergonic biosynthetic reaction that has to be driven by energy from catabolism, and the exergonic reaction.

Transfer of energy released from a carbon energy source to ATP and from ATP to new molecules of cells is by no means 100% efficient. McCarty (1965) calculated, from measured COD of substrate and of the cells, the efficiency of energy transfer from substrate to ATP for different pure substrates and for pure and mixed cultures of microorganisms. The efficiency varied between 40-70% for autotrophic and heterotrophic bacteria under both aerobic and anaerobic conditions. However, for heterotrophic aerobes, the calculated energy transfer efficiency could be as low as 12% due to high maintenance energy requirement and energy "uncoupling". Lehninger (1971) estimated that about 75% of the energy released by ATP for the synthesis of protein is lost as heat in order to guarantee perfect fidelity in the translation of the genetic message from mRNA into the aminoacid sequences.

The quantity of energy released by metabolism of a simple and defined substrate converted into a defined product can be calculated from tabulated thermodynamic data. When the catabolic reactions are complex or even unknown none of these calculations are possible. Even more difficult is the investigation of anabolic metabolism, mainly due to the uncertainties in the chemical formulae used for bacteria (Belaich, 1980).

The basis of the heat from metabolism is in the inefficiency of energy transfer from the metabolism of the substrate to energy storage and biosynthesis of cells. When a mol of glucose is metabolised in the tricarboxylic acid cycle (Krebs cycle) 36 mols of ATP are formed (Lehninger, 1971).

$$C_6H_{12}O_6+6O_2+36ADP+36P_i \text{--->} 6CO_2+6H_2O+36ATP$$

Lehninger (1971) calculated that the energy conservation of this process will be 38% if a minimum of 7.3 kcal is required for formulation of 1 mol of ATP. Thus the rest of the energy is dissipated as heat (enthalpy) and entropy as is described by the third thermodynamic law

$$G = \Delta H - T\Delta S$$

where G is free energy, H is enthalpy, S is entropy and T is absolute temperature.

Kleiber (1965) compares the combustion of organic

compounds in oxygen with the analogous process - respiration. In aerobic metabolism of a carbon substrate the terminal electron acceptor is oxygen and the products of oxidation are carbon dioxide and water. The calorific equivalent of oxygen (g.eq.O_2) for different kinds of organic compounds is similar: fat - 26kcal/g.eq.O_2, protein - 26.77kcal/g.eq.O_2 and carbohydrates - 28kcal/g.eq.O_2.

Ho (1979) calculated from the combustion of 24 specific compounds, the heat production of microbial metabolism as 0.101kcal/mmolO_2 (3.67kWh/kgO_2).

Lloyd *et al.* (1978) measured the heat evolved in cultures of *Tetrahymena pyroformis* and correlated it with oxygen consumed. For each nmol O_2 consumed by biomass 1620 microJ of heat was produced.

Glanser *et al.* (1979) measured the heat output from a continuous culture of a mixture of 35% *Aerobacter sp.*, 30% *Corynebacterium sp.* and 35% *Flavobacterium sp.* grown on molasses at 35°C. The average heat output was about 0.2 kWh/kgO_2. The quantity of liberated heat corresponded to the changes in the specific growth rate of biomass and to the accompanying changes in the ratio of strains in the mixed culture.

The similarity between combustion and respiration was supported by Minkevich and Eroshin (1973) who elaborated on a new theory of "available electrons" and calculated, for some various low-molecular weight

substrates, and for yeast and bacterial cell biomass, the heat per "equivalent" of "available electrons" (similar to g.eq.O_2) to be 27kcal+- 5%.

Cooney *et al.* (1968) measured the metabolic heat evolved by pure cultures of four different organisms : *Escherichia coli, Bacillus subtilis, Candida intermedia* and *Aspergillus niger* grown on media containing glucose, molasses and soy bean meal. Heat generation was measured in the insulated fermenters from temperature increments and calculated heat losses. The rate of heat production correlated with oxygen consumption produced a linear relationship of 0.124+-0.003kcal/mmolO_2. They suggested that this linearity exists irrespective of the growth rate, substrate and the type of organism. When the total heat produced was compared with total oxygen consumption a linear relationship 0.11+-0.01kcal/mmol O_2 was found. The scatter of the data suggests that this relationship will be dependent on the species of organisms which differ in their efficiency of substrate oxidation.

4.3. Aerobic treatment at elevated temperature

Heat energy evolved from aerobic metabolism of liquid organic wastes is not usually evident in conventional treatment systems of either diluted wastes such as sewage or concentrated animal wastes in oxidation ditches. The large volumes of water in diluted effluent absorb the heat or heat is dissipated to the

environment.

According to the classic thermodynamic rule of Van'tHoff-Arrhenius, the biochemical reaction rates almost double with each 10^{o}C increase in temperature. Therefore the higher metabolic reaction rates of mesophilic or even thermophilic micro-organisms should enable treatment of concentrated wastes in a shorter period of time (Match & Drnevich, 1977; Ginnivan *et al.*, 1981; Ganczarczyk *et al.*, 1980). The possible advantages of treatments at elevated temperatures have been outlined elsewhere (Surucu *et al.*, 1976; Popel and Ohmacht, 1972).

The higher decay rates and higher maintenance energy requirements would decrease the amount of residual activated sludge (Matche and Andrews, 1973; Allen, 1953)

A computer simulation technique was used by Kambhu and Andrews (1969) and showed the possibility of the self-sustaining, autothermal, thermophilic, aerobic digestion of sewage sludge. They predicted that the treated sludge should increase its temperature by 40^{o}C at residence times greater than 7.5 days.

Popel and Ohmacht (1972) calculated the heat production from aerobic metabolism of a mixture of 21.6 kg/m^3 dextrose, 21.12 kg/m^3 butyric acid and 21.36 kg/m^3 alanine from the following reaction

$$C_6H_{12}O_6+2C_4H_8O_2+2C_3H_7N+12O_2 \longrightarrow 2C_5H_7O_2N+10CO_2+14H_2O$$

Based on heat production of 7.87 kcal/g of carbon and 34.15 kcal/g of hydrogen oxidised, this reaction should produce 228,060 kcal/m^3 of the mixture and use 46.08 kg of oxygen. The heat produced would be amply adequate to raise the temperature of 1 m^3 of substrate from 15 to 65^oC and to cover the heat losses and the energy required for growth of new biomass. Popel (1971) estimated that 1.604 kcal is required for growth of one gramme of new cells.

Terwilleger and Crauer (1975) aerated diluted piggery slurry (approximately 20gTS/l) in a batch experiment using a 3.75kW Centrirator aerator and 1.5 kW foam cutter in a concrete tank (LICOM Process). The temperature of the mixed liqour (ML) averaged 30^oC and BOD, COD, TS and VS were reduced by 80%, 73%, 7% and 8% of the original values respectively after 12 days of treatment. In another batch with 25 days of treatment TS and VS were significantly decreased by 65% and 74% respectively but BOD_5 and COD were reduced less than in the first batch by only 69% and 70% respectively. Using a similar system with three reactors in series and separated cattle slurry containing 60gTS/l, mixed liqour temperatures between 40 and 52^oC were achieved.

Grabbe et al. (1975) aerated, with a Centrirator aerator, a batch of cattle slurry, containing about 80gTS/l, in a 24.8m^3 insulated tank. The ML temperature rose to 50^oC but after two days declined to 42^oC

signalling lack of readily biodegradable matter. In other experiments using more dilute cattle slurry the temperature remained below 30^{o}C and nitrification was observed.

During these experiments it was estimated that about two thirds of the heat energy was derived from metabolic processes and one third from electric motors. At least one half of this generated heat was lost in evaporated water.

Match and Drnevich (1977) estimated the oxygen requirement for catabolism of cell mass on basis of the two following reactions

1. $C_5H_7NO_2+5O_2$ --->$5CO_2+2H_2O+NH_3$+energy
2. $C_5H_7NO_2+7O_2$ --->$5CO_2+3H_2O+NO_3^-+H^+$+energy

The substrate was sewage sludge in which the dry matter contained between 30 to 70% of organic material.

In the first case, when 1.4kg O_2 is required for destruction of 1.0kg VSS, 1mol of CO_2 is produced per mol of oxygen. In the second case 1.98kg O_2 is required for the destruction of 1.0kg VSS and only 0.71mol CO_2 is produced per mol of oxygen.

Andrew and Kambhu (1973) indicated that the the quantity of metabolic heat energy released from biological destruction of one kilogram of organic matter (VS) would be 5Mcal. They further suggested the use of pure oxygen instead of air in order to reduce heat

losses in the water evaporated in the exhaust air.

Jewel and Kabrick (1980) estimated the heat evolved during the oxidation of glucose and cell growth using the equation: $C_6H_{12}O_6+O_2+NH_3----->CO_2+4H_2O+C_5H_7O_2N$

The immediate energy released and dissipated to the environment, 128kcal, is the difference between the free energy of complete oxidation of glucose, 688kcal/mol, and the estimated chemical energy of biomass, 560kcal, but further heat will be evolved during endogenous respiration of the cell biomass.

The simplest measure of the oxidisable matter in a heterogeneous substrate is COD. Servitzi and Bogner (1963) estimated that the heat released from biological metabolism as F = 3.5 COD, where F is total heat released in kcal/l and COD is gCOD/l.

Jewel and Kabrick (1980) used a direct relationship between heat generated (kcal/l) and reaction temperature reached during aeration of activated and primary sewage sludge in an insulated reactor. The reactor was fed with sludge of 5% TS, oxygen transfer was in excess of 23%, residence time was approximately 8 days and 70% of generated heat was conserved. The change of the ML temperature was then estimated as T = 2.4 COD

The temperature of the ML in a continuously-fed reactor in the steady state is influenced by evolution of metabolic heat, heat input from mechanical devices and heat losses from the system.

Woods *et al.* (1979) described such an energy

balance and calculated the balance for the treatment of $4.5m^3$/day of piggery slurry containing 45gTS/l with a mean treatment time of 2 days at 55^oC. This temperature would be maintained by using an aerator with an oxygenation efficiency of $1kgO_2/kWh$, and with an oxygen transfer coefficient (K_La value) of 175/h and an hourly air flow rate of $1.46m^3/m^3$. The metabolic heat production was estimated, on the basis reported by Cooney *et al.* (1968), as $4.03kWh/kgO_2$.

The effect of the aerobic exothermic reaction was shown by Sneath (1978) who was able to maintain the temperature of the mixed liquor between 19.8 and 38.7^oC in a surface tank of $19.9m^3$ using a plunging jet aerator. The separated piggery slurry, fed continuously into the reactor, had a COD/TS ratio of 1.7.

Williams *et al.* (1989) used insulated reactors with a capacity of $0.5m^3$ for treatment of piggery slurry which had been mechanically separated by passage through 1.6 mm mesh. The slurry was fed to the reactors at intervals of one or two hours. Although the TS of the slurry varied between 14 and 39g/l, the temperature of the mixed liqour in the reactor was maintained between 27.8 and 50.3^oC. The heat was generated from a continuously-operated impeller and from aerobic metabolism.

Sneath *et al.* (1990, 1992) continuously aerated separated piggery slurry with a venturi type of aerator

in a reactor with a capacity of $18m^3$. The temperature of the ML was minimally 10^oC above ambient during treatment times of 1 to 4 days.

Gobel (1981) controlled the temperature in an insulated $35m^3$ reactor at 33.5^oC by extracting the excess heat. Slurry containing 3.3% dry matter (TS) from 280 fattening pigs was aerated during a five-day residence time by a 2.2KW aerator (Alfa Laval-Centrirator) which introduced $70m^3$ of air per hour into the ML with 25% oxygen transfer efficiency and an oxygenation efficiency of $1.6kgO_2/kWh$. Foam was controlled by a 0.3kW foam cutter.

The total solids were 2% of the ML and 60% of the organic matter was broken down.

An average of 186 kWh of heat was extracted daily with four flat $1.5m^2$ heat exchangers positioned in the mixed liquor around the aerator. The heat losses for warming incoming slurry accounted for 30%, air warming and evaporation 10% and surface losses 10% of the total heat energy available. Thus 50% of the heat energy generated was extracted for potential utilisation.

Treatment at 50^oC was assumed to be impracticable for the size of this plant because the greatly increased heat losses would result in very little energy being available for extraction.

Evans *et al.* (1982) calculated the theoretical heat evolution from continuous aerobic treatment of

piggery slurry. They used equations which described the changes in COD in piggery waste aerated at temperatures of 15 to 50^{o}C and treatment times of 0.5 to 8 days. The change in COD was assumed to be equivalent to the oxygen consumed by the microorganisms and to generate 4kWh of heat per kilogram of oxygen (Cooney *et al.*, 1968). It was further assumed that 1.2 kWh was released per kilogram of oxygen (Sharma and Ahlert, 1977) and that 4.57kgO_2 was required for the oxidation of one kilogram of ammoniacal nitrogen.

The potentially recoverable heat was calculated for piggery slurry diluted to 25gTSS/l, aerator oxygenation efficiency 1kgO_2/kWh with 30% oxygen transfer efficiency, 0^{o}C ambient temperature and reactor insulated to an overall 'U' value 0.5W/m^{2}K. It was shown that, under these conditions, treatment temperatures of 35, 40 and 50, and 45^{o}C could be achieved at treatment times of 1, 2 and 3 days respectively.

Similar assumptions were later used in a computer program (Baines *et al.*, 1986) for the calculation of metabolic heat, heat losses from the plant and the extractable heat for treatment times of 1 to 15 days and temperatures of 15 to 50^{o}C. An example given showed that a plant treating slurry, diluted 1:1 with water, from 5000 pigs at a treatment temperature of 35^{o}C would be capable of delivering 1393kWh/d of heat while using only 196kWh/d of electrical energy for an aerator with

an oxygenation efficiency of 2.5kgO_2/kWh.

Tjernshaugen (1982) described three plants for piggery slurry aeration which had submersible pumps with ejectors in the tanks under the slatted floor and outside the piggery. During a treatment time of 30 days the temperature of the ML was maintained between 37 and 50°C. The heat energy, recovered as hot water at 36 to 43°C, was 3 to 4.3 times greater than the electrical energy required for aeration.

A similar treatment plant was constructed and operated in Sweden (Thyselius, 1982). About 5m^3 of piggery waste containing 80gTS/l and 80% VS of TS was processed daily in a 177m^3 reactor. The temperature of the mixed liquor, which was aerated by a submersible Flygt pump (4.7kW) and a compressor (2kW), varied between 40 and 52°C. The average reductions of TS, total nitrogen and COD were 46, 29 and 35% respectively.

The heat extracted, by a water to water heat exchanger, was used for underfloor heating of the piggery and supplemented space heating in the farmhouse. The ratio of heat energy extracted to electrical energy used (heat effect), even with an uninsulated reactor at an ambient temperature of 10°C was between 2.5 and 3.6. The largest heat loss estimated was 23% from the reactor surfaces. Heating of the incoming slurry and the loss from the exhaust air accounted for 16% and 10% respectively. After the reactor was insulated, the

heat effect increased to 4.9 (Thyselius, 1986).

The utilisation of heat from a low temperature heat source for heating space or water is not attractive. Hughes (1984) applied a heat pump to extract heat from a lagoon where separated piggery slurry was continuously aerated by a 14kW aerator. The temperature of 540m^3 of aerated ML in the open lagoon was very stable at about 35^oC during the whole year. The heat pump rated at 21.6kW output was extracting an average of 6.5kW and heated a secondary hot water circuit to 55^oC. The overall coefficient of performance (COP) of the heat pump for the year of experimental measurement was 3.45. If the cost of treatment is regarded as a necessity for pollution control, then the pay-back period for the heat pump and its installation and maintenance was calculated as being less than 3 years.

5. SCOPE OF WORK

The main objectives of this study are to evaluate a theoretical model and laboratory-scale experimental results of aerobic treatment of piggery slurry in a larger scale plant operated under practical conditions. The project became possible because of an opportunity to design and operate an integrated fattening pig unit with waste collection, treatment facilities and heat recovery system which could be fully monitored.

The design of the unit is described and the experimental results obtained are discussed in relation to the laboratory and theoretical models and in relation to their practical application in the control of pollution from intensively housed animals.

Fresh and treated slurry were analysed for their biochemical characteristics which were compared with values previously obtained in laboratory reactors and summarised in a mathematical model.

The effects of variable concentrations of input slurry on characteristics of treated slurry were examined.

Extracted heat was measured and heat losses from the treatment plant were calculated, thus enabling an estimation of heat evolved.

Values of evolved heat and heat losses from the reactor were compared with values predicted by a mathematical model.

An assessment of the characteristics of an aerator used during the study was made.

6. EXPERIMENTAL DESIGN

6.1. Operation of the treatment plant

Slurry from about 300 fattening pigs and 100 weaning pigs was collected daily in a reception pit from where, at hourly intervals, an aliquot of approximately 1/24 of the daily slurry production was pumped into the reactor (Fig. 3).

The liquor (ML) in the reactor was continuously mixed and aerated with a subsurface aerator. The concentration level of dissolved oxygen was controlled between 1 and 70% of saturation. Redox potential was controlled from -350 to +100mV E_{cal}. The control of slurry treatment time, over the range from 5 to 20 days, was achieved by maintaining a constant rate of slurry input and changing the working volume of the reactor between 9 and 20 m^3. The ML was maintained at a constant temperature for each experiment by extracting heat with a water to water heat exchanger placed in the reactor.

Experiments were conducted over the range 35^{o} to $55^{o}C$. Extracted heat in the form of hot water was used for space heating of the weaner house and/or heating one of the algal ponds. At treatment temperatures over $50^{o}C$, the hot water from the heat exchanger was used directly for heating. When treatment temperatures were less than $50^{o}C$, a heat pump extracted heat from the heat exchanger circuit in order to increase the temperature in the space heating circuit to a maximum of $55^{o}C$.

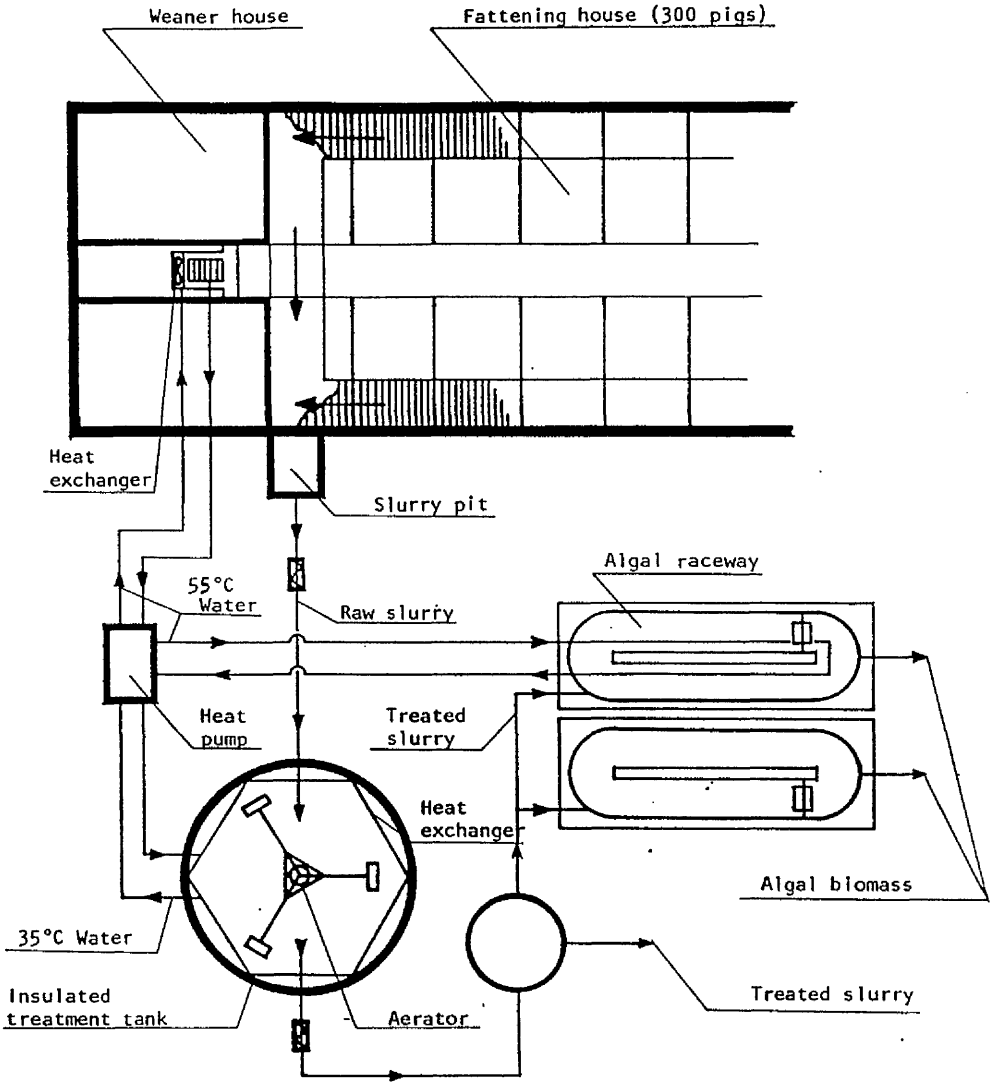

Fig.3 Piggery with the treatment plant.

6.2. The piggery

The piggery (Fig. 4 and 5) was built for the purposes of studying the ventilation and the heating systems and for the aerobic treatment of excreta in the form of slurry from weaning and fattening pigs.

This piggery was divided practically into three parts, a weaner house (WH_1 and WH_2), fattening house A (FA_1 and FA_2) and fattening house B (FB_1 and FB_2). The fattening houses were divided by a corridor FP, an area used for feed preparation and for handling and weighing pigs.

Both sections of the weaner house were continuously ventilated by air blown across a heat exchanger HE which was supplied with hot water extracted from the reactor. When the temperature in the weaner house was lower than required, additional heat was supplied by electric heaters.

Fattening house A had a forced ventilation system, air entered under the eaves and was expelled by three extractor fans through the piggery roof ventilators.

Fattening house B was ventilated using an automatically-controlled natural ventilation system (ACNV). Air was allowed to flow across the house from automatically-opened windows at the eaves above the slatted floor S. Therefore in both houses A and B, because the coldest areas were under the eaves, pigs were encouraged to defecate on the slatted floor S.

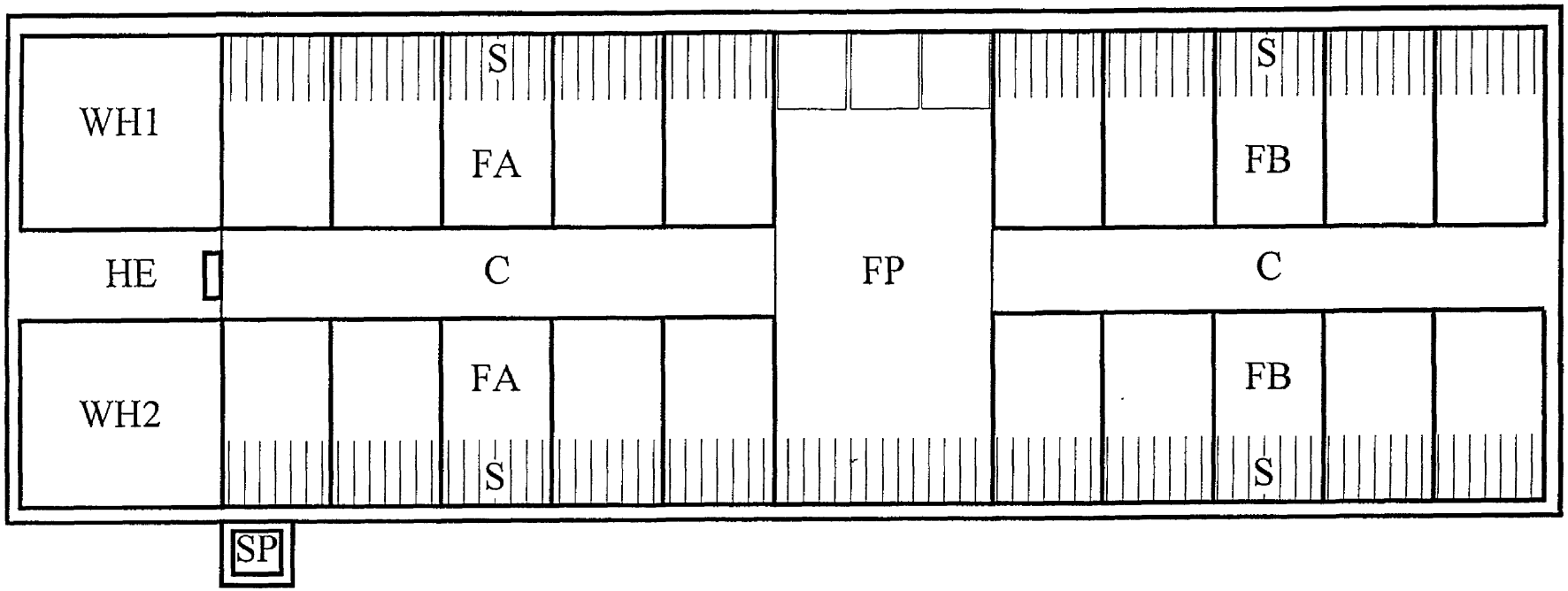

Fig.4 Plan of the piggery.

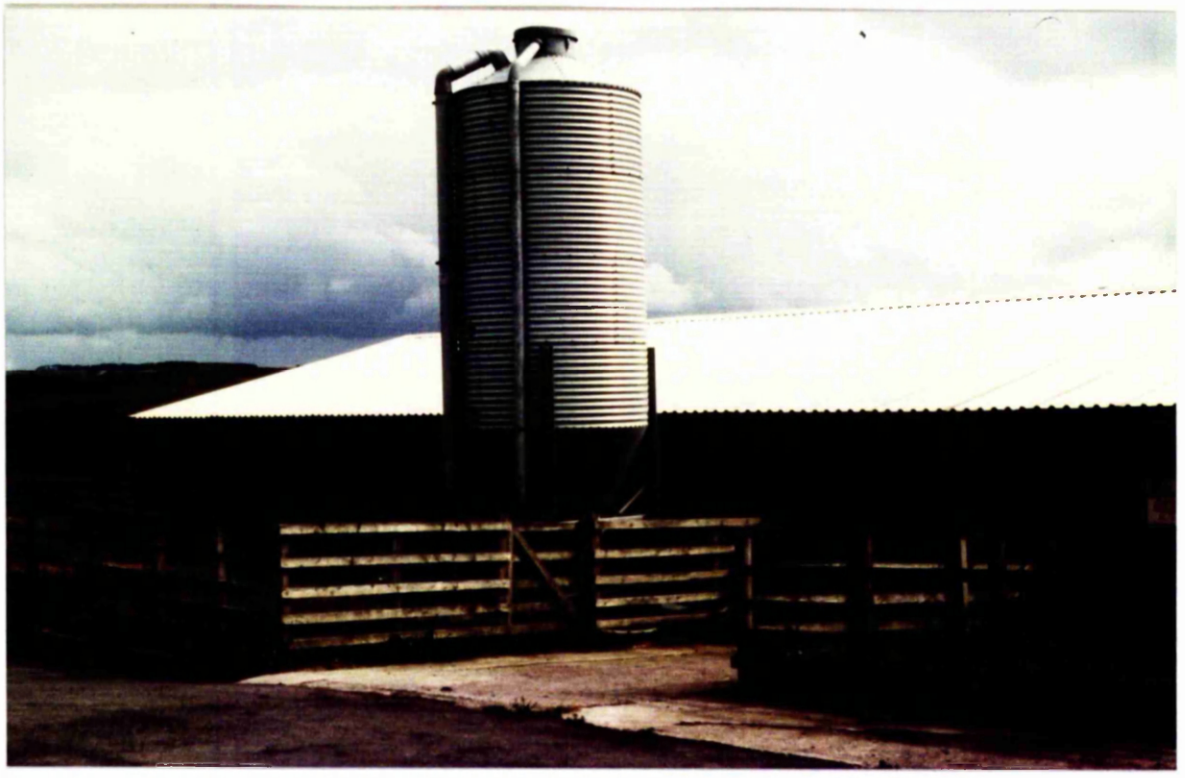

Fig.5 The piggery.

6.3.Slurry collection

In the fattening houses, the slurry was accumulated in 225mm deep channels underneath the partially-slatted floors of the pens. Once each day, slurry was automatically scraped and deposited into a 450mm deep under-floor cross channel, located between the end of the fattening house FA (Fig. 4) and the two flat deck weaner rooms (WH_1 and WH_2). Slurry from these rooms, collected under the perforated floor, was drained by gravity into the cross channel and scraped together with other slurry into a slurry pit (SP) just outside the piggery. The slurry was stirred for 5 minutes at intervals of 1 hour and an aliquot (1/24 of the slurry produced daily) was pumped into the reactor through a plastic pipe (76mm internal diameter) which was protected from frost by electrically heated tapes and insulation.

6.4. The reactor

The reactor (C.O.Smith, Harvestore) (Fig. 6 and 7) was a cylindrical tank 3.4m in diameter with a wall 2.65m high, constructed from steel plates coated with fused glass. The outer surface of the wall was sprayed with polyurethane insulation foam with 'U' value of $0.74W/m^2K$. The floor was a sandwich formed by two 50mm layers of concrete and a middle layer of 40mm expanded polystyrene and had a total 'U' value of $0.458W/m^2K$.

The reactor lid, which was air tight, was made of

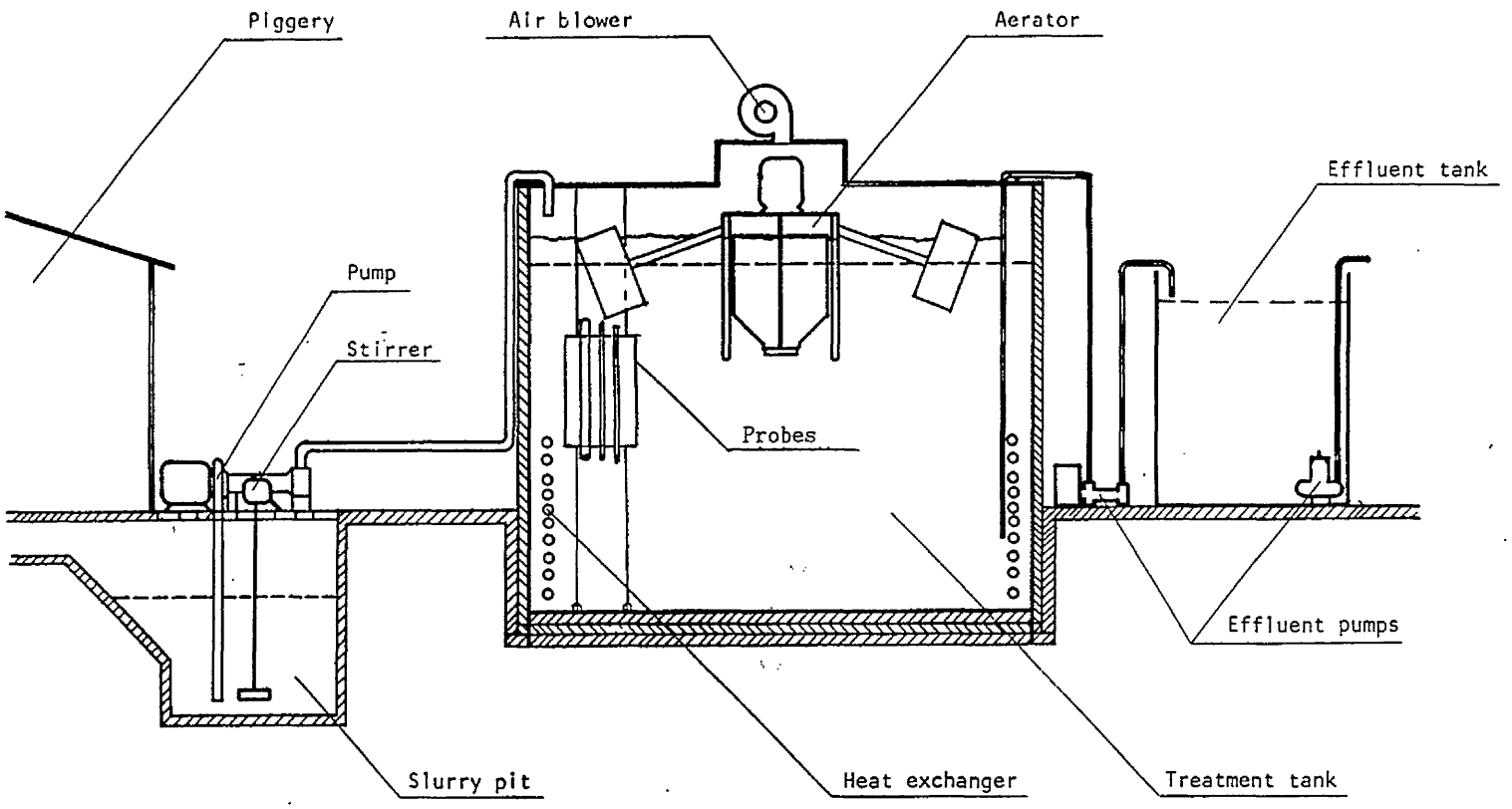

Fig.6 Cross section through the treatment plant.

Fig.7 The aerobic reactor with algal ponds.

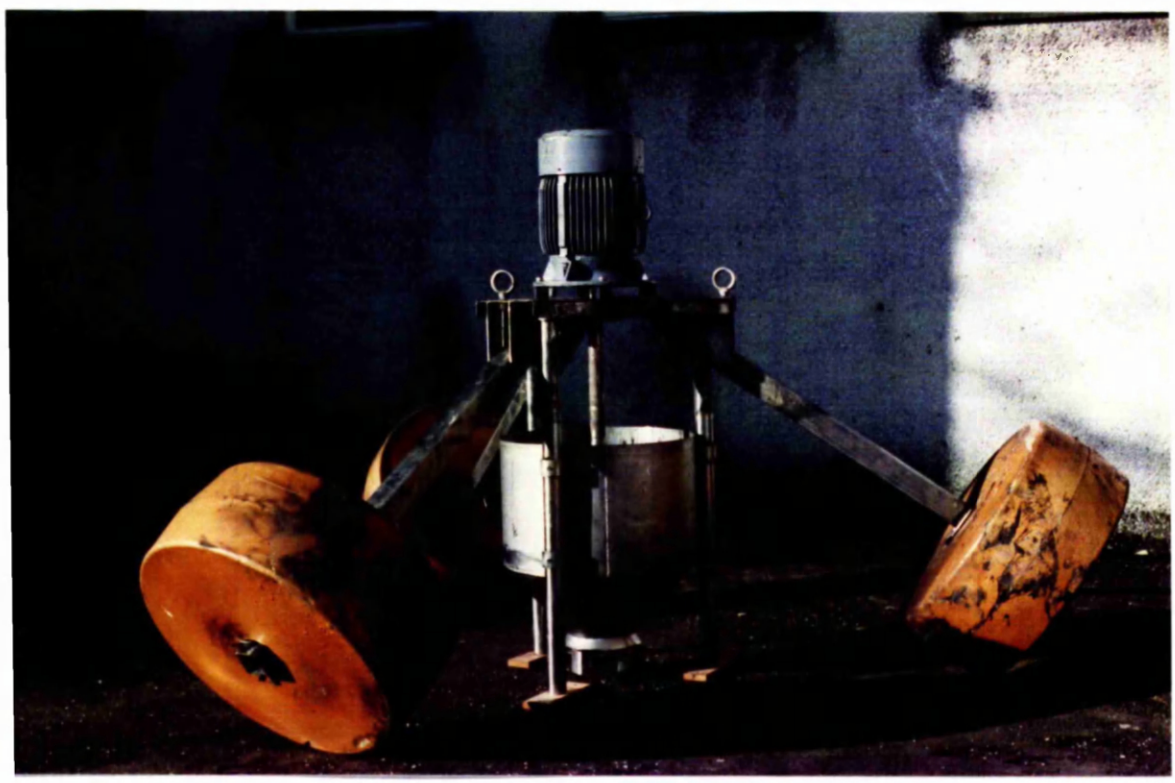

Fig.8 The aerator.

22mm plywood with a 'U' value of $7W/m^2K$. The lid was insulated later by the addition of 50mm of 'styrofoam' to give a total 'U' value of $0.536W/M^2K$. The rectangular opening in the centre of the lid was covered with a box (Fig. 6) and was used for access to the reactor.

A centrifugal fan with an air flow measuring tube was mounted at the side of the box (Fig. 6). It supplied fresh air into the reactor.

6.5. The aerator

The floating subsurface aerator (BRV 040, G. Velebil, Germany) (Fig. 8) was made from stainless steel. During the trials, two impellers of a different size were used. The power demand of the small impeller was 2 to 2.5 kW and that of the large impeller 3 to 4kW (Fig. 9), depending on the depth of submersion, the ML depth, and the flow rate of foam through the cone. The aerator maintained a constant layer of foam on the ML surface by sucking excess foam into the cone and returning it into the ML. By changing the depth of submersion of the aerator the thickness of foam layer could be regulated.

6.6. Heat extraction

The temperature of the ML in the reactor was controlled by heat extraction using a water-water heat exchanger (Fig. 10). It was made from a 100m length of stainless steel tubing with a 22mm diameter, as an octagonal,

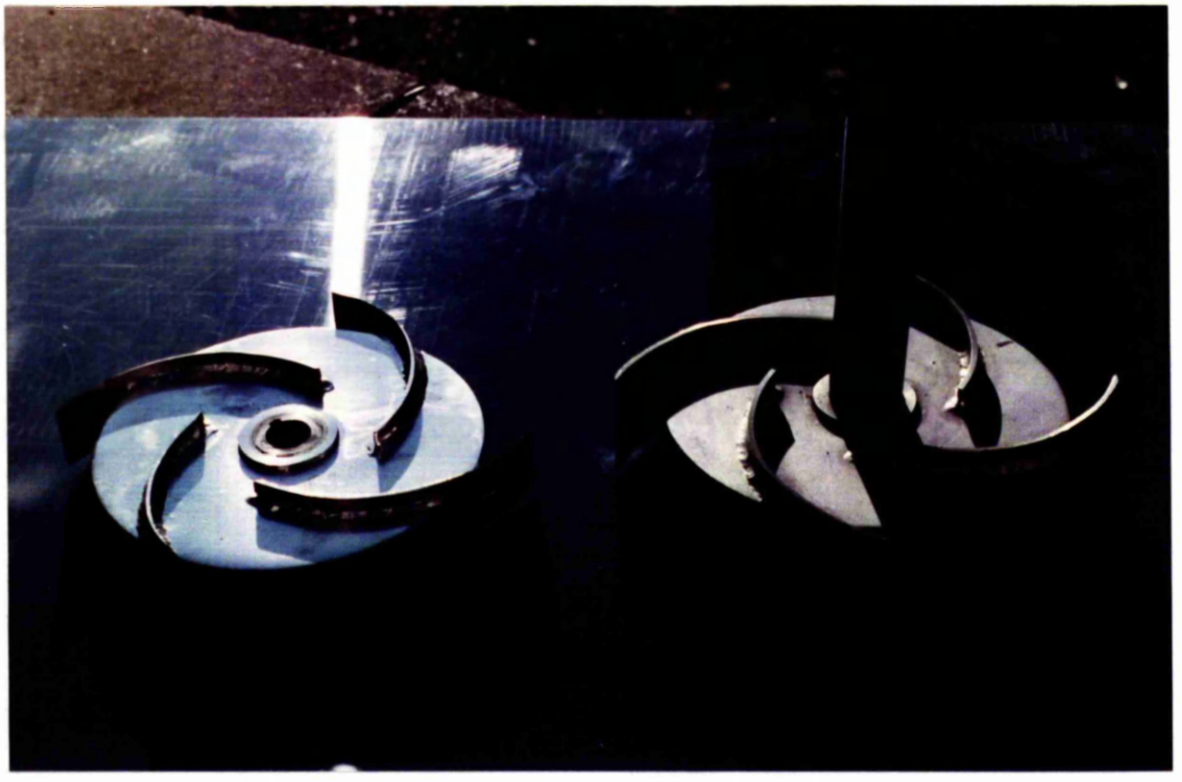

Fig.9 The aerator impellers.

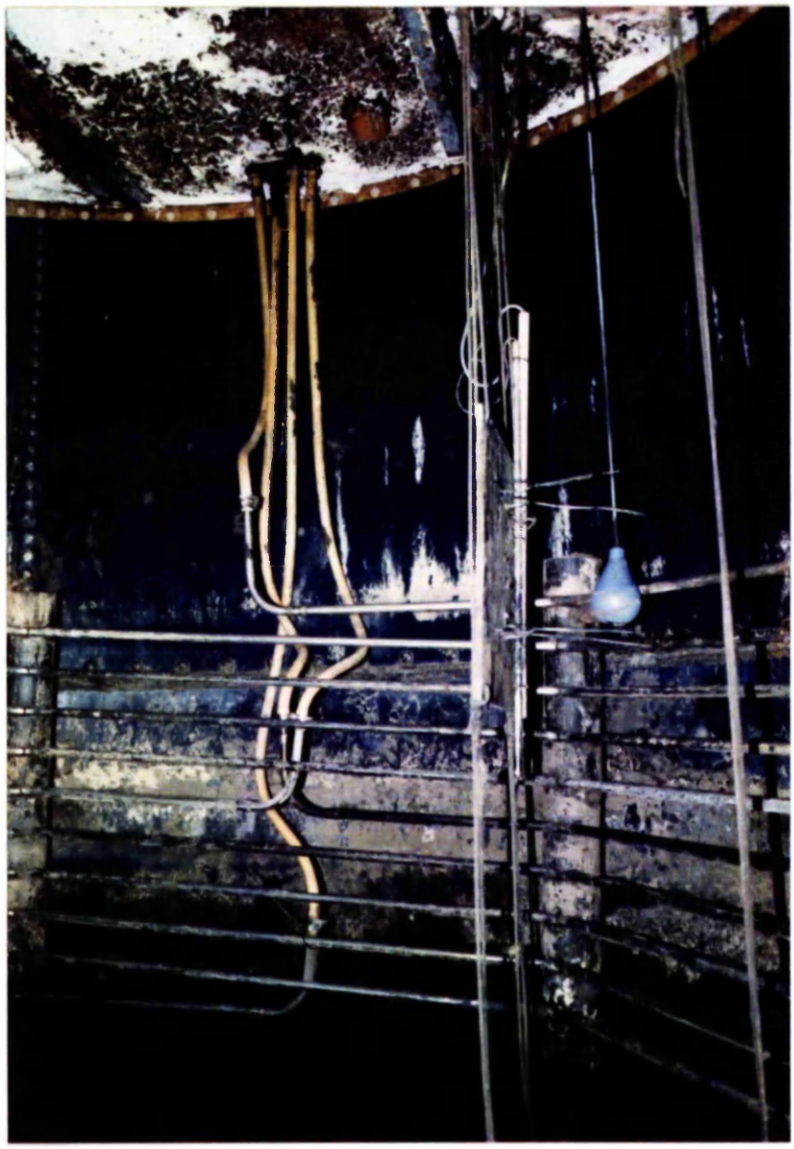

Fig.10 The reactor heat exchanger.

single layer, vertical helix with two parallel circuits to reduce the frictional losses of the circulated water. The hot water from this primary circuit was a source of energy for a 12kW heat pump (Loewe CTH 12/6, manufactured by Loewe Pumpenfabrik GMBH, Germany) which was used for heating water to a maximum of 55^{o}C in a secondary circuit supplying heat, through a water-air fan-supported heat exchanger, into the two weaner houses. In some experiments, heat in excess of that required for the weaner houses or all the extracted heat was diverted to the one of the algal ponds. When the treatment temperature was controlled at 50 or 55^{o}C, the hot water from the primary circuit was used directly in the weaner house or in the algal pond, by-passing the heat pump.

7. METHODS AND MATERIALS

7.1. Analytical methods

7.1.1. Sampling of raw and treated slurry

Raw slurry, collected daily in the reception pit (Fig. 6) was stirred with a mechanical stirrer for 5 minutes before a one litre sample was taken with a dip bottle.

Treated slurry (mixed liquor-ML) was collected from the effluent pump outlet (Fig. 6) after pumping for a minimum time of 2 minutes, to allow the discharge of slurry held in the pump and the pipe. The average sample volume was 3l. Before the ML was subsampled for chemical analyses, the sample was stirred with a magnetic stirrer for 5 to 10 minutes to collapse any foam. In extreme cases, when the foam was very stable, a few drops of antifoam (Polyethyleneglycol, BDH) was added.

Both raw slurry and ML were thoroughly stirred with a magnetic stirrer to achieve homogeneous suspensions before subsampling for chemical analyses. Subsampling was executed with plastic, wide-end pipettes (1 to 10ml, Sterilin Ltd.) by drawing in the sample to the required volume in one action. If this was not achieved at a first attempt, the pipette was emptied and the process repeated. This procedure prevented a discharge of rapidly-settling particles at the bottom of the pipette which would occur if any excess volume was

discharged to reach the required level in the pipette.

7.1.2. Supernatant preparation

The liquid portion of slurries and ML containing dissolved solids - the supernatant - was separated from suspended solids by centrifugation. Samples were subjected to centrifugal force (RCF) 10,000g for 20 minutes at 10^{o}C.

7.1.3. Total and volatile solids

Total solids (TS) were determined by drying 2x 20ml volumes at 105^{o}C for 24 hours. The samples were then placed in dried, weighed crucibles and heated at 550^{o}C in a muffle furnace for two hours. Volatile solids (VS) were calculated from the final weight of ash.

7.1.4. Total and volatile suspended solids

10ml of sample was filtered, using mild vacuum, through 90mm, dried and weighed, glass fibre filters (Whatman type GF/A, BDH), then dried for 24 hours at 105^{o}C and weighed, to calculate total suspended solids (TSS). Volatile suspended solids (VSS) were determined by weighing the cooled ash and filter after muffling the dried sample at 550^{o}C for 1 hour.

7.1.5. Chemical oxygen demand

Chemical oxygen demand (COD) of samples was determined by boiling and refluxing 20ml of a suitably-diluted sample, with a mixture of sulphuric acid, silver

sulphide catalyst, mercury sulphide and potassium dichromate for 2 hours as described in Standard Methods (1971).

7.1.6. Biochemical oxygen demand of supernatant

The biochemical oxygen demand of supernatant (BOD_{5s}) was determined by a modified dilution method described in Standard Methods (1971). The solution for dilution was prepared from deionized water (Millipore R/Q Water purifier) at a controlled temperature of 20°C. It was aerated with a sinter stone for about two hours and, to prevent supersaturation, the water was then left unaerated for a minimum of 30min. An inoculum of a bacterial population was then added. The inoculum was prepared from a 3 litre reactor continuously stirred and aerated at 20°C. The reactor was fed once daily with raw piggery slurry diluted to 36g COD/l and the residence time was maintained at 15 days.

The sample for inoculation was withdrawn before feeding the reactor and was allowed to settle for 20 minutes. The liquid portion was used as inoculum. Into one litre of deionised water, 2ml of the inoculum was added along with 1ml of each of four mineral salt solutions described in Standard Methods (1971).

To achieve about 50% utilisation of the dissolved oxygen available in the solution for dilution, samples of raw slurry and the ML were appropriately diluted with dilution water before adding into the solution.

The determinations were duplicated in 250ml glass bottles with ground stoppers. Before closing, the bottles were tapped to allow all trapped bubbles to escape. The closed bottles were submerged in deionised water, to prevent ingress of air, and incubated for 5 days at $20^{o}C$.

Blank bottles, prepared with deionised aerated water, inoculum and minerals were incubated along with the samples. After five days, the remaining DO was measured with a dissolved oxygen probe (Kent Industrial Measurements LTD, Model 8012) using a pH/ion meter (EIL, Model 7030). Corrected to $20^{o}C$ and atmospheric pressure (p), the dissolved oxygen in the 100% saturated water was

$$DO = 9.08p/760 \qquad (mgO_2/l)$$

The $BOD_{5(s)}$ was then calculated as

$$BOD_{5(s)} = (DO\ Blank - DO\ Sample) * 9.08 * Dil.factor$$

7.1.7. Total biochemical oxygen demand

To avoid errors caused by sedimentation of solids in the unmixed bottles and by the very high dilution of samples, a different method to that for supernatant was used. Gilson respirometers with continuously shaken bottles containing up to 10ml of sample diluted 15 to 200 times (Hissett *et al.*, 1975) were used. This method is also advantageous in allowing the BOD to be

calculated every day at frequent intervals to establish the BOD curve of the sample over an extended period without disrupting or destroying the sample.

7.1.8. Kjeldahl nitrogen

To determine Kjeldahl nitrogen (Kj-N), a 15ml sample was digested with zirconium dioxide and $CuSO_4$ catalyst and the solution described by Glowa (1974) and then distilled by steam. The distillate was titrated by Standard Methods (1971).

7.1.9. Ammoniacal nitrogen

The determination of ammoniacal nitrogen (NH_4^+-N)was carried out as prescribed by Standard Methods (1971) with some modification. 40ml of diluted sample was used for steam distillation. Ammonia was distilled into 20ml of boric acid (20g/l) which was then titrated as described in Standard Methods (1971).

7.1.10. Organic nitrogen

Organic nitrogen (Org-N) was calculated as a difference between Kjeldahl nitrogen and Ammoniacal nitrogen.

7.1.11. Nitrite nitrogen

Nitrite nitrogen (NO_2^--N) was semiquantitatively determined with 'Merckoquant' indicator strips (BDH Ltd.).

7.1.12. Nitrate nitrogen

Nitrate nitrogen (NO_3^--N) was measured with an ion-selective electrode (Orion Research Laboratory), connected to a pH/ion meter (Model 7030, EIL Ltd.). To avoid errors caused by the presence of unknown quantities of various ions, a known-increment method was used.

7.1.13. Total organic acids

Total organic acids (TOA) were determined by a method used for sewage sludge liquor (Montgomery *et al.*, 1962). The optical density at 500nm of 0.5ml sample of supernatant was measured after reacting with ethylene glycol, hydroxylamine and ferric chloride. A standard curve with zinc acetate was prepared daily for each batch of samples.

7.1.14. pH values

pH values were measured with a combination pH electrode and a pH meter (Models 41B EIL Ltd. on fermenters and 730 EIL Ltd. for single samples).

7.1.15. Dissolved oxygen

The dissolved oxygen (DO) concentration in the ML in the reactor was measured with a Mackereth type electrode and a DO meter (Model 94A, EIL Ltd.). The electrode output was compensated with a thermistor for temperatures up to 50^{o}C.

7.1.16. Redox potential

Redox potential was measured with a combination electrode Hg/HgCl-Pt, filled with 3M KCl and connected to a pH meter (91B EIL Ltd.). The electrode was checked for the upper part of its scale with a Zobell's solution (Jacob, 1970)

KCl	7.4560g
$K_3Fe(CN)_6$	1.0975g
$K_4Fe(CN)_6 \cdot 3H_2O$	1.4080g

made up to one litre with deionised water. The normal reading of the clean electrode was +190mV E_{cal}.

To check the lower part of the scale, raw piggery slurry was used. The normal reading was about -400mV E_{cal}.

When these check readings were not obtained, the platinum electrode was cleaned and the debris from the salt bridge was scraped off. If the calibrating values were still not obtained after cleaning, the electrode was replaced by a new one.

Values of the redox potential were expressed as mV E_{cal}.

Logging of the redox values with a BBC computer - logger required optical isolation of the redox signal from the meter, otherwise great distortion of the values was experienced.

7.1.17. Capillarity suction time

Capillarity suction time (CST), as an indicator of

filterability of slurry, was measured with a CST apparatus (Triton-WRC, Model 131&92) using a cylinder with 18mm diameter.

7.1.18. Sedimentation volume index

Sedimentation volume index (SVI) was measured in a 1 litre graduated glass cylinder and volumes of settled sludge were read at intervals between 0.5h and 24h.

7.1.19. Temperature

All temperatures at the treatment plant were measured with a 590kΩ sensor (RS Components), an integrated circuit temperature transducer providing a linear output voltage of 1mV/K.

Temperatures were scanned at 24second intervals, logged and stored on a floppy disc.

7.1.20. Relative humidity

A differential temperature of wet and dry Pt-100 temperature probes, placed in a fan-aspirated box was measured with an electronic thermometer (Control and Readout Ltd.). Relative humidity was then determined using this differential and ambient temperature, from tables for relative humidity (Casella, London).

7.2. Control and monitoring of the treatment plant and auxiliary equipment

Automatic control of the following parameters of the treatment plant was required:

1. Depth of raw slurry in the reception pit

2. Mixing of raw slurry and subsequent pumping into the reactor
3. ML discharge
4. ML temperature
5. ML dissolved oxygen level

7.2.1. Reception pit

The slurry depth was continuously monitored with an ARCON ultrasound level monitor and recorded on the chart. A minimum depth of slurry had to be maintained to prevent the Mono-pump from running dry. It was achieved by a power cut-off relay, activated by the ARCON ultrasound level monitor when sensing a depth of 250mm or lower and inactivated when the depth returned to 250mm.

7.2.2. Transfer of raw slurry to the reactor

The mixing of raw slurry before and during pumping into the reactor, the period of pump operation and the periods between pumping and between mixing were controlled by an industrial timer which, at hourly intervals, activated a multiple cam timer controlling the duration of mixing and pumping. The stirrer was always activated approximately 2 minutes before pumping. The average pumping interval was 45 seconds. The timing device was included in a control box (Fig. 11) which housed a majority of control equipment.

7.2.3. Discharge of mixed liquor (ML)

Various treatment times of slurry (constant residence times in the reactor) were achieved for the constant

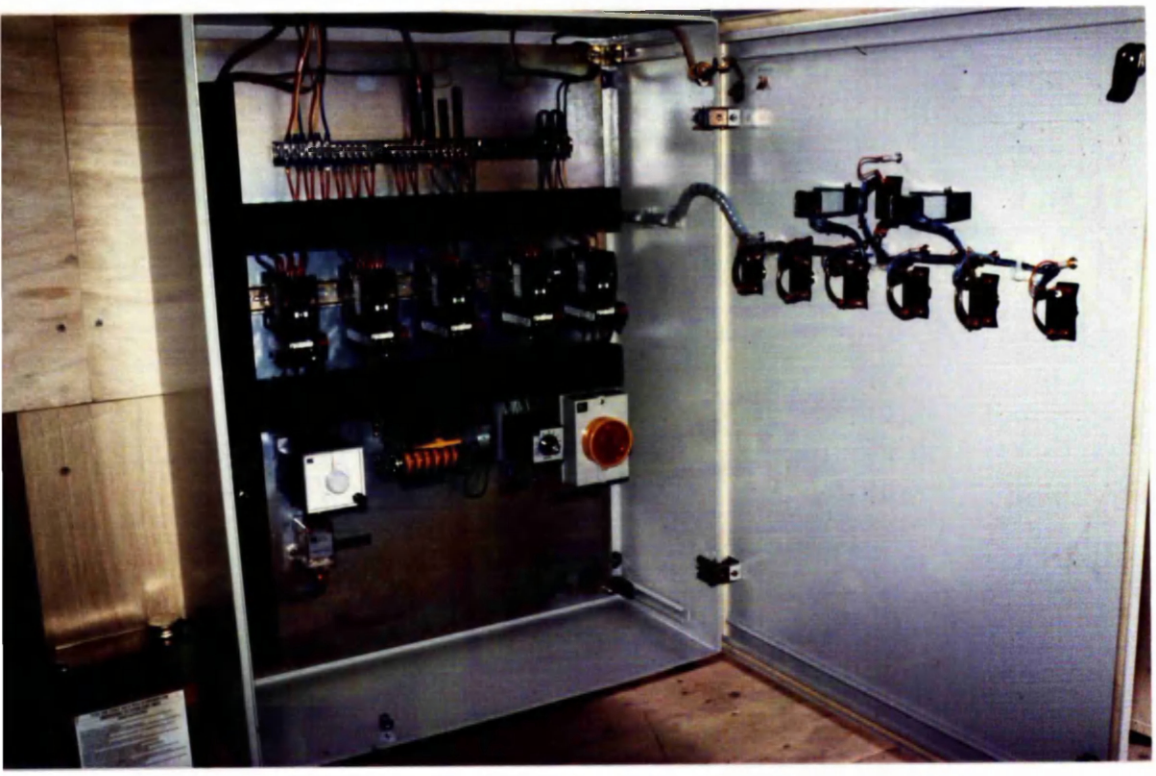

Fig.11 The plant electrical control box.

Fig.12 The plant control room.

feed rate by varying the volume of the ML in the reactor. The depth of the ML, the only variable, was controlled by pumped discharge activated by a float switch. A time delay relay was an essential requirement in the circuit to prevent repeated starting and stopping of the pump due to the disturbance of the surface level of the ML by the aerator.

During experiments 1 to 6 the volume of ML discharged was measured with a tipping bucket. This method, due to wear, rusting, failures of the counting meter and accumulation of foam under the tipping bucket, which destabilised the bucket balance, was substituted in all other experiments by measuring the duration and the rate of the ML discharge.

7.2.4. Temperature of ML

The temperature of the ML was controlled at predetermined levels of 35, 50 and 55^{o}C by heat extraction. Water circulation through the heat exchanger was activated by a temperature controller (Clearspan P 130 L, Foster, Cambridge) measuring the temperature with a platinum resistance probe (Pt 100) suspended in the ML (Fig. 6).

7.2.5. Dissolved oxygen level of ML

The DO level in the ML was measured with a DO meter (Model 94A, EIL Ltd) using a temperature-compensated Macareth type electrode suspended in the ML. The

continuously-running aerator incorporated the gas, from the space between the liquid level and the reactor lid, into the ML and the oxygen in this head space was slowly used up. Thus the oxygen transfer rate in the ML decreased and the DO level fell. When DO reached the preset value, the DO meter activated, through a time delay relay, a fan on the reactor lid which started blowing fresh air into the reactor. The oxygen level in the head space was thereby increased, oxygen transfer rate improved and DO returned to its preset level. Originally the large quantity of foam overflowing into the aerator cone prevented most of the air being drawn into the ML and the DO did not therefore reach the predetermined levels. To overcome this problem the fresh air from the fan was ducted through a flexible 75mm pipe straight into the cone below the level of the foam. By this means DO concentrations up to 70% were obtained.

When the DO concentration was required at levels around 1% of saturation, the external fan was controlled by the redox meter, instead of the DO meter. The redox level was then controlled between +100 and -350 mV E_{cal}.

The concentration of oxygen in the exhaust gas was measured and monitored continuously with a paramagnetic O_2 analyser (Model 6800, Kent Industrial Instruments Ltd). The concentration of CO_2 in the exhaust gas was measured occasionally by an Orsat gas analyser.

7.3. Monitoring and recording of plant parameters

Parameters affecting the performance of the plant and parameters used for calculation of mass balance and energy balance were measured and recorded a) manually once a day and b) continuously by a logger, designed and constructed by National Institute of Agricultural Engineering at Silsoe, Bedfordshire (recent name is Silsoe Research Institute).

7.3.1. Daily records

Daily records were made of the volume of water used in the piggery, volume of water circulated through the primary heat exchanger, minimum, maximum and instantaneous ambient temperature, and operating spans of DO concentration and Redox potential. Duration (hours) of running of 1) fan exchanging air in the reactor, 2) ML discharge pump and 3) primary heat exchanger pump were also noted daily.

Daily records of electrical energy (Fig. 12) consumed for aeration, foam control, heat pump, mixing and pumping of raw and treated slurry and for controlling equipment were maintained. Heat energy extracted from the reactor was measured by heat meter-integrator (ISS Clorius Ltd., Type SVME-62-5-6-0-1-2-3). Further daily records were made of values of a counter on an integrator recording the concentration of oxygen in the exhaust gas during the fan operation.

7.3.2. Continuous recording

A logger designed and constructed by National Institute of Agricultural Engineering was used (Fig. 12) with a BBC computer to record nine plant parameters every 24 seconds. They were : dissolved oxygen concentration, redox potential, the temperature differential of wet and dry thermometer and the temperatures of ambient air, raw slurry, the ML, tank surface (a mean of three temperature probes attached at different places), exhaust gas and the soil beside the reactor insulation at a depth of 0.6m. Mean, minimum and maximum values were recorded hourly on a floppy disc. These recorded data were then processed to obtain mean, minimum and maximum values for each experimental run.

7.3.3. Data processing

The analytical data of characteristics of raw and treated slurries were handled using the MINITAB statistical package.

The relationships between individual characteristics were examined using linear regression. The standard deviations and correlation coefficients R^2 adjusted were produced.

In the graphs describing the relationships between individual characteristics of raw slurry are subjected to a 95% confidence data range.

Monitored and analytical data were processed (calculation of energy and mass balance of the reactor)

with a computer program "Hepcal" which was written in BBC Basic and is listed in Appendix D and its use described in Chapter 8.

Data resulting from calculations using "Hepcal" program were compared with the data predicted by "Farm Waste Management" program described elsewhere (Baines *et al.*, 1986; Svoboda, 1989). It has been developed from the work of Evans *et al.* (1982) and used for predicting the characteristics of treated slurry and heat recoverable from the farm scale aerobic reactor used in the current experiments (Svoboda and Evans, 1987; Svoboda and Fallowfield, 1989).

8. ENERGY BALANCE

The flow of energy in and out of the reactor is described in a flow diagram, Figure 13. Energy of two different forms, electrical and heat, was involved in the reactor energy balance. Electrical energy was used to power the aerator and a foam cutter. Since both these units were located inside the reactor, all the electrical energy consumed by the electric motors of the aerator and the foam cutter was transformed, eventually, into heat energy. Therefore the electrical energy formed part of the energy input, while the energy output was entirely heat energy.

Energy input was divided into several streams.

i) Heat of influent slurry

ii) Heat of influent air

iii) Heat of external radiation from the sun

iv) Electrical energy for aeration and foam destruction

v) Heat from aerobic metabolism - derived from measured COD and total nitrogen available for oxidation

Heat energy output from the reactor was as follows:

i) Heat of discharged treated slurry

ii) Heat of exhaust air

iii) Heat from reactor surfaces

iv) Extracted heat energy

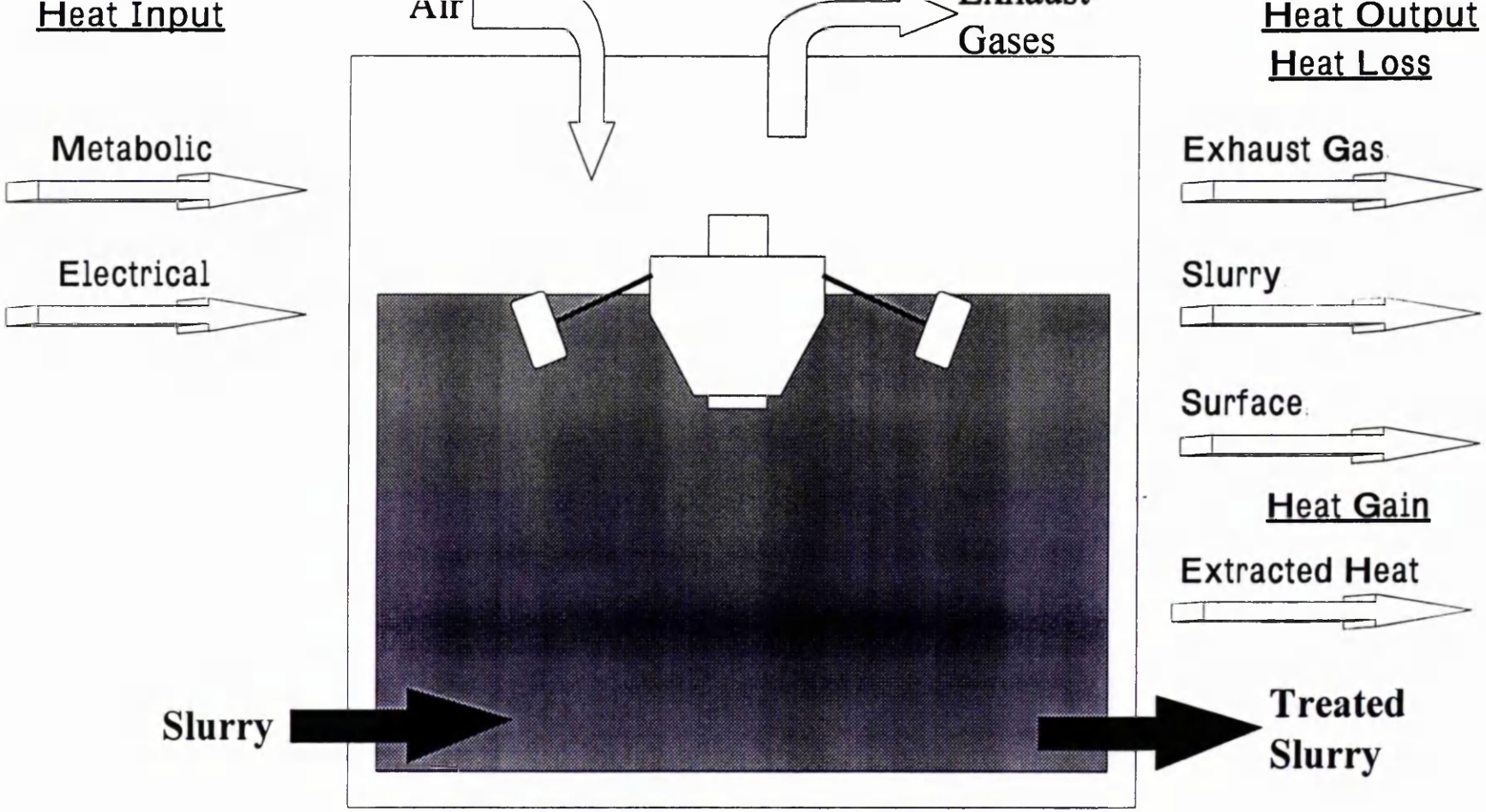

Fig.13 Mass and energy flow diagram of the reactor.

The difference between the energy input and the energy lost as heat during the experiments, was the heat energy extracted from the reactor in order to keep the mixed liquor in the reactor at the preset temperature.

The limitations in techniques for measuring heat gains and losses at the reactor surface by radiation, water evaporation and wind cooling, were identified and an alternative method of measurement to include these heat differences was substituted by measuring the temperature of the reactor surface in three different places.

The heat extracted from the reactor was directly measured and compared with that theoretically obtainable and with the difference between the heat input and heat losses from the reactor, calculated from known measured parameters.

The heat input as electrical energy and heat output as extracted heat were directly measured. The changes in biochemical energy were calculated from the changes in COD and oxidisable nitrogen and the theoretical quantity of heat evolved during oxygen consumption (Evans *et al.*, 1982).

The 'net' loss of heat from the reactor was calculated from the quantities of heat associated with the liquids (feed and treated slurry), gases (inlet air and exhaust gas) and that transmitted at the reactor surface.

The extractable heat was then calculated as the

difference between heat input and heat loss. This value was compared with that obtained by measurement of extracted heat.

A short computer program (HEPCAL) was constructed in BBC Basic to calculate the energy balance of the reactor from the measured and monitored data. This program is listed in Appendix D and its use described in Chapter 8.1.

8.1. Energy input

8.1.1. Mechanical energy input

The electrical energy supplied to the aerator and the foam cutter was measured in kWh by two separate meters.

The aerator was powered by a 4kW three-phase motor. The electrical consumption of the motor was dependent on several parameters. The size of the impeller was the most important. During these experiments two sizes were used, 2kW and 4kW, so the consumption of electrical energy of the motor was about 2 or 4kWh. The direction of rotation, when changed from anticlockwise to clockwise, increased the electrical consumption by about 80%. The depth of submersion of the aerator, the total solids of the ML and the foam dispersion in the ML also affected the power input. All these effects were accounted for by the daily measurement of total electricity consumption by the aerator meter.

The electrical energy consumption of the foam cutter motor was affected by the foam depth and its

density (when a standard size, 300mm, foam cutting blade was used). Such variations were accounted for by daily readings of total electricity consumption by this motor.

8.1.2. Heat energy from metabolism

Heat energy released from slurry by biochemical oxidation of compounds within the slurry during aerobic microbial metabolism was calculated by multiplication of the weight (kg) of oxygen required for oxidation of carbon and nitrogen compounds and the heat evolution rate (kWh/kgO_2) corresponding to the metabolic reaction (Evans *et al.*, 1982). The quantity of oxygen required was measured as :

i) the difference (DCOD) between the total COD of slurry input and output

DCOD = AVRAW * cod - VEFF * code (kg) (line 500)

where AVRAW is the volume of raw slurry, VEFF is the volume of treated slurry, *cod* is the COD of raw slurry, and *code* is the COD of treated slurry.

ii) the quantity of oxygen (NOH) used to oxidise nitrogen to nitrate

NOH = (nloss + nox) * 4.57 (kg) (line 550)

where *nloss* is nitrogen lost during the treatment and *nox* is nitrate nitrogen in the treated slurry. The multiplication factor, 4.57, is the stoichiometric

requirement of oxygen (kg) for every kg of ammonia nitrogen oxidised to nitrate from the following equation:

$NH_4^+ + 2O_2 \rightarrow 2H^+ + H_2O + NO_3^-$

The quantity of oxygen, NOH only, is used for calculation of heat evolved from nitrification.

iii) the total quantity of oxygen (NO) used for nitrification

NO = (nloss * 0.375+ nox)* 4.57 (kg) (line 530)

where the coefficient 0.375 is the stoichiometric proportion of oxygen not used during denitrification which is described by the equation:

$4NO_3^- + 4H^+ \rightarrow 2N_2 + 5O_2 + 2H_2O$

Of the oxygen in NO_3^-, 62.5% is reused for carbon degradation (Johnstone, 1984) and is therefore included in the difference between the total COD of slurry input and output (DCOD).

The total oxygen requirement is then calculated as

AOX = NO + DCOD (kg) (line 960)

The rate of evolution of heat from heterotrophic carbon metabolism related to the oxygen requirement was found to be 4kWh/kgO_2 by Cooney *et al*. (1968) and this value was used in the calculation of the quantity of heat evolved:

HC = DCOD*4 (kWh) (line 610)

The heat evolution rate for nitrification, oxidising ammonia to nitrate, was taken as 1.2kWh/kgO_2 (Sharma and Ahlert, 1977; Evans *et al.*, 1982) and was calculated as

```
HN = NOH*1.2                    (kWh)    (line 620)
```

Thus the total analytical metabolic heat was

```
AHMET = HC + HN                 (kWh)    (line 950)
```

The value, AHMET, was then compared with the observed value, Hmet, calculated from measured heat inputs and heat losses from the reactor.

```
Hmet = he - Htot + ASLOS        (kWh)    (line 920)
```

where *he* is the measured extracted heat, *Htot* is the heat input into the reactor from the aerator and the foam cutter and *ASLOS* is the sum of air, liquid and surface losses from the reactor.

8.2. Heat losses from the reactor

8.2.1. Heat losses in effluent (treated slurry)

The volume of slurry pumped into the reactor was calculated from the number of pumping shots of the MONO pump and the duration of the shots. The wear of the pump and, especially the continuous change of the suction head caused unaccountable variations in the delivered volumes and this method of measurement was

therefore abandoned. A tipping bucket was then used to measure the volume of effluent. Due to the build up of foam in the tank under the tipping bucket the balance of the tipping bucket was upset and this method proved to be unreliable and was discarded.

The method adopted for the subsequent experiments (7 onwards) was based on measurements of the pumping time of the discharge pump and the pumping rate which was checked twice weekly. The level in the reactor was controlled by a level switch, thus the suction head of the pump was constant and the flow rate was very stable.

The volume of slurry pumped into the reactor was calculated as the sum of the volume of effluent and the volume of water evaporated from the reactor during aeration. Two methods were used to calculate the volume of evaporated water from the weight of air passing through the ML. The weight of air was calculated in the first method from the stoichiometric requirement for oxygen to satisfy the observed decrease of COD (line 500) and oxygen used for nitrification (line 530). Thus the total weight of air was

AAIR=[(DCOD+NO)/1.429)/(21-oc)1.293*100 (kg) (line 570)

DCOD - difference between COD of raw and treated slurry
1.429 - specific gravity of oxygen
21 - volumetric percentage of oxygen in air
oc - concentration of oxygen in the exhaust gas
1.293 - specific gravity of air

Total evaporated water was obtained by the equation:

$AWATER=AAIR(ewc-iwc)/10^6$ (m^3) (line 580)

where ewc and iwc are the weights (g) of water (g/kg gas or air) transferred by exhaust gas, and inlet air at measured temperatures and humidities.

This quantity of water is included in the measured volume of input slurry thus the COD difference increases causing an increase of evaporated water and so on. This was solved by an iterative method (lines 590 and 600).

In the second method, the flow rate of air through the reactor was directly measured. Because the air was blown in only when required, the total air volume was equal to the product of the flow rate and the time the fan was working. This volume was then transformed to the normal volume by the following calculation

$A = fh*av*p/760$ (m^3) (line 400)

where A, fh, av and p, are the normal volume of air, working hours of the fan delivering air to the air pocket above the ML, the air rate and the atmospheric pressure respectively. The total air weight was

$AIR=1.293\ A$ (kg/m^3) (line 410)

and the volume of evaporated water was calculated from the line 580.

These values, calculated by the second method, were

used for orientation only because of the uncontrollable variations in the air flow rate.

The total heat loss in the treated effluent, which is equivalent to the heat required to warm the input slurry to the temperature of discharged effluent slurry was thus calculated as

ALLIQ = AVRAW*1.16*(temp-t1) (kWh) (line 690)

where ALLIQ, AVRAW, 1.16, temp and t1 are the effluent heat loss, volume of raw slurry, calories to kilowatt hours conversion coefficient, temperature of the ML and temperature of raw slurry. A specific heat of one was assumed for all slurries. The correction factor for solids content in the slurry was not known but calculations have shown that it would be in the range of error, due to the relatively low TS concentrations (Chen and Hashimoto, 1983).

8.2.2. Heat losses in exhaust gas

Air entered the reactor at ambient temperature (t_2), lower than the reaction temperature and a partially oxygen-depleted gas, saturated with water was exhausted at a temperature (t_4) lower than that of the ML. The lower temperature was a result of the insulation properties of a foam layer, approximately 200mm in depth, constantly present on the surface of the ML.

Various researchers (Kordes and Bauer 1986; Vismara, 1985) in calculating heat loss, have used the

values of specific heat of air and water and heat of vaporisation. An alternative method (Woods *et al.*, 1979), used in this study, was to calculate the change of enthalpy of input and exhaust air. This was extrapolated from the psychrometric tables (CIBS Guide C1&2, 1975) using the temperature and relative humidity of input air, in this case ambient air, and the temperature of exhaust gas saturated with water which was measured at the gas outlet (Chapter 7). Then the air heat loss in the exhaust gas was

ALAIR=AAIR*(eent-ient)/3600 (kWh) (line 690)

where ALAIR was heat loss in exhaust gas(kWh), AAIR weight of dry input air (kg) and eent and ient were enthalpies of exhaust gas and input air (kJ/kg).

The analyses of exhaust gas showed in general that the volume of oxygen consumed was replaced by carbon dioxide, corresponding with the equation describing oxidation of glucose

$$C_6H_{12}O_6+6O_2 \text{ ---> } 6CO_2+6H_2O$$

8.2.3. Heat losses from the reactor surfaces

It was not possible to measure the heat losses caused by radiation and conduction. The reactor was partially shaded by the piggery and an instrumentation hut and the different parts of the reactor were exposed to various influences of weather elements. Calculation of

the gains by radiation from the sun or heat losses due to wind and rain would be, therefore, highly erroneous. As an alternative, in order to obtain some measure of the effects of these elements, the temperature of the reactor surfaces was measured in three different places by temperature probes placed on the lid and wall of the reactor. The average temperature of these probes was then used as the temperature of reactor outer surfaces above the ground, and the calculations of heat losses were derived from these average temperatures.

The degree of insulation varied in different parts of the reactor, therefore appropriate insulation values were applied according to the different areas (line 740 of the program).

Heat loss by transmission from the reactor surfaces, was calculated from surface area (S) in m^2 and the coefficient of thermal conductivity (k) in W/mK and temperature differences between the inner and outer surface of the reactor. The 'U' values (W/m^2K) of the appropriate areas were calculated according to the following equation

$$U = 1/[(a1/k1) + (a2/k2) + ...+ (an/kn)] \quad (W/m^2K)$$

where a is the thickness of the material and k is its k value.

Table 7. Thermal conductivity values of materials used for construction and insulation of aerobic reactor.

Material		Thermal conductivity W/mK
Base	- concrete	0.66
	polystyrene	0.034
Walls	- steel	70.0
	glass	0.7
	polyurethane	0.026
Lid	- styroform	0.029
	plywood	0.14

During experiments the change in treatment time was effected by varying the volume and hence the level, of the ML in the reactor. This affected the temperature differential between the inner and outer surfaces. In order to be able to describe these variations, the surface area was divided into sections (computer model Chapter 8) which were calculated using the depth of the ML (*v*-defined on line 710) in the reactor. The inner and outside temperatures of these sections could then be defined.

For example, the heat loss calculated for an area of the reactor wall below ground with a uniform 'U' value and a constant difference in temperature between inside and outside was as follows

```
LS1 = con * v * (temp - t3)        (kWh)        (line 760)
```

where con is a constant which is a result of multiplication of 3.1415(Pi) by the diameter of the reactor and 'U' value of the area of wall calculated, v

is the height of the wall with a temperature difference (temp - t3) where temp is the temperature of the ML and t3 is the temperature of soil surrounding the insulated reactor wall. The heat losses from other areas were calculated similarly (lines 750 to 880). The total surface heat losses LSS (line 890), where the outside temperature of exposed parts of the reactor was the reactor surface temperature (t5), were used for calculation of total heat losses from the reactor.

LSS=(LSB+LS1+LS2+LS7+LS8+LS9+LS10+LS10L)*0.24*num (kWh)

LSB	- heat loss from base
LS1 and LS2	- heat loss from two parts of the reactor wall bellow ground level
LS7 and LS8	- heat loss from two parts of the reactor above ground level
LS9	- heat loss from the reactor lid
LS10	- heat loss from the walls of the top box
LS10L	- heat loss from the lid of the top box
factor 0.24	- conversion of Watts to kilowatt-hours
num	- number of days of the experiment

8.2.4. Total heat losses from the reactor

The total heat loss from the reactor is described on line 910 of the computer calculation. A theoretical value for recoverable heat was then obtained by subtraction of the total heat loss from the sum of the heat input and the theoretical heat gains from heterotrophic and autotrophic oxidation

AEXH=Htot+HN+HC-ASLOS (kWh) (line 930)

This value was then compared with the measured value of

recovered heat.

Since the heat losses from the reactor were calculated on the basis of insulation properties derived from tabulated values, direct measurements of heat losses were attempted.

Direct measurements of heat losses were obtained on two occasions during the experiments. On the first occasion the reactor contained tap water and the heat loss was calculated from the heat energy input and the rise in water temperature. Since these measurements were obtained before slurry treatment was started, the heat flux steady state of the system was not established and the heat losses were unrealistically high. Therefore a second experiment was performed when steady state was established during treatment at 50^{o}C, as described in Chapter 9.5.

9. EXPERIMENTAL RESULTS

9.1. Characteristics of untreated piggery slurry

9.1.1. Total Solids (TS)

Slurry was collected once a day in a slurry pit (Chapter 7) during the first phase of experiments (June - December 1986) and diluted with water to about 40g TS/l. The true mean value for this period was 48.1gTS/l with a standard deviation of 10.55g/l (Table 9). The concentration of TS increased to 67.55g/l (Table 10) during 1987 and 1988 when the slurry was collected and fed into the reactor in its original undiluted state.

During the entire three year period, the TS concentration varied between 17.6 and 101.8g/l with a mean value of 63.8g/l indicating a dilution with water of less than 1:1 when compared with the value of 100gTS/l given by Hissett *et al.* (1975), SAC Publication No.16. (1980) and Code of Good Practice (Scotland, 1992).

The chemical and biochemical characteristics of slurry are influenced by feed composition, feed conversion which further depends on the weight of the animal and, subsequently, by the time interval between excretion and analysis.

The fattening pigs weighed between 20 and 75 kg, and were fed a standard dry diet, containing 19.5% protein, 3% fibre, 5.5% oil, 6% ash and were allowed water *ad lib*. The diet of the weaning pigs was similar,

except for a higher protein content of 22%.

The diet of the fattening pigs contained twice the oil content and half the fibre content of the diet of pigs from which slurries were analysed by Evans *et al.* (1978) and O'Callaghan *et al.* (1971) who found that the TS of slurry, collected daily from below individually caged pigs, varied between 70.6g/l and 110.9g/l when the water-meal ratio was 2.5:1 and between 53g/l and 65.4g/l when the water-meal ratio was 4:1. The feed composition detailed in Table 8 was equivalent to 18.7% protein, 5.7% fibre, 2.6% oil and 6.1% ash.

Table 8. Feed composition (O'Callaghan *et al.*, 1971)

Material	Percent by weight
Barleymeal	65
Wheatings	25
Soya bean meal	2.5
White fish meal	7.5
Protein	16.5-17
Crude fibre	4.5
Drivite	0.066

The total solids of the supernatant (TSs) (Table 9 and 10) increased in proportion to the whole TS as shown by the regression of 391 analyses of these two parameters and described by the equation

$$TS_s = 2.27 + 0.183\ TS \qquad (g/l)$$

393 analyses, R^2 adj. 85%, $P<0.001$

This equation and all the following equations can be applied only within the minimum and maximum values

Table 9. Whole and supernatant slurry characteristics, during the year 1986. The units are g/l except %TS.

Whole slurry	N	True mean	%TS	St.deviation	Min	Max
TS	127	48.1	-	10.5	17.6	94.7
VS	127	34.7	72.1	8.1	11.9	71.2
TSS	124	38.6	80.2	8.8	10.8	73.1
VSS	124	29.5	61.3	6.7	7.9	56.6
COD	122	59.8	124.3	12.8	19.0	99.5
NH_4-N	78	2.27	4.72	0.64	1.25	3.86
Kj.-N	51	4.22	8.77	0.99	2.63	7.44
Org.-N	51	1.96	4.07	0.75	0.32	4.89
BOD_5	32	14.6	30.3	3.56	8.16	22.8
Supernatant						
TS	125	10.6	22.0	2.47	6.00	22.2
VS	125	4.85	10.1	1.35	2.50	13.4
COD	121	13.3	27.7	3.65	5.50	27.2
TOA	115	4.43	9.21	1.40	2.10	9.24
NH_4-N	78	1.81	3.76	0.54	0.69	3.41
Kj.-N	78	2.56	5.32	0.72	1.21	4.85
Org.-N	78	0.73	1.52	0.40	0.05	2.02
BOD_5	34	6.45	13.4	1.57	3.00	9.70

Table 10. Whole and supernatant slurry characteristics during the years 1987 and 1988. The units are g/l except for %TS.

Parameter	N	True mean	%TS	St.deviation	Min	Max
TS	504	67.6	-	10.7	25.2	101.8
VS	502	48.8	72.2	8.47	10.9	78.9
TSS	261	56.0	82.8	9.80	16.6	85.8
VSS	260	42.9	63.5	7.66	12.0	68.6
COD	493	80.8	119.5	16.8	32.3	128.0
NH_4-N	255	3.81	5.64	0.99	2.01	7.14
Kj.-N	253	6.84	10.1	1.32	4.09	11.1
Org.-N	250	2.97	4.41	0.70	0.66	5.67
BOD_5	65	19.5	28.8	5.33	10.1	34.3
CST	48	2254	-	441	1330	3728
Supernatant						
TS	268	15.1	22.3	2.52	8.00	22.0
VS	268	7.20	10.7	1.58	3.40	11.9
COD	262	18.2	26.9	3.99	8.20	28.3
TOA	252	6.87	10.2	2.06	2.18	15.9
NH_4-N	249	3.24	4.79	0.88	1.26	6.15
Kj.-N	252	4.52	6.69	1.13	2.51	7.66
Org.-N	238	1.26	1.86	0.59	0.03	3.15
BOD_5	157	7.77	11.5	1.85	1.03	14.4

of the correlated parameters.

The mean value of TSs as a proportion of TS was 0.21 which is 1.6 times higher than the values observed by Hissett *et al.* (1975) and Evans *et al.* (1979).

9.1.2. Volatile Solids (VS)

The organic matter content of the slurries was expressed as a percentage of TS as shown in Tables 9 and 10. The VS values and hence the percentage of TS values were consistently slightly lower than those reported elsewhere. As a percentage of TS, the VS varied between 43 and 83% with a true mean value of 72.3%.

O'Callaghan *et al.* (1971) found that the VS content of slurry did not change significantly with changes in TS concentrations and was on average 83% of TS.

Piggery slurry was analysed by Evans *et al.* (1979), over a period of more than three years. Slurry from fattening pigs of 20 to 100kg weight, was collected twice weekly in a tray suspended underneath the slatted floor of a pen. The average value of VS was 81.9% of TS. The same source continued to be analysed and the value of VS as a proportion of TS declined as reported by Williams and Evans (1981), as follows: slurry collected in summer 1978 - 81%, winter 1978 - 80% and winter 1979 - 76%.

A similar value of 80% of TS, in slurry from pigs fed on the diet of ground corn and soybean meal and a

mix of vitamins and minerals, was reported by Schulte *et al*. (1985).

Variable values were obtained by Sutton *et al*., (1985). In a diluted pig slurry, VS varied between 48 and 54% while in slurries of 50 to 100 g TS/l the value increased from 55 to 77% of TS.

Barth (1985) calculated the percentage of VS in TS using estimated values based on the digestibility of feed components. For rations containing 14% of protein, it varied between 80.5% for pigs weighing 4.5 to 11.3kg and 87.8%of TS for finishing pigs weighing 56.8 to 99.8kg. However the ASAE Year-book (1983) lists the value as 80% for pigs of the all these weights.

Similarly high figures were observed by Payne (1986) at 11 commercial pig farms near Perth (Australia) and at the Medina Research Station (MRS). The average values of VS were 85.2% and 86.5% of TS of slurries from the 11 farms and from MRS respectively.

The lower values of VS obtained in the present study might be partially due to the inclusion of slurry from weaning pigs. This was collected below the perforated floor of the weaner house and could have undergone some anaerobic degradation during storage at temperatures of 18 to 28^{o}C before overflowing into the cross channel and mixing with the slurry from the fattening pigs. Lower VS, about 71% of TS, for slurry from weaners were reported by Donham *et al*. (1985).

Figure 14 is the graphical expression of the regression equation

$VS=-2.14+0.756\ TS$ (g/l)

629 analysis, R^2 adj. 97.2%, $P<0.001$

The correlation coefficient R^2 observed for correlation between the supernatant total solids (TSs) and supernatant volatile solids (VSs) was lower than that for whole slurry, but the relationship was still highly significant.

$VS_s = -0.656 + 0.522\ TS_s$ (g/l)

393 analyses, R^2 adj. 85%, $P<0.001$

9.1.3. Total Suspended Solids (TSS)

Total suspended solids are those which can be partially removed by gravity settlement or mechanical separation. The mean values are shown in the Tables 9 (1986) and 10 (1987-1988).

The relationship between TSS and TS is described by the equation

$TSS = 0.222 + 0.802\ TS$ (g/l)

385 analyses, R^2 adj. 89%, $P<0.001$

and graphically, together with 95% confidence intervals in Fig. 15.

The true mean value of the percentage of TSS as TS was 80.6% and varied from 57.9% to 97.4%. This was

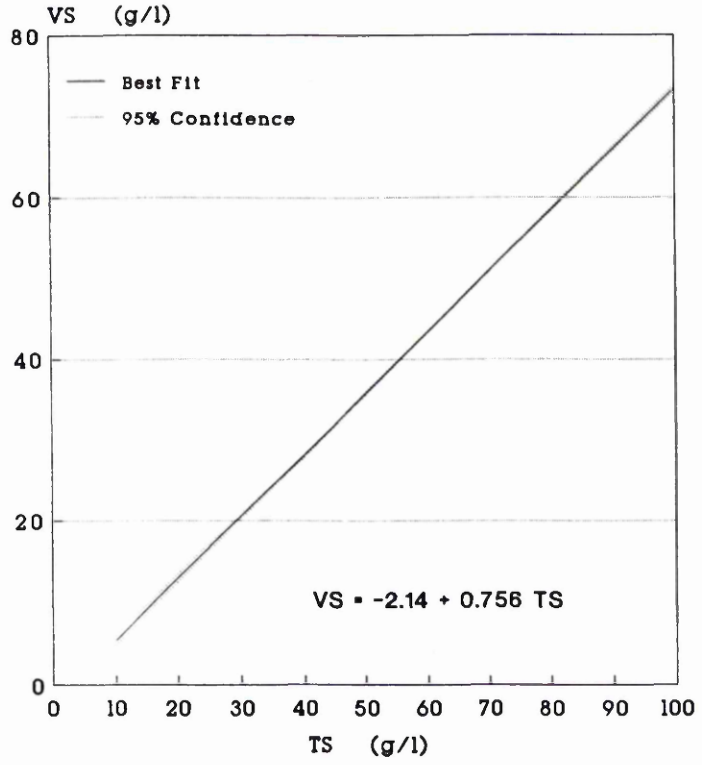

Fig.14 Best fit for linear regression of VS and TS of input slurry.

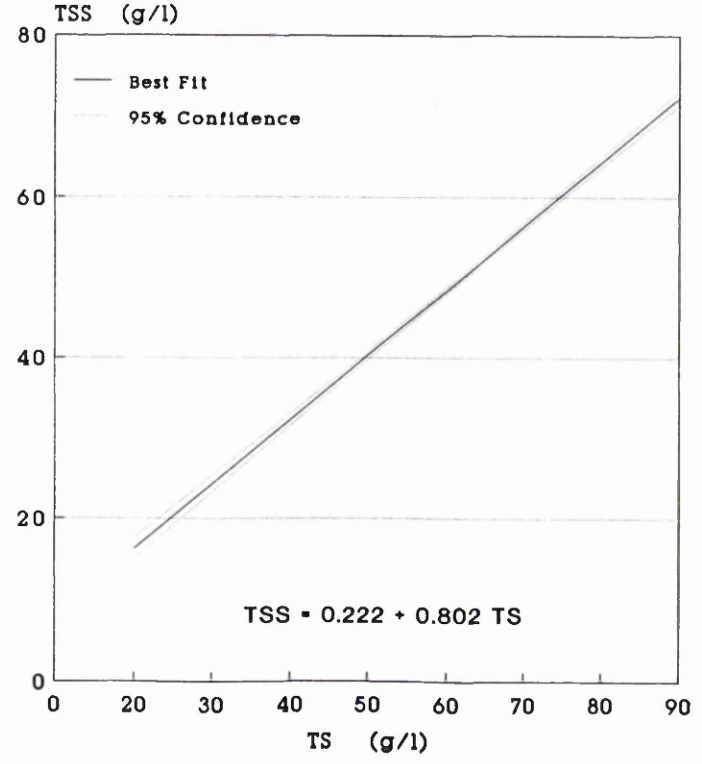

Fig.15 Best fit for linear regression of TSS and TS of input slurry.

lower than the values stated by Evans *et al.*, (1979, 1980, 1983) (86%), Williams and Evans (1981) (82 to 87%) and Payne (1986) (88.4%). The lower value may be explained by the lower fibre content of the diet as mentioned above (Chapter 9.1.1.).

The correlation between VSS and TSS is described by the equation

$$VSS = 0.310 + 0.759\ TSS \qquad (g/l)$$

384 analyses, R^2 adj. 96.7%, $P<0.001$

and with 95% confidence intervals in Fig. 16.

The true mean value of VSS as a proportion of TSS was 77% and the values ranged from 59 to 87%.

9.1.4. Chemical oxygen demand

The COD varied widely as shown in Tables 9 and 10 due to the variable dilution with water during the years 1986 to 1988.

The relationship between COD and TS is described by the equation

$$COD = 7.45 + 1.09\ TS \qquad (g/l)$$

615 analyses, R^2 adj. 60.3%, $P<0.001$

and graphically expressed in Fig. 17.

COD varied between 60 to 187% of TS with a mean value of 120% which although slightly lower than recorded by Evans *et al.*, (1979) (133%) and Payne (1986) (167%), agrees with the lower VS value obtained above.

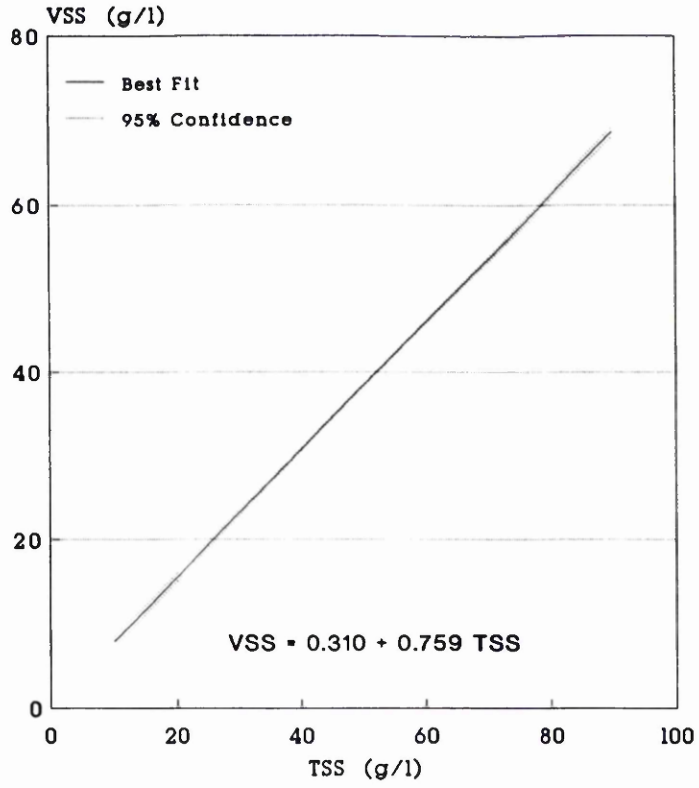

Fig.16 Best fit for linear regression of VSS and TSS of input slurry.

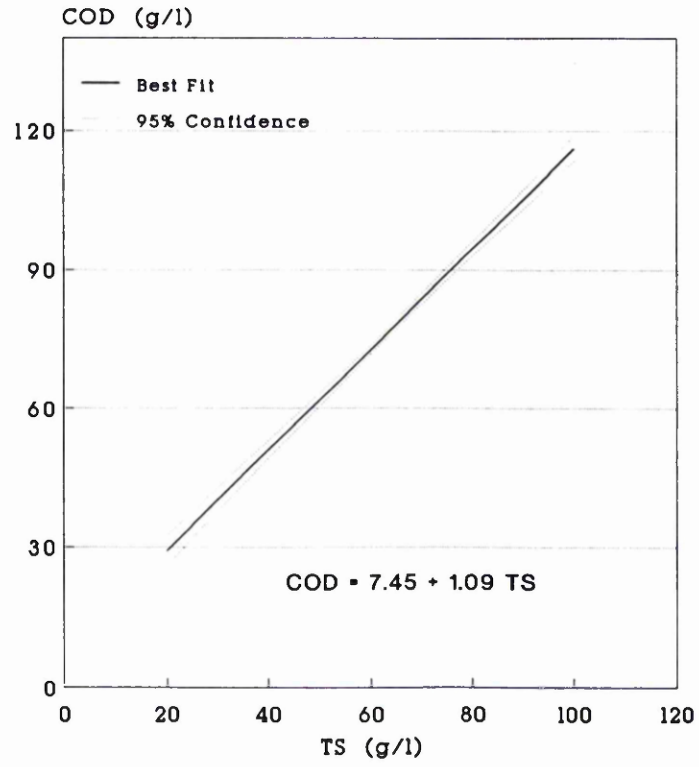

Fig.17 Best fit for linear regression of COD and TS of input slurry.

Lower values were measured by O'Callaghan *et al.* (1971) (94 and 79%) and Lock *et al.* (1982) (67 and 91%). These low values do not correspond particularly well with the high VS value of 83% reported by O'Callaghan *et al.* (1971).

Schulte *et al.* (1985) also reported COD as a lower proportion (96%) of TS although the proportion of VS was relatively high at 80% of TS.

Better correlation was achieved by regression analyses between COD and VS. The regression equation

$$COD = 9.96 + 1.45\ VS \qquad (g/l)$$

615 analyses, R^2 adj. 62.7%, $P<0.001$

is graphically expressed in Fig. 18.

An even higher correlation coefficient was found for COD as a function of VSS.

$$COD = -12.22 + 2.25\ VSS \qquad (g/l)$$

84 analyses, R^2 adj. 66.8%, $P<0.001$.

This indicates a greater influence of suspended volatile solids on COD than that of total solids.

On the contrary, the total dissolved solids (TSs) had a greater influence on the supernatant COD (CODs) than did dissolved volatile solids (VSs) as described by the equations

$$CODs = -0.052 + 1.23\ TSs \qquad (g/l)$$

383 analyses, R^2 adj. 79.1%, $P<0.001$

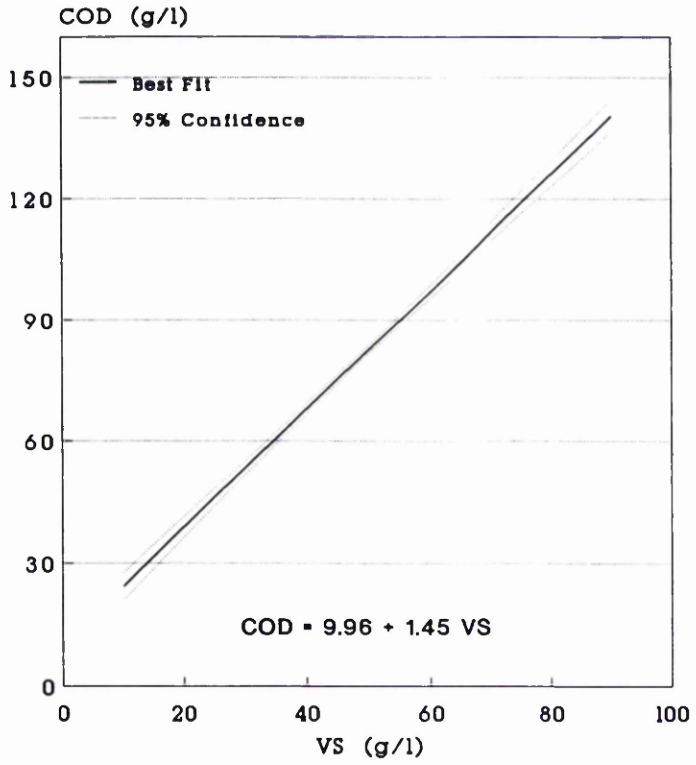

Fig.18 Best fit for linear regression of COD and VS of input slurry.

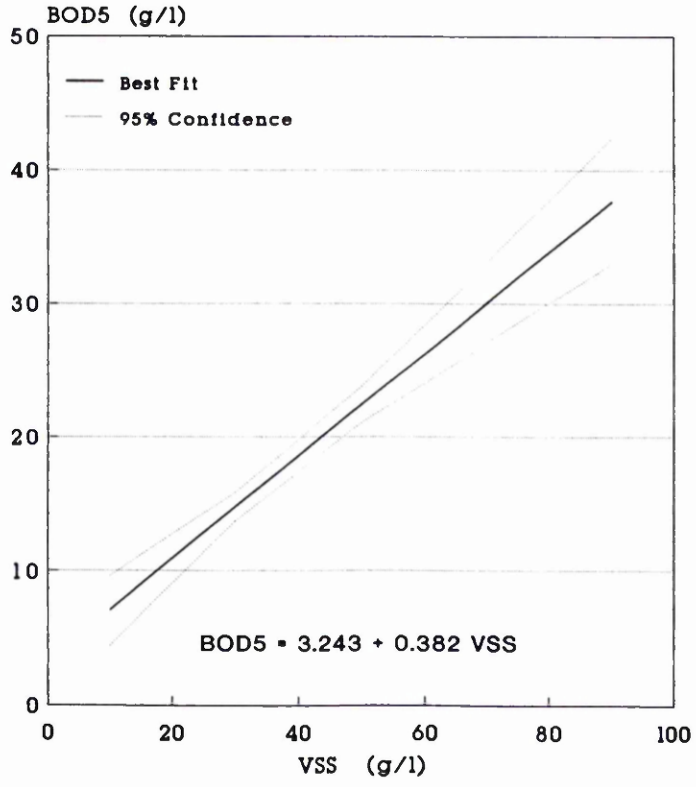

Fig.19 Best fit for linear regression of BOD_5 and VSS of input slurry.

$CODs = 3.74 + 2.10\ VSs$ (g/l)

383 analyses, R^2 adj. 68.7%, $P<0.001$.

9.1.5. Biochemical oxygen demand (BOD_5)

The BOD_5 of the piggery slurry varied as shown in Tables 9 and 10 and was dependent on the concentration of TS. The BOD_5 as a proportion of TS varied from 16.3 to 52.8% with a mean of 29.5%. The mean value was slightly lower than that obtained by O'Callaghan *et al.* (1971) (31%) and Evans *et al.* (1978) (34.7%), but higher than the 25% reported by Payne (1986).

This relationship is described more accurately by the regression equation

$BOD_5 = 2.447 + 0.255TS$ (g/l)

97 analyses, R^2 adj. 43.7%, $P<0.001$

As was found in the case of COD, the BOD_5 was more closely related to VSS than to TS, as described in the regression equation

$BOD_5 = 3.243 + 0.382\ VSS$ (g/l)

97 analyses, R^2 adjusted 44.7%, $P<0.001$

and expressed graphically in Fig. 19.

The BOD_5 averaged 25% of the total COD and varied from 13 % to 42%. The function of BOD_5 as COD was highly significant although the regression coefficient was not particularly high

BOD_5 = 3.136 + 0.204 COD

97 analyses, R^2 adj. 36.8%, P<0.001.

A similar relationship was described by O'Callaghan *et al.* (1971) who expressed COD as a function of BOD_5, and reported low correlation coefficients from 50% to 85%.

The relationship is valid strictly only within the range of measured values. These are 8.2 to 34.3g BOD_5/l and 19.0 to 128.0g COD/l.

The BOD_5 of supernatant (BOD_{5s}) averaged 42.4% of the total BOD_5, in good agreement with the value of 47.5% obtained by Evans *et al.* (1979).

The true mean value of variation of BOD_5 and BOD_{5s} is given in Tables 9 and 10. The ratio of BOD_{5s} to COD varied from 0.19 to 0.5 with an average ratio of 0.45.

9.1.6. Nitrogen

The concentration of total nitrogen (Kj-N) was found to be very variable (Tables 9 and 10). Analyses of 304 slurry samples provided values of total nitrogen as a percentage of TS ranging from 5.5% to 29.6% with a true mean value of 9.7%. Similar values of 10% and 9.5% were observed by O'Callaghan *et al.* (1971) and Westerman (1985) respectively.

Somewhat lower values of 8% are quoted in the SAC leaflet on Handling and Utilisation of Animal Wastes No.16 (1980), while Evans *et al.* (1978) obtained a value of 6.6% of TS from long-term observation. Similarly

Sutton *et al.*(1985) found concentrations of 6.5 to 8% in concentrated slurry but in the diluted slurry, they varied from 13 to 27%. These wide variations were also observed by Schulte *et al.* (1985) and Welty *et al.* (1985) who reported values of 3.1% and 9 to 20% respectively.

The correlation between these two parameters, although very highly significant, was poor and is described in Fig. 20 and in the equation

Total Nitrogen = 2.07 + 0.065 TS (g/l)

304 analyses, R^2 adj. 28.8%, P<0.001.

This regression equation is very similar to that derived from analyses of 218 samples of pig slurry and reported by Piccinini and Bortone (1991)

Total Nitrogen = 1.095 + 0.060 TS (g/l)

Although their regression coefficient was higher (r=0.90), the standard error of the estimation was 0.93.

Correlations of ammonia and of organic nitrogen with TS, although significant (P<0.001), mainly due to the high number (>300) of analyses, had low correlation coefficients of 34.7% and 12.2% respectively.

The concentration of ammonia varied from 33% to 90% of the total nitrogen and averaged 54% (Tables 9 and 10). This is near to the value of 49% (Evans *et al.*, 1978) but 10% lower than that quoted by Westerman

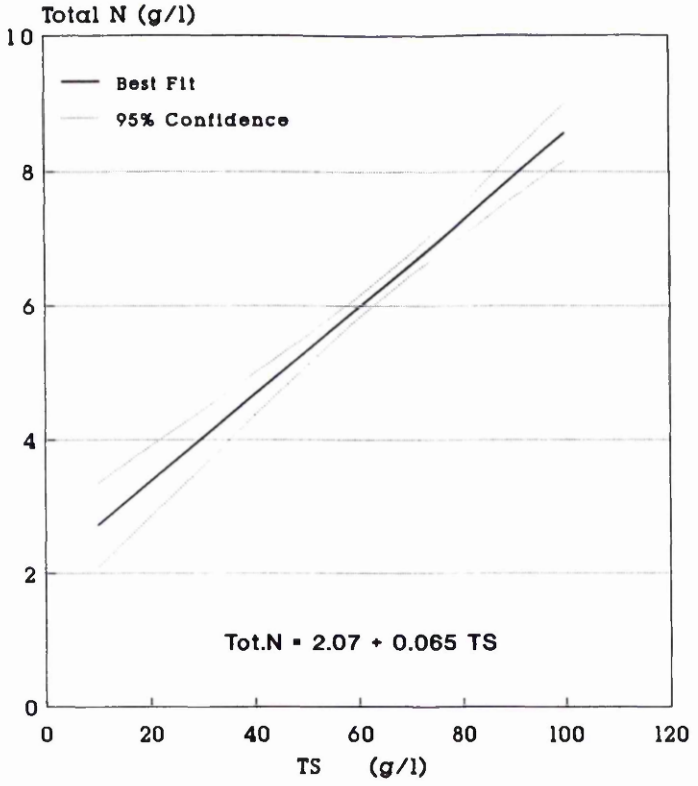

Fig.20 Best fit for linear regression of total nitrogen and TS of input slurry.

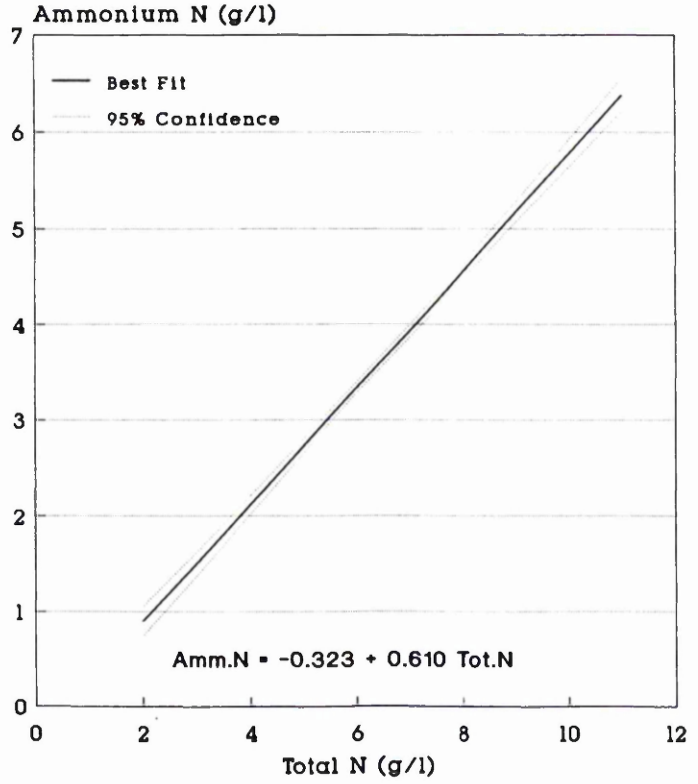

Fig.21 Best fit for linear regression of ammoniacal nitrogen and total nitrogen of input slurry.

(1985). It is closer to the value of 50 to 72% obtained by Sutton *et al.* (1985) for concentrated wastes containing 50 to 100gTS/l than to the higher values of 74% to 87% for the diluted wastes analysed by the same workers.

The ratio of NH_4 to total N was shown to be greatly influenced by the length of the storage period and the temperature during storage (Williams and Evans, 1981).

The regression of 330 analyses of total nitrogen and ammonia nitrogen was very significant as shown in the equation

Ammonium Nitrogen = −0.323 + 0.610 Tot.N (g/l)

333 analyses, R^2 adj. 79.3%, $P<0.001$

which is illustrated with 95% confidence intervals in Fig. 21.

Similarly a good relationship was found between the ammonia nitrogen and total nitrogen in the supernatant

$\text{Ammonium Nitrogen}_S = 0.116 + 0.690\ \text{Tot.N}_S$ (g/l)

327 analyses, R^2 adj. 82.0%, $P<0.001$

The total nitrogen in solution accounted for 60.5% of the whole total nitrogen, 84% of the ammonia nitrogen was dissolved but only 41.3% of organic nitrogen was in liquid form. These values were about 15% higher than those quoted by Evans *et al.*, (1978, 1983), 43%, 68% and 29% respectively.

As expected there was good correlation between the

total nitrogen in the supernatant and in the whole slurry (Fig. 22) and between the ammonium nitrogen in the supernatant and in the whole slurry

$$\text{Total Nitrogen}_S = -0.494 + 0.731\ \text{Tot.N} \qquad (g/l)$$

304 analyses, R^2 adj. 82.3%, $P<0.001$

$$\text{Ammonium Nitrogen}_S = 0.083 + 0.818\ \text{Amm.N} \qquad (g/l)$$

327 analyses, R^2 adj. 82.9%, $P<0.001$.

9.1.7. Total Organic Acids (TOA_S)

The TOA_S in the untreated slurry varied between 2.1 and 15.9g/l with a true mean value of 6.11g/l. The correlation with other values such as COD_S, BOD_{5S} (Fig. 23) and the ammonia nitrogen in the supernatant was rather poor as assessed by correlation coefficients, although highly significant with $P < 0.001$ in each case.

$$COD_S = 9.07 + 1.23\ TOA_S \qquad (g/l)$$

367 analyses, R^2 adj. 35.9%, $P<0.001$

$$BOD_{5S} = 3.85 + 0.59\ TOA_S \qquad (g/l)$$

191 analyses, R^2 adj. 27.8%, $P<0.001$

$$TOA_S = 4.62 + 0.52\ \text{Ammonium-N} \qquad (g/l)$$

327 analyses, R^2 adj. 6.8%, $P<0.001$.

The very low correlation coefficient was influenced by a sudden increase of TOA_S to over 10g/l unaccompanied by an increase in the concentration of ammonium nitrogen

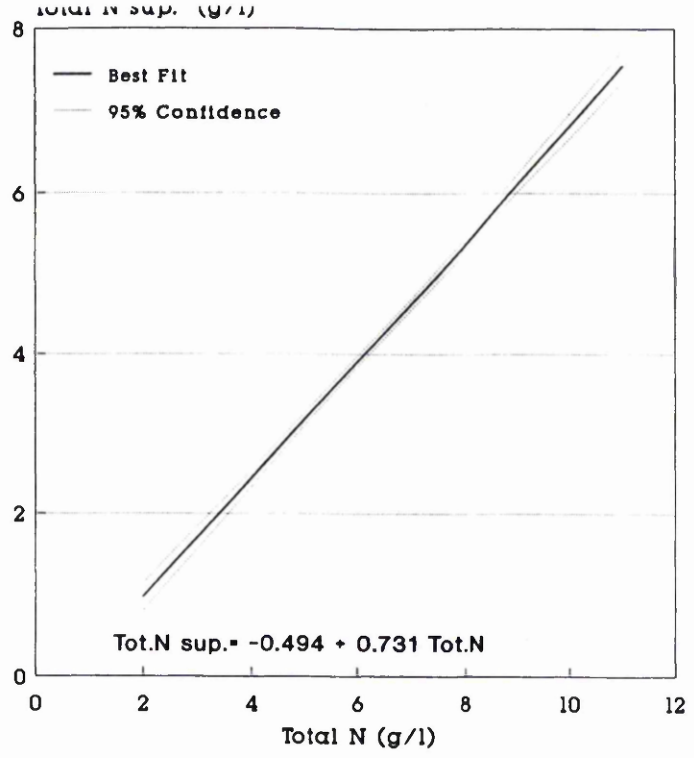

Fig.22 Best fit for linear regression of supernatant nitrogen and total nitrogen of input slurry.

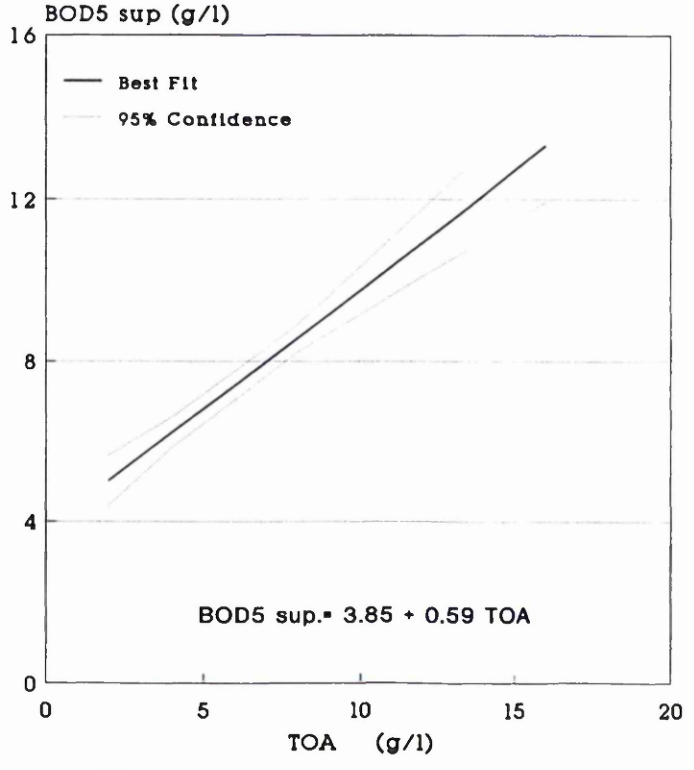

Fig.23 Best fit for linear regression of BOD_{5s} and TOA of input slurry.

which remained related to the concentration of total nitrogen. The increase in TOA_S may have been caused by an increase in the temperature at which the slurry was stored for up to one day under the slatted floor. The temperature of the slurry in the collection pit averaged 14.4°C and reached a peak of 17.9°C.

9.1.8. Capillarity suction time (CST)

The capillarity suction time is a measure of the dewaterability of sludges and slurries. Theoretically, high values of CST indicate inferior dewatering properties while low values indicate superior dewatering properties (Smollen, 1986a,b).

Some examples of the CST of treated and untreated municipal sewage sludges are given in Table 11.

Table 11. CST and solids concentration of municipal sludges (After Smollen, 1986b).

Sludge type	CST sec.	Solids conc. %
Primary sludge:		
Thickened	22 - 240	2.3 - 5.6
Digested	48 - 400	2.5 - 6.7
Activated sludge:		
Returned	5 - 35	0.3 - 0.8
Thickened	22 -100	2.4 - 4.4
Mixture of primary and secondary sludges		
Digested	152-860	1.5 - 2.4

In Smollen's report (1986b) there was no apparent correlation between CST and solids concentration both expressed in log scale in contrast to the correlation which is often postulated in the literature (Vesilind, 1988).

The CST of raw slurry varied between 1330 and 3728 seconds with a true mean value of 2235 seconds for TS concentrations between 58.8g/l and 91.8g/l. There was a significant relationship between these two values which is described by the equation

$$CST = -820 + 42.5\ TS \qquad \text{(seconds)}$$

48 analyses, R^2 adj. 57.2%, $P<0.001$

and in Fig. 24.

A similarly significant relationship was found for CST and VSS and is described by the equation

$$CST = 21 + 50.5\ VSS \qquad \text{(seconds)}$$

48 analyses, R^2 adj. 53.3%, $P<0.001$.

9.2. Commissioning of the reactor

After the treatment plant was built it was commissioned for experiments at mezophilic temperature and a high level of dissolved oxygen.

The reactor was started on three occasions during the experimental runs. Detailed monitoring of the commissioning period was performed only for the initial start of the reactor when the slurry was aerated at high

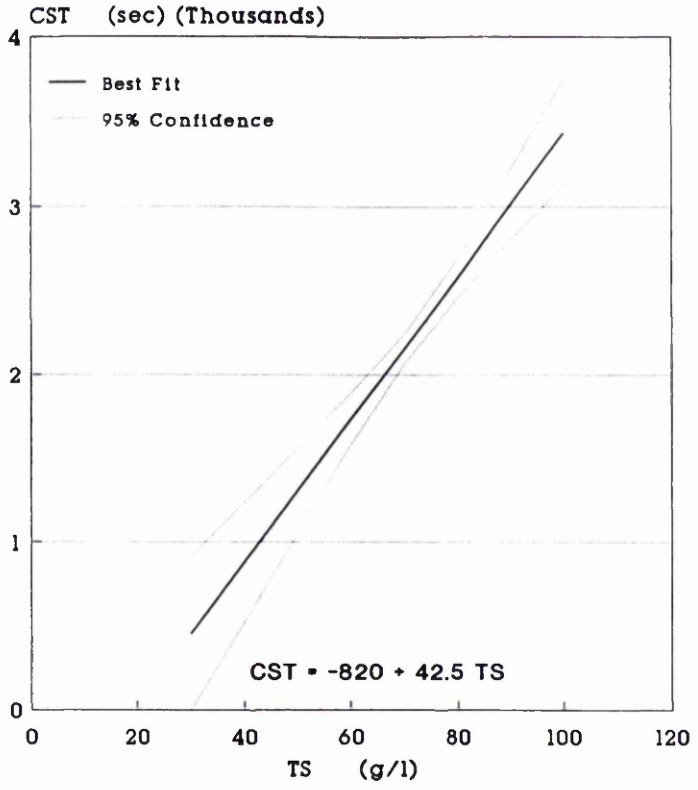

Fig.24 Best fit for linear regression of CST and TS of input slurry.

DO to encourage nitrification .

The reactor was restarted on two further occasions. Each time the reactor was emptied and settled residues were removed. About $4m^3$ of stored treated slurry was returned to the reactor and the system was then operated under the designated conditions for the following series of experiments. When the ML reached the level required for the designated treatment time the discharging pump was activated by a level switch and a commissioning period for the series of experiments commenced.

The reactor was commissioned over a period of five months. During this time there were a number of mechanical faults with the scrapers and pumps. The heat exchange and aeration rates were also adjusted several times. However, despite interruptions, a suitable microbial population developed for the succeeding experiments.

The treatment tank was filled with $13m^3$ of tap water and the aerator was started. The initial temperature of water in the reactor was 7^oC but within five days during which slurry was fed every hour, it had risen to 36^oC and temperature control by heat extraction was initiated. After nine days the TS, COD and BOD_{5s} of the mixed liquor increased to 16g/l, 18.1g/l and 320mg/l respectively. Ammoniacal nitrogen reached 2g/l (Fig. 25) and microbial activity declined. Experience with laboratory reactors (unpublished) has shown that with insufficient numbers of nitrifying bacteria

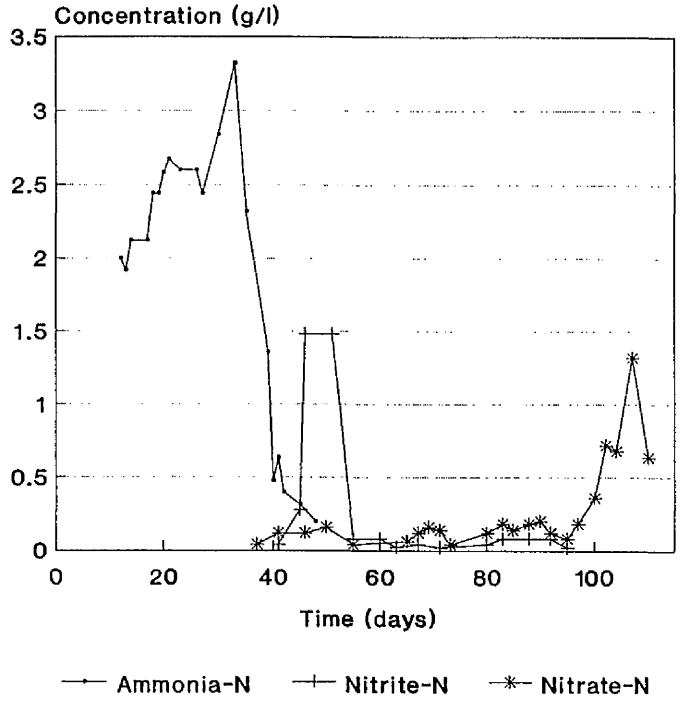

Fig.25 Concentrations of forms of nitrogen in the ML during commissioning period.

entering the reactor their growth rate is insufficient to prevent accumulation of ammonia resulting in pH values reaching inhibitory levels.

To provide a seed and thereby maintain the population, 7 litres of mixed liquor from a laboratory reactor containing active populations of nitrifying bacteria were added daily to the reception pit. However, after 21 days, feeding of the reactor stopped for 3 days because of mechanical failure of the scrapers in the piggery on day 21. Ammoniacal nitrogen was still present at 2.5g/l and the pH value was about 8. The total COD and supernatant BOD_5 were 17g/l and 270mg/l respectively.

Prior to the breakdown, the dissolved oxygen level varied between 0 and 8% of saturation. The quantity of foam overflowing into the cone was so high that it filled it completely, allowing only gas trapped in the foam to aerate the mixed liquor. Fresh air from the fan was therefore directed through a flexible pipe into the aerator cone to mix with the overflowing foam and to be sucked into the mixed liquor. Every second day, 100ml of polypropylene glycol antifoam were added to control the foam. These procedures increased the minimum dissolved oxygen level to 8% and the maximum to 45% of saturation.

As expected the population of *Nitrosomonas sp.* had increased sufficiently for nitrification to commence and

nitrite nitrogen was detected. When feeding restarted, the ammoniacal nitrogen remained low and during the next 2d the concentration of nitrite nitrogen increased to 30mg/l before another mechanical failure occurred on day 45 (Fig. 25).

During the next few days without feeding, the concentration of nitrite nitrogen dramatically increased to 1.5g/l and remained high for the next 5 days after feeding commenced. Nitrite had been shown to accumulate in treated piggery slurry at high pH values by Fenlon and Mills (1980), in calf slurry by Ten Have (1990) and in sewage by Alleman (1985).

Nitrite nitrogen then fell rapidly to less than 15mg/l. The population of *Nitrobacter sp.* had now developed and nitrate nitrogen was present, but only at 50mg/l .

The net loss of mineral nitrogen can be explained by denitrification and was not unexpected since it had been observed in earlier laboratory experiments (Smith and Evans, 1982) at 15^{o}C when the dissolved oxygen level fell below 15% of saturation in a reactor for even short periods of time.

During the next 6 weeks the concentration of nitrate nitrogen stabilised at about 600mg/l and all the other chemical parameters remained fairly constant.

The two other occasions on which the reactor was restarted were less dramatic than that described above,

since only ammonification was required. No seed other than the stored treated slurry was used at the start of aeration. A large quantity of foam always developed and, except during the aeration mode for nitrification, it was present during the experimental steady state conditions. To avoid using relatively large quantities of antifoam, a mechanical foam cutter was developed and suspended on ropes within the reactor so that the total energy used by the foam cutter could be included in the calculations of the energy balance. This arrangement later proved impractical and, when the experiments finished, the foam cutter motor was mounted on the reactor lid and the shaft length adapted to the level of the ML in the reactor.

9.3. Treatment experiments

The treatment parameters (treatment time, treatment temperature, DO concentration, redox potential) were controlled as described in Chapter 6.

The treatment temperature was controlled at three levels (35, 50 and 55^{o}C) and the DO at low and high level to promote ammonification and nitrification respectively. The results of treatment are therefore clustered and assessed in four groups i) nitrification at mezophilic temperature, nominal temperature 35^{o}C, (Experiments 1 to 6), ii) ammonification at mezophilic temperature, nominal temperature 35^{o}C, (Experiments 7 to 9), iii) ammonification at thermophilic temperature 50^{o}C (Experiments 10 to 15) and iv) ammonification at thermophilic temperature 55^{o}C (Experiments 16 to 20).

The pH value was not controlled since in practice it would be uneconomical. The pH value therefore established itself according to the treatment conditions.

Although the rate of slurry production varied depending on the number of housed animals and ingress of rain water and/or leakage from the drinkers, the rate of slurry input into the reactor was adjusted so that the maximum quantity of undiluted slurry produced was utilised. Despite the unwanted dilutions the daily slurry production never exceeded 1.8m^{3} per day.

The reactor had to be sufficiently large to accommodate the smallest commercial subsurface aerator

available and this determined the minimum treatment time. The treatment times were therefore relatively long, the shortest being 4.7 days during the treatments at thermophilic temperatures and the longest 12.2 days during the nitrification experiments.

The commissioning period for each experimental run lasted for a minimum of three residence times during which constant treatment parameters were maintained. The period of analyses of untreated and treated slurry usually lasted for three or more weeks to accumulate approximately 10 complete analyses on which to base the mean and standard deviation values.

9.3.1. Treatment experiments at mezophilic temperature and high dissolved oxygen concentration

After running the reactor for approximately three residence times during the commissioning period and thus reaching steady state conditions, the first experiment commenced.

During the commissioning periods of the reactor and of the first four experiments, the concentration of TS in the input slurry was adjusted to approximately 45g/l by dilution with tap water. This minimised the effect of widely varying concentrations of TS in the slurry as collected on the characteristics of the treated slurry. Although such an approach would not be acceptable on a farm, it was consistent with the laboratory experiments where the TS of the input slurry was maintained at a

constant concentration. After the reactor was commissioned, six experiments were run similarly except for the input TS concentration in Experiments 5 and 6. During these experiments input slurry was not diluted and was fed into the reactor at the concentration of TS as it was collected.

The main objective of these experiments was to maintain a high DO concentration and to achieve complete nitrification of convertible nitrogen so that the results of treatment would be comparable to those obtained in laboratory-scale experiments (Smith and Evans, 1982). The treatment temperature of the first six experiments was controlled at around 36°C. It fluctuated from a minimum value of 33.6°C during Experiment 4 to a maximum value of 41.9°C in Experiment 1 (Table 12). It was therefore always in the mezophilic range and the characteristics of the treated slurry could therefore be compared with the values predicted by model equations (Evans *et al.*, 1983) which were valid for the temperatures from 25 to 45°C.

Table 12. Dissolved oxygen concentration (% of air saturation) and ML temperature during Experiments 1 to 6.

Experiment	TT (d)	DO (%)		ML Temp. (°C)	
		Range	Mean	Range	Mean
1	8.6	6-42	37	35.9-41.9	37.1
2	10.9	5-74	34	35.2-39.3	36.4
3	11.3	6-53	34	35.8-40.2	36.7
4	11.7	8-65	37	33.6-38.4	35.8
5	11.8	0-54	24	35.8-40.0	36.8
6	12.2	0-95	52	35.1-40.2	36.4

The DO concentration of the ML was controlled at 35% in the Experiments 1, 3, 4 and 5. In Experiments 2 and 6 there was no control and the DO was allowed to reach maximum values. The reason for this was to prevent denitrification in anoxic zones within the reactor or in the centre of a biological floc (Rittman and Langeland, 1985) and thereby accumulate the maximum quantity of nitrate nitrogen in the treated slurry. The results showed that unlike in the laboratory reactors (Smith and Evans, 1982) the DO concentration of 15% of saturation was not high enough to prevent denitrification. The nitrogen balance is discussed in Chapter 9.3.1.2.

9.3.1.1. Characteristics of treated slurry and correlation with modelled data

The mean values of TS, TSS, COD, BOD_5 and BOD_{5s} of the treated slurry in the first six experiments (Table A1 to A6) were compared with the values predicted from the model equations (Evans *et al.*, 1983). The percentage difference between observed and modelled (expected) data is described in Table 13 and 15 to 18 and illustrated in Figs. 26 and 28 to 31. It was calculated as

% difference=(observed-expected)*100/expected

Total Solids

The degradation of TS during all six experiments was

greater than that calculated from the model equation for TS

$$TS = [0.262/(1+0.4R)+0.744]TS_f \quad (g/l)$$

The observed and expected values together with their percentage differences are listed in Table 13 and illustrated in Fig.26.

Table 13. Observed and predicted values of total solids in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
1	41.8	42.2	-2.1
2	38.6	39.8	-3.0
3	35.1	38.0	-7.6
4	34.4	36.2	-5.1
5	57.3	58.2	-2.1
6	58.6	59.6	-1.7

The maximum difference of 7.6% was within the limits of variation expected from these experiments (Evans *et al.*, 1983). Although Evans *et al.* (1983) did not state the square root deviations of the measured values from the model curve for the mezophilic range of treatment temperatures, they would not be expected to be very different from the 6.07% calculated for a treatment temperature of 15^{o}C (Evans *et al.*, 1979).

The greater reduction of TS compared with that expected from the model equation was consistent although slight and not significant. Since some other analytical results (TSS, COD, BOD_5) from Experiments 1-6 also indicated greater reductions, two explanations of

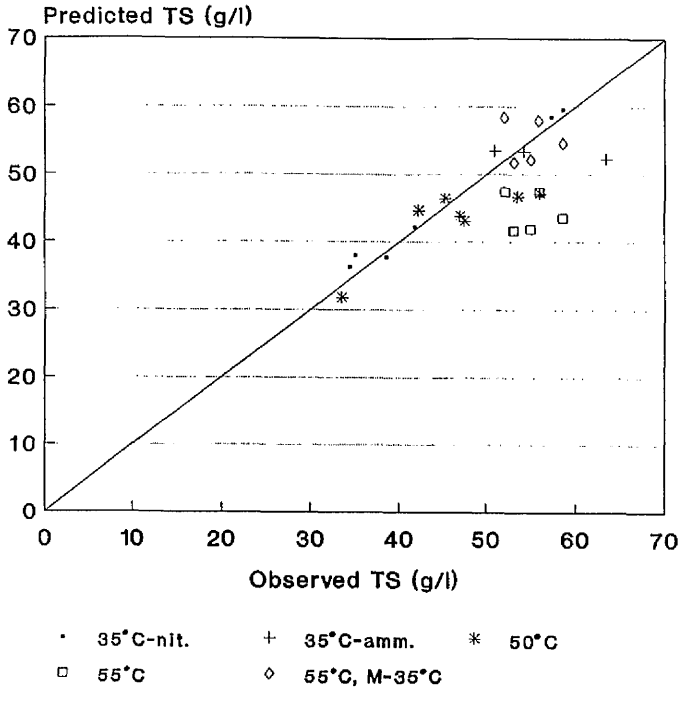

Fig.26 Predicted and observed TS of slurry treated at mezophilic and thermophilic temperature.

this phenomenon are possible.

A very high intensity mixing, with a specific energy input during these six experiments of between 243 and 278 W/m^3 of the ML in the reactor, could increase the mechanical breakdown of particles, thereby increasing the surface area of the particles and the accessibility to bacterial attack.

A second explanation, possibly more credible, is the effect of the sedimentation of particles on the base of the tank, mostly around the perimeter where even such high intensity mixing was inadequate to maintain these particles in suspension. Such deposits were found after the first four experiments when the reactor was emptied and cleaned.

The depth of the sediment averaged 60mm over the full area of the reactor base giving a volume of approximately $0.5m^3$. The chemical analyses (Table 14) showed that the material was very dense with a very low concentration of volatile solids. More than 44% of the ash consisted of calcium and magnesium carbonate. During the time before the reactor was cleaned after Experiment 4, about 12000 kg of total solids entered the reactor in the input slurry. Therefore the quantity of sediment (approximately 500 kg) represents 4% of the input TS and accounts for the consistent differences in TS reduction between the model and the experimental results.

Table 14. Analyses of the sediment from the reactor.

Parameter	Units	Value
TS	g/kg w.w.	650
COD	"	53
VS	%TS	17
Carbonate	%Ash	44
Fe	g/kg w.w.	6

The particle size distribution of this sediment is illustrated in Fig. 27 which shows that more than 99% of the weight of the sediment consists of particles smaller than 1mm. Formation of this sediment would not therefore be prevented by commercial mechanical separators with screen apertures generally equal to or larger than 2mm.

Total Suspended Solids

The observed values of TSS were, as with TS, lower than those predicted from the equation

$$TSS = [0.542/(1+0.4*R)+0.696]*TSS_f \quad (g/l)$$

The differences between the observed data and the model were even greater than with TS indicating that the proportion degraded was larger than expected. Similar explanations as those for TS are plausible, but the emphasis would be again on the accumulation of sediment on the reactor base.

The total TSS input into the reactor until the time of cleaning was assessed as 9600kg. Since the TSS of

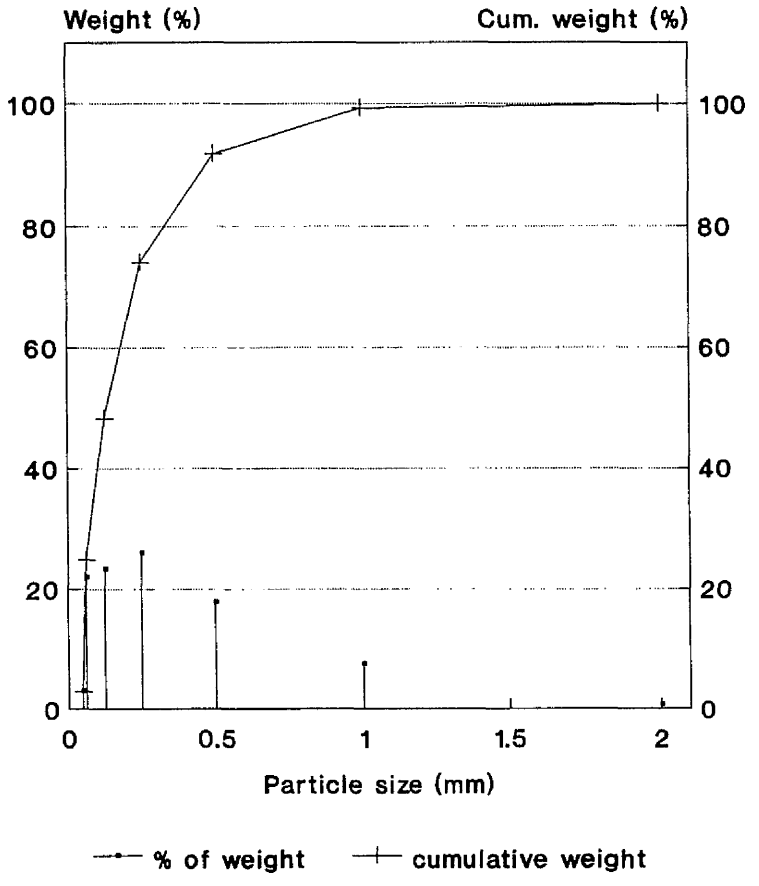

Fig.27 Particle size distribution of the reactor sediment.

the sediment were not very different from the TS, about 500kg of TSS were deposited, representing 5.2% of the decrease in TSS during treatment.

The increase in the removal of TSS, compared with that predicted by the model, varied from 3.1% to 17.8% (Table 15, Fig. 28) and averaged 9.15%. This was only slightly higher than the 8.09% difference calculated from the results of laboratory treatment and that predicted by the model (Evans *et al.*, 1983).

Table 15. Observed and predicted values of total suspended solids in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
1	28.3	29.2	-3.1
2	25.6	31.2	-17.8
3	25.7	29.5	-12.9
4	26.4	28.0	-5.7
5	38.7	42.3	-8.5
6	42.1	45.2	-6.9

Chemical Oxygen Demand

The changes in COD reflect changes in TS and show, in all cases, greater degradation than predicted (Table 16 and Fig. 29). Although the COD values varied from 0.7% to 14.3% from the model equation

$$COD = [0.333/(1+0.4*R)+0.535]*COD_f \quad (g/l)$$

The deviations calculated from the equation for 15^{o}C treatment were 6.01%. The observed values were therefore in a good agreement with the model prediction.

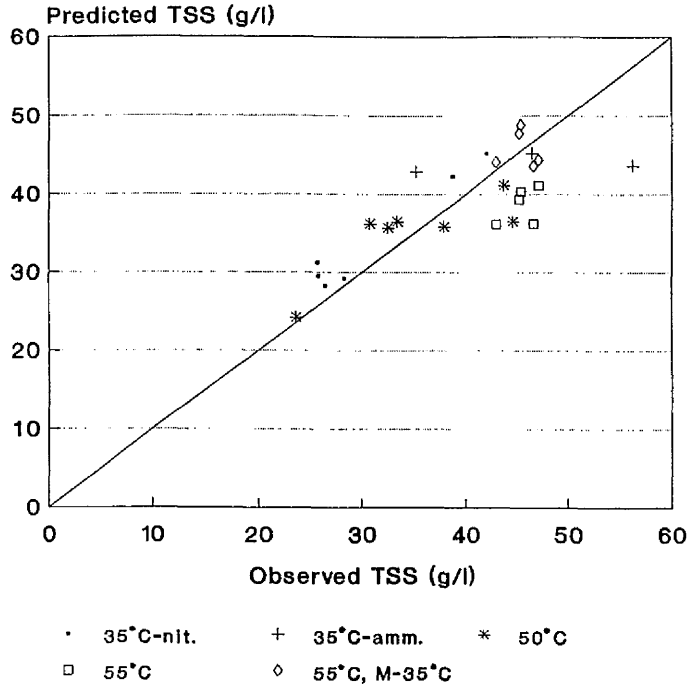

Fig.28 Predicted and observed TSS of slurry treated at mezophilic and thermophilic temperature.

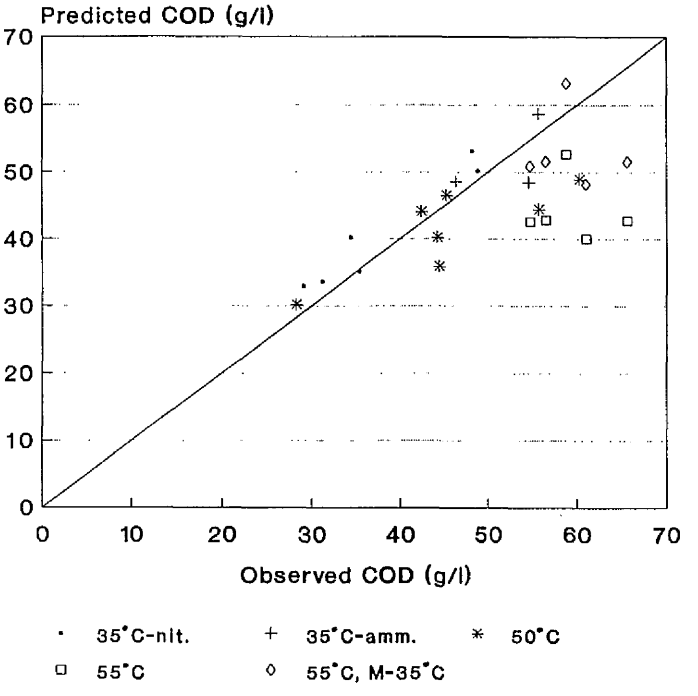

Fig.29 Predicted and observed COD of slurry treated at mezophilic and thermophilic temperature.

Table 16. Observed and predicted values of COD in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
1	35.4	35.1	-0.7
2	31.2	33.6	- 7.3
3	34.4	40.2	-14.4
4	29.0	32.9	-11.9
5	48.8	50.2	-2.8
6	48.1	53.1	-9.4

Biochemical oxygen demand of whole treated slurry

The overall values were substantially lower by 30.6 to 52.6% than those predicted by the equation

$$BOD_5 = 1.568/R + BOD_{5f} \quad (g/l)$$

(Table 17 and Fig. 30).

This, once more, agrees with the trend of the previous parameters, but the difference is greater than the root mean square value of deviation for 15°C of 22.1%. The total BOD_5 value is composed of BOD_5 of dissolved and suspended solids.

Table 17. Observed and predicted values of BOD_5 of whole treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
1	1.48	2.91	-49.8
2	1.52	2.41	-36.9
3	1.12	2.03	-44.8
4	1.68	2.61	-35.6
5	2.50	3.60	-30.6
6	1.70	3.59	-52.6

Although the BOD_5 of the sediment would be small

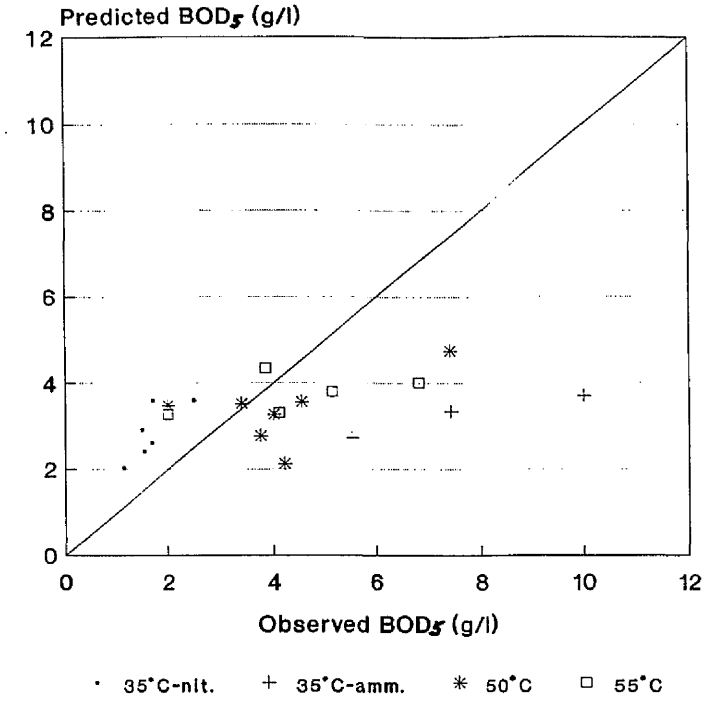

Fig.30 Predicted and observed BOD_5 of slurry treated at mezophilic and thermophilic temperature.

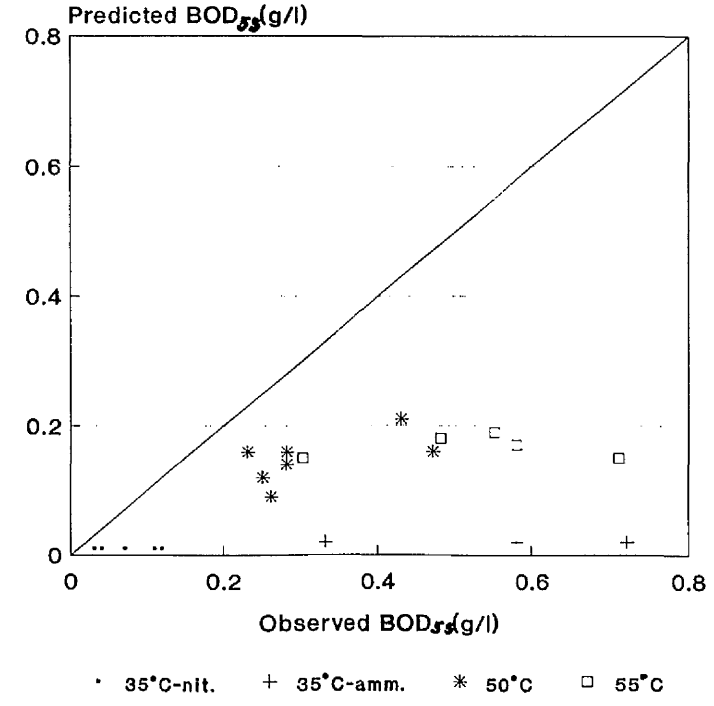

Fig.31 Predicted and observed BOD_{5s} of slurry treated at mezophilic and thermophilic temperature.

due to the low VS concentration, removal of solids by settlement in the reactor would result in a decreased value for total BOD_5 of the treated slurry.

Biochemical oxygen demand of supernatant

Contrary to the previously described characteristics of treated slurry, the supernatant BOD_5 was higher than predicted by the equation

$$BOD_{5s} = 0.11/R \quad (g/l)$$

(Table 18, Fig. 31).

Table 18. Observed and predicted values of BOD_{5s} in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
1	0.07	0.01	+600
2	0.11	0.01	+1000
3	0.12	0.01	+1100
4	0.04	0.01	+300
5	0.03	0.01	+200
6	0.03	0.01	+200

The predicted absolute values of treated supernatant BOD_5 were 9 to 13mg/l and the observed values 30 to 120mg/l, so the relatively slight changes represented very large percentage variations of 200 to 1100%. This was also observed by Evans *et al.* (1979), who calculated the root square value of the deviation for 15°C as 147%.

When the percentage of removal of BOD_{5s} is considered, then the observed value in the best case

represents 99.7% removal and the worst, 98% while the predicted reduction would be 99.8%. Such a difference cannot be significant.

The consistently higher BOD_{5s} may be explained in three ways.

Firstly, the concentration of TS in the input slurry to the large reactor was 1.7 to 2.5 times higher than the TS of the input in the laboratory reactors (Evans *et al.*, 1979). Consequently the BOD_{5s} would also be higher and this alone may cause a higher value of BOD_{5s} in the treated slurry. Such a phenomenon is called a "concentration effect" and was observed during activated sludge treatment (Chudoba *et al.*, 1991).

Secondly, it is possible that in the layer of sediment, anaerobic fermentation released substrates which might not be removed during treatment and although their quantities would be small in comparison with, for example, recalcitrant COD, their presence was reflected in the supernatant BOD_5 values.

Thirdly, Chudoba *et al.* (1991) demonstrated that microbial populations release metabolites (uronic acids, amino acids etc.) the concentration of which increases with the concentration of microorganisms. Analyses of BOD_5 of filtrates (supernatants) of samples from slurry treatment plants on commercial piggeries in Czechoslovakia showed that the minimum attainable value was 50mg/l.

Total organic acids

The percentage removal of TOA during the treatment experiments increased as the initial concentration of TOA increased, and was therefore highest for Experiments 5 and 6 (99.4%) and lowest for Experiment 4 (97.8%) with the lowest initial concentration of 3.98gTOA/l (Tables A1 to A6).

The range of concentrations of TOA in the treated slurry was from 40mg/l to 90mg/l (Eperiments 5 and 4 respectively) and indicates an odour offensiveness rating 'inoffensive', using the following equation:

Odour offensiveness rating = 2.378*logTOA+2.327

Such a result would be expected from the extended treatment times in these experiments (Thacker and Evans, 1985).

9.3.1.2. Ammonification, nitrification and denitrification.

The parameters of treatment in Experiments 1-6 were designed to promote oxidation of available nitrogen. The minimum treatment time of 8.6 days and the minimum DO mean value of 24% of saturation fulfilled such a requirement (Fig. 2).

Nitrogen available for oxidation, the 'convertible nitrogen' of Smith and Evans (1982), consisting of ammoniacal nitrogen and of a portion of organic nitrogen could therefore be converted to nitrite and nitrate (Table 19).

Table 19. pH values, convertible nitrogen as percentage of total input nitrogen, and concentration of nitrate expressed as percentage of total input nitrogen.

Exp.	pH -	Convert.N % of Tot.N	NO_3^--N g/l	NO_3^--N % of Tot. N
1	7.3	67.4	0.36	7.2
2	5.8	65.3	1.35	32.3
3	7.3	68.7	0.38	8.6
4	7.1	67.6	0.51	12.6
5	6.9	68.2	0.44	6.9
6	7.6	65.1	0.34	5.6

The analyses showed that the mean value of convertible nitrogen was 67.1% of the total nitrogen input. Since more than 90% of organic supernatant nitrogen and 98% of ammonia nitrogen (Table 20) was removed then 94% of the convertible nitrogen was oxidised.

Table 20. Percentage decrease of total, ammoniacal, organic and supernatant organic nitrogen in comparison with its respective feed raw slurry.

Exp.	Tot.N %	Ammon.N %	Org.N %	$Org.N_S$ %
1	60.1	99.6	32.6	94.2
2	33.2	90.0	34.9	85.5
3	60.0	99.8	35.5	92.0
4	55.0	99.9	22.5	89.1
5	61.3	99.1	33.5	93.4
6	59.5	99.4	23.1	90.6

The removal or transformation of organic nitrogen reached a maximum of 35.5% (Table 20), in good agreement with the results of Evans *et al.* (1986b) who found that up to 40% of organic nitrogen was converted to ammonia

at 35°C. Since more than 90% of ammonia was oxidised it is possible to conclude that at least 90% of the supernatant organic nitrogen was removed by oxidation.

The remaining oxidised nitrogen was found always in the form of nitrate. Nitrite (after the commissioning period, when its concentration reached 1450mg/l), was oxidised to nitrate and never appeared during the series of experiments. The concentrations of DO, reaching 95% of saturation in Experiment 6, did not ensure nitrogen conservation and the nitrate concentration was much lower than expected. According to Fig. 2 nitrogen should have been conserved in the liquid as nitrate when the DO exceeded 15% of saturation, but up to 61% of the total nitrogen was lost. This can only be accounted for by denitrification.

Although the maximum and mean levels of DO were well above 15%, the DO levels decreased to between 5 and 8% during the first four experiments and to 0% during Experiments 5 and 6. The fluctuations in the level of DO resulted from the hourly input of slurry to the reactor.

It was possible to control the DO at the predetermined level during the experiments (Chapter 9.7) all the time except during the short period (approx. 15 minutes, depending on the TS concentration in the input-feed slurry) immediately following the hourly input of slurry. This period increased with

increased concentration of TS and with decrease in treatment time.

The total nitrogen concentration varied from a minimum of 4.04g/l for diluted input slurry to 6.36g/l for undiluted input slurry (Tables A1 to A6) during Experiments 1-6. The final total nitrogen concentration in the ML was as low as 1.8g/l in Experiment 3 and reached 2.8g/l in Experiment 2, where the contribution of the highest concentration of nitrate nitrogen in all the experiments was a major factor.

After the failure to conserve all the oxidised nitrogen in Experiment 1, an attempt was made to increase the DO concentration to a maximum possible level to prevent denitrification. This was partially achieved in the Experiment 2. Although the average DO was the same as in Experiment 1 the higher DO values must have had some effect since the nitrate nitrogen concentration reached 1.35g/l, representing 32% of the total nitrogen in the input slurry. However, 33% of total nitrogen was still lost as gases from denitrification.

The higher concentration of nitrate (1.35g/l) resulted in a relatively low pH value of 5.8, far lower than the optimal value for nitrification in diluted effluents (Jones and Paskins, 1982) but acceptable in concentrated effluents such as surplus activated sludge which has been digested and nitrified at pH values as

low as 5.7 (Bhargava and Datar, 1984). Despite these observations the low pH value affected the rate of nitrification as was observed by other researchers (Painter, 1986; Rittman and Langeland, 1985) and about 10% of ammonia remained unoxidised in the ML, while 99% of ammonia was oxidised in the other five experiments.

During Experiment 6, a similar attempt to conserve nitrogen as nitrate was made by increasing the DO concentration. But even a maximum DO level of 95% of saturation (the highest mean of all six Experiments) and a mean DO level of 52% failed to achieve any significant effect. Only 6% of the total input nitrogen remained oxidised as nitrate and 60% was lost.

It was therefore concluded that, in a large reactor with concentrations of TS in the ML from 34 to 59g/l, the lower limit of DO concentration of 15% of saturation (Smith and Evans, 1982) cannot be guaranteed all the time and, therefore, losses of nitrogen through denitrification will always occur. Denitrification maintains the pH value in an optimal range for the maximum oxidation of convertible nitrogen and subsequent denitrification. Thus, 94% of the convertible nitrogen was oxidised and, in the event of total denitrification 63% of the total nitrogen in the input slurry would be removed.

Some other factors which contribute to denitrification are also evident. In the ML with a high

concentration of TS, large conglomerates of floc are created. Anoxic conditions prevail in the centre of these large conglomerates and denitrification occurs (Rittman and Langeland, 1985). The settled solids on the base of the reactor created an anaerobic zone. An anoxic zone would exist in close proximity contributing to denitrification.

9.3.1.3. Effect of variation in the characteristics of the input slurry on those of the treated slurry.

The composition of the input slurry was influenced by the ratio of weaning to fattening pigs, drinking and wash water consumption, ambient temperature, ingress of rain water and other factors. The varying concentrations of TS, COD etc. of the input slurry would be expected to cause variations in the characteristics of the mixed liquor compared to those expected from the predictive model, which was derived from laboratory experiments in which a constant composition of slurry was attainable.

The input slurry composition was stable during the 24-hour intervals between scrapings of slurry, therefore the hourly load to the reactor was constant during each day. To reduce the variations between daily batches, the collected slurry was diluted with water to approximately 50gTS/l during the first four experiments.

Despite this standardisation, some variations were observed and the changes in characteristics of the input

slurry (TS, COD, nitrogen and TOA) and their influence on the ML characteristics are illustrated for Experiment 3 in Figures 32 to 35 as examples.

The input slurry was not diluted to a standard TS concentration during Experiments 5 and 6. Therefore the input slurry was more concentrated than in Experiments 1-4 and the variations were more pronounced. These variations and their influence on the ML characteristics are shown for Experiment 6 in Figures 36 to 39.

Experiment 3 and 6 were selected as two examples, one with diluted and the other with undiluted slurry, for the description of the effect of variation in characteristics of the input slurry on those of the mixed liquor.

Experiments 3 and 6

The concentration of TS in the input slurry fluctuated slightly during Experiment 3 with one large change from 41 to 57.8g/l on day 12. Neither this large fluctuation or other smaller ones were reflected in the TS of the ML which, although decreasing slightly, remained stable between 38.2 and 32.6g/l during the whole experiment.

The values for the ML predicted by equation (5) using the daily TS values in the input slurry, showed fluctuations mirroring the TS of the feed, but such fluctuations were not observed in the TS of the ML in Experiment 3.

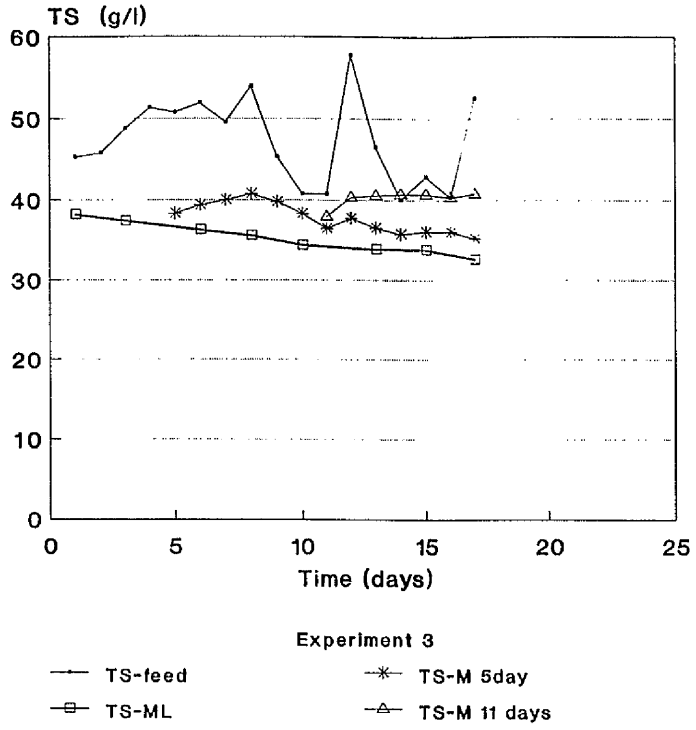

Fig.32 Effect of input slurry TS on the ML TS and predicted values (M) for 5 and 11 day running mean TS of input slurry.

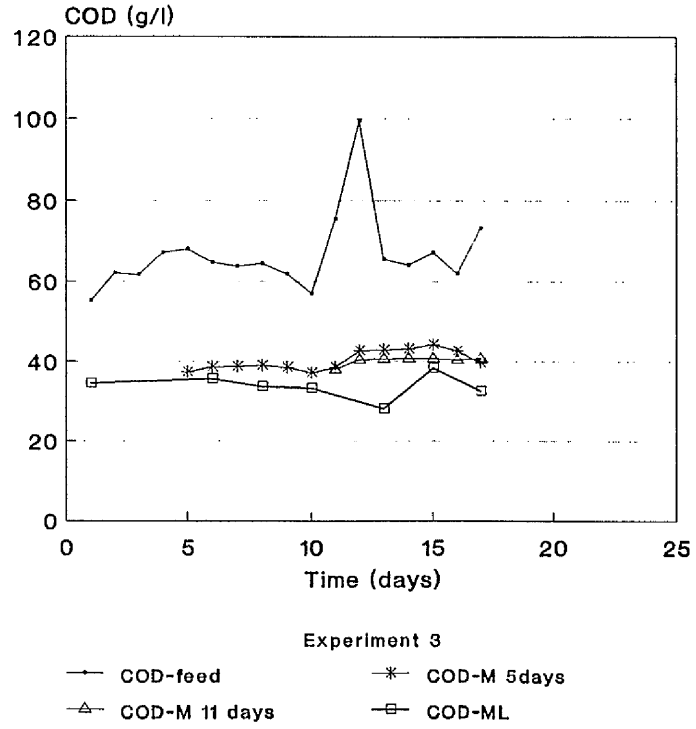

Fig.33 Effect of input slurry COD on the ML COD and predicted values (M) for 5 and 11 day running mean COD of input slurry.

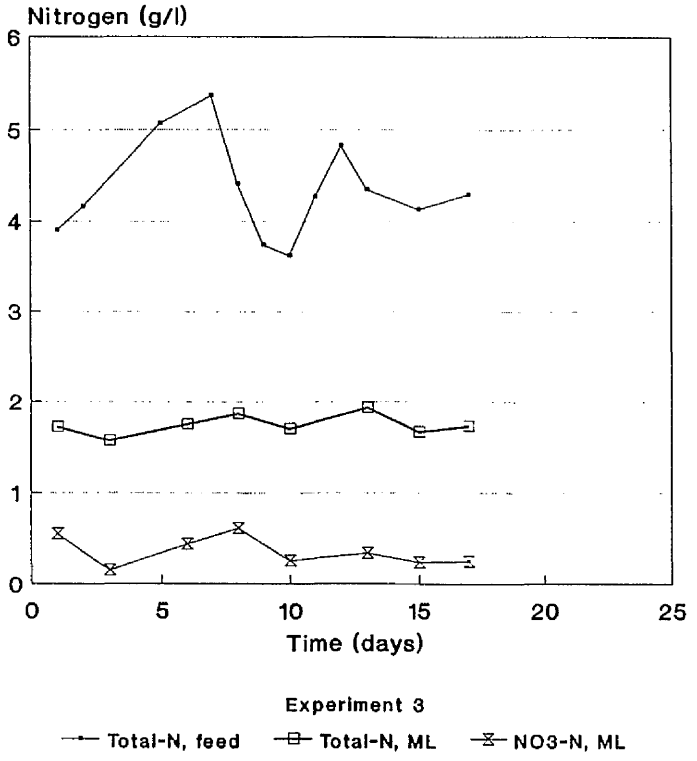

Fig.34 Effect of input slurry total nitrogen on the total nitrogen and nitrate nitrogen of the ML.

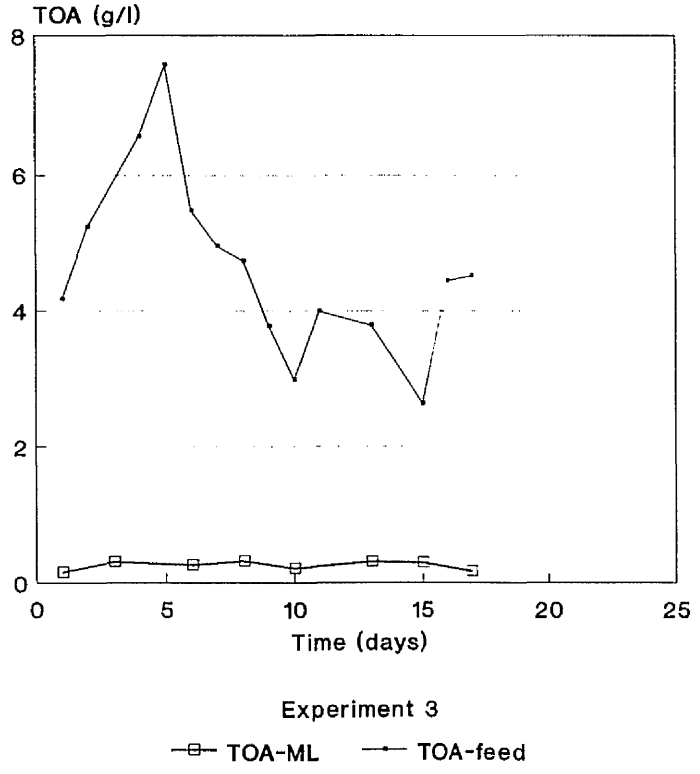

Fig.35 Effect of input slurry TOA on TOA of the ML.

Sneath *et al.* (1992) used four-day mean values of the feed COD and daily-assessed residence times for the calculation of COD of slurry treated at a nominal residence time. This was largely successful, the changes in the predicted values and in the observed values were in agreement although they were dissimilar in magnitude. The changes in COD of the feed were therefore directly reflected in the COD of the treated slurry. In the present study, however, the TS and COD of the ML were stable and were little affected by the TS and COD of the input slurry in both Experiment 3 and 6. Therefore eleven-day mean values of TS and COD of the input slurry and the mean treatment time were used in the calculations for Experiment 3 and 12-day means of TS and COD and the mean treatment time for Experiment 6. The calculated results (Fig. 32 and Fig. 36) indicated that the predicted values of TS in both experiments were still not accurate reflections of the observed results. The best fit for TS prediction was obtained from a five-day mean value of TS in the input slurry and the best fit for COD prediction came from 11 and 12-day mean values of COD in the input slurry.

The total nitrogen concentration in the ML varied by 18% from 1.6 to 1.95g/l while total nitrogen in the input varied by 33% from 3.6 to 5.4 g/l during Experiment 3. Similar variations were observed in Experiment 6, 19% from 2.3 to 2.82 gN/l in the ML and a

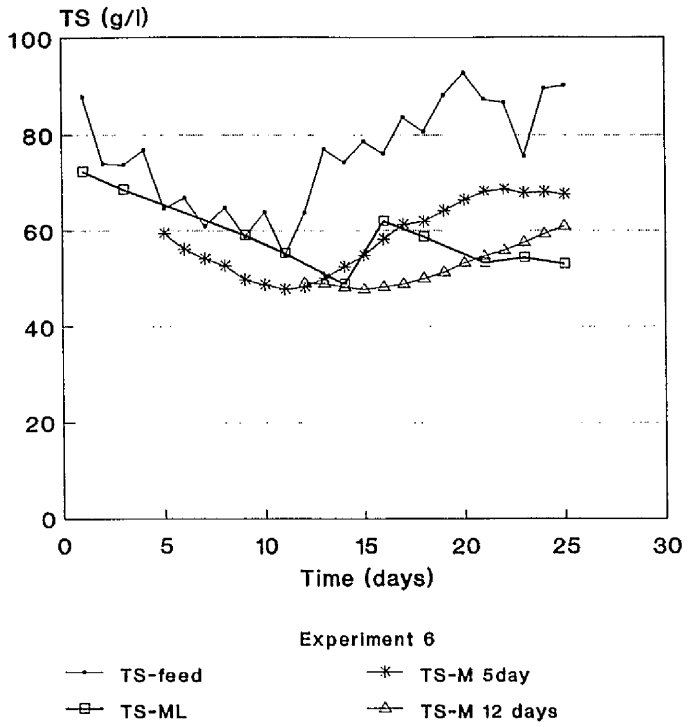

Fig.36 Effect of input slurry TS on the ML TS and predicted values (M) for 5 and 12 day running mean TS of input slurry.

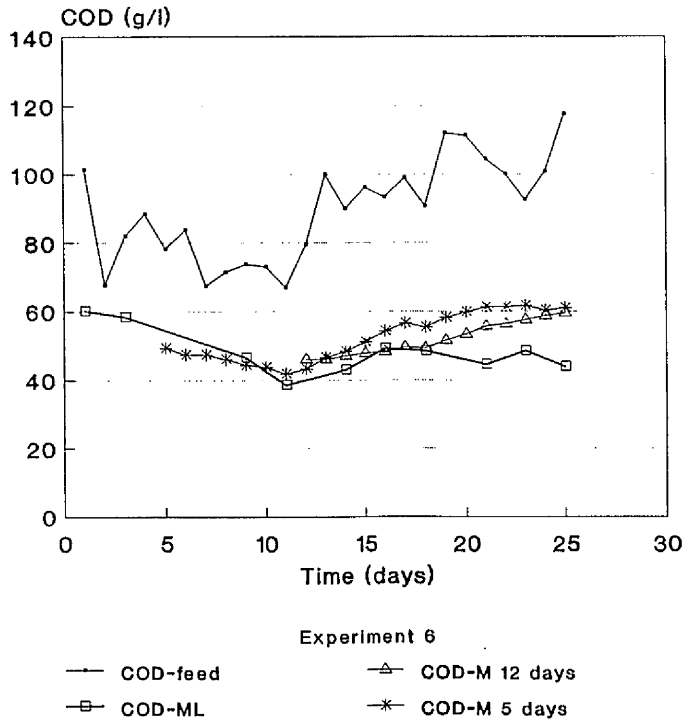

Fig.37 Effect of input slurry COD on the ML COD and predicted values (M) for 5 and 12 day running mean COD of input slurry.

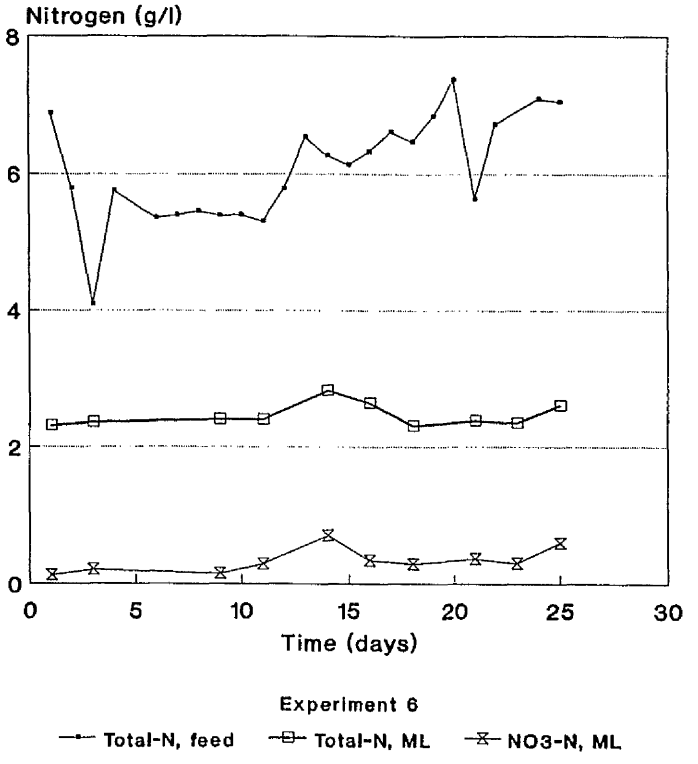

Fig.38. Effect of input slurry total nitrogen on the total nitrogen and nitrate nitrogen of the ML.

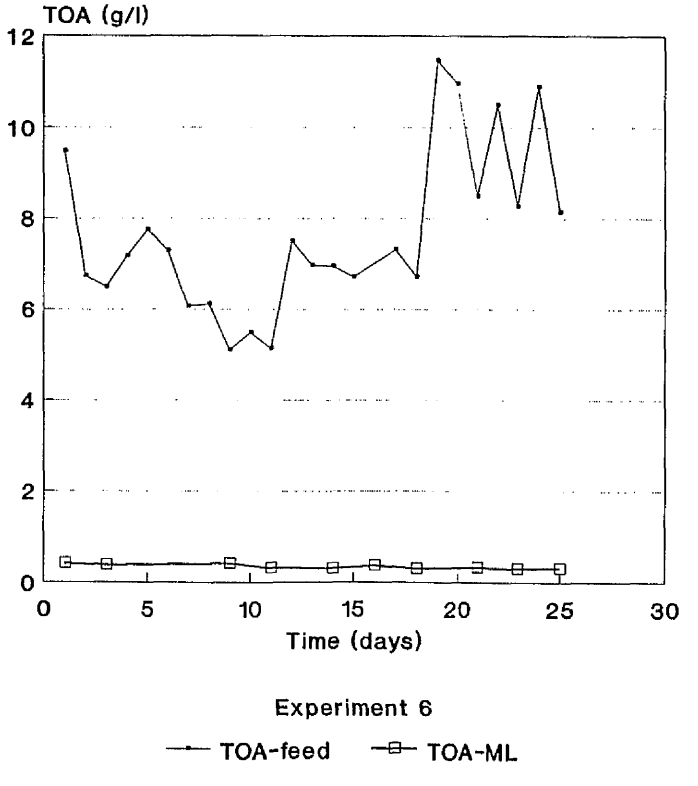

Fig.39. Effect of input slurry TOA an TOA of the ML.

much larger figure of 44%, from 4.1 to 7.37.g N/l in the input. Although the nitrogen losses varied from 53 to 66% for Experiment 3 and from 44 to 66% for Experiment 6 the average losses were very similar at 60.0% and 59.5% respectively (Table 20).

The nitrate concentration in the ML varied from 130 to 610mg/l in Experiment 3 and from 130 to 710mg/l in Experiment 6. The higher concentrations reflected higher concentration of total nitrogen in the input slurry.

Total organic acids fluctuated considerably during both experiments. The minimum values were 2.6 and 5.1g/l and the maximum 7.6 and 11.5g/l for Experiments 3 and 6 respectively. Neither the mean or the extreme values of TOA concentration affected the TOA concentration of the ML which remained nearly constant at 260mg/l and 350mg/l for Experiments 3 and 6 respectively. The removal rates of TOA, therefore, varied between 2.7 and 8.5kg/d during Experiment 3 and between 4.0 and 9.8kg/d during Experiment 6.

9.3.2. Treatment at mezophilic temperature and low dissolved oxygen concentration

Subsequent to Experiments 1-6 in which nitrification occurred, three Experiments 7, 8 and 9 were conducted at mezophilic temperature and at DO concentrations that encouraged ammonification of the available nitrogenous compounds but suppressed nitrification.

The treatment time was shortened by decreasing the depth, and thereby the volume of ML, in the reactor and the dissolved oxygen in the ML was controlled by redox potential. All three experiments had a similar treatment time (Table 21) but the DO concentration and redox potential varied (Table 22). Control by redox potential proved to be less sensitive than by DO probe and resulted in higher DO concentrations, although only for short periods of time, than those that would be expected at such low redox potential.

Low DO concentrations were maintained throughout by controlling redox potential in laboratory experiments (Evans *et al.*, 1986a). More frequent feeding at maximum intervals of 10 minutes with relatively lower doses of feed slurry did not allow wide variations in redox potential, and a fine control of the rate of aeration supplied just enough oxygen to be consumed by the microbial population without an apparent increase in DO concentration.

Although problems with DO control by redox potential were not reported by Williams *et al.* (1989) or Sneath *et al.* (1990) aerating separated piggery slurry in a $0.5m^3$ reactor and in a $23m^3$ reactor respectively, a similar problem was observed by Svoboda and Deans (1990) during laboratory-scale aeration of strong silage effluent. Feeding the 3-litre reactors at 8-minute intervals caused large changes in DO concentration

while the redox potential was much less affected and remained low even when the DO concentration reached high values.

Table 21. Treatment time and ML temperature during Experiments 7, 8 and 9.

Experiment	TT (days)	ML Temp. (^{o}C) Range	Mean
7	5.5	33.5 to 40.5	37.5
8	5.2	37.8 to 40.0	38.7
9	5.3	38.1 to 41.8	39.9

Table 22. DO and redox potential during Experiments 7, 8 and 9.

Experiment	DO (%) Range	Mean	Redox potential (mV E_{cal}) Range	Mean
7	0 to 10	2	-440 to 65	95
8	0 to 33	8	-320 to 5	-55
9	0 to 60	14	-400 to -30	-90

9.3.2.1. Characteristics of treated slurry and correlation with modelled data

Mean analytical values of treated slurry of Experiments 7, 8 and 9 were compared with the values predicted from the model equations (5) to (8) and (13). The results are tabulated together with the percentage differences between model and analytical data in Tables 23-27 and illustrated in the Figs. 26 and 28 to 31.

Total Solids

The degradation of total solids during all three

experiments was well within the range of expected decrease predicted by the model equation (5) (Table 23).

Table 23. Observed and predicted values of total solids in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
7	54.2	53.4	+1.6
8	51.9	52.3	-1.0
9	51.0	53.5	-4.7

Despite the variations in the DO concentration and in the redox potential in the ML, similarly observed by other researchers (Evans *et al.*, 1986a; Williams *et al.*, 1989), the residual values of TS were those expected from treatment at minimum or high levels of aeration (Fig. 26).

Total suspended solids

The variation from the expected values of concentration of TSS during these three experiments was similar to that predicted in Fig. 28. A slightly larger negative difference than that for TS points to the effect of sedimentation during treatment (Table 24).

Table 24. Observed and predicted values of total suspended solids in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
7	46.6	45.2	+3.1
8	42.1	43.6	-3.4
9	39.1	42.9	-8.9

Chemical oxygen demand

The differences of observed from predicted values of COD were between -5.2 and +13% (Table 25).

Table 25. Observed and predicted values of COD in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
7	55.7	58.7	- 5.2
8	54.7	48.4	+13.0
9	46.3	48.6	- 4.7

The wide-range of redox potential during the treatment appears to have had little effect in restricting COD removal (Fig. 29). As documented by Evans *et al.* (1986a), the removal of COD was restricted only when the redox potential was continuously controlled at levels lower than -300mV E_{cal}.

Biochemical oxygen demand

Evans *et al.* (1986a) demonstrated, in laboratory experiments during which the pH value of the ML was controlled at 7.8, that minimal aeration had a significant effect on increasing the value of residual BOD_5. Treatment at 35°C for 2 days with redox potential controlled at -100mV E_{cal} or -400mV resulted in differences between the observed BOD_5 and that expected from high-rate aeration experiments of approximately 2g/l and 5g/l respectively. These values are somewhat lower than those values observed in Experiments 7-9

(Table 26) in which the pH was uncontrolled and averaged 8.8 during longer residence times.

Table 26. Observed and predicted values of BOD_5 in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
7	7.41	3.35	+121.2
8	10.00	3.70	+170.3
9	5.52	2.73	+102.2

The high pH value and the intermittent, very low redox potential of -440mV must have been the main causes of the observed increase in residual BOD_5 (Fig. 30).

Biochemical oxygen demand of supernatant

The effect of minimal aeration was most noticeable on the level of BOD_{5s} (Table 27).

Table 27. Observed and predicted values of BOD_{5s} in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
7	0.58	0.02	+2795
8	0.76	0.02	+3700
9	0.33	0.02	+1550

Although the BOD_{5s} did not reach very high levels, the observed values differed from those predicted by between 1550 and 3700%, but the absolute differences were small ranging from 31mg/l to 740mg/l. These increased values were to be expected since minimal

aeration produced similar effects during laboratory trials (Evans *et al.*, 1986a). BOD_{5s} exponentially increased as redox potential decreased and during 2 days treatment at 35°C, BOD_{5s} changed from the expected 50mg/l at high DO to 1000mg/l at -400mV E_{cal}.

Visually the supernatant in Experiments 7-9 were cloudy in comparison with the transparent supernatants of nitrified ML. This high BOD_{5s} was also a reflection of higher concentration of TOA in the treated slurry.

Total organic acids

The concentrations of TOA in the treated slurry were 1.1, 0.89 and 0.91g/l for Experiments 7, 8 and 9 respectively as shown in Tables A7, A8 and A9, and were about three times those found in the experiments with high DO concentration. Although the treatment time was approximately half of that in the experiments with high DO concentration, it has been reported (Thacker and Evans, 1985; Williams *et al.*, 1989) that at high DO concentration a minimum of only 3 days was required to degrade TOA to levels lower than 30mg/l. These higher levels of TOA were, therefore, the result of oxygen limitation under conditions of low redox potential. A similar effect was observed by Evans *et al.* (1986a) who showed an exponential increase of TOA concentration with decreasing redox potential from 100 to -500mV E_{cal}.

The concentrations of TOA in Experiments 7-9 would represent 'faintly offensive' odour (Thacker and Evans,

1985) rating 2.4, compared with the "very faintly offensive" odour rating 1.1, for slurry treated at high DO.

Nitrogen

The nitrogen compounds in slurry were not oxidised during these three experiments. The low DO concentration encouraged ammonification but prevented growth of nitrifying microorganisms (Smith and Evans, 1982; Evans *et al.*, 1986b). Despite the high pH value of 8.8 and high aeration rates during the intervals after feeding to compensate for the rapid decrease of redox potential in the ML, the losses of nitrogen were low (Table 28) and within the range expected from this type of treatment (Williams *et al.*, 1989; Sneath *et al.*, 1990; Evans *et al.*, 1986b) (Table 28).

Table 28. The pH value and percentage change of total, ammoniacal, organic and supernatant organic nitrogen in the ML compared with the input slurry.

Exp.	pH	Tot.N %	Ammon.N %	Org.N %	$Org.N_S$ %
7	8.8	-4.8	-5.2	-4.5	-0.0
8	8.9	-11.2	-8.0	-16.7	-24.0
9	8.8	-3.6	-6.9	+4.0	+26.7

Such low losses can only be explained by the aeration system used during these experiments. Recycling of air through the ML in the enclosed reactor prevented excessive evaporation and the stripping of ammonia which would be expected at these high pH values.

Losses of organic nitrogen from whole slurry and supernatant were expected due to ammonification (Evans *et al.*, 1986b). The increase in organic nitrogen observed during Experiment 9 may have been a result of anaerobic activity in the settled solids releasing organic nitrogenous compounds into solution.

9.3.2.2. Effects of variation in the characteristics of the input slurry on those of the treated slurry

During Experiments 7, 8 and 9 the concentrations of TS and COD in the input slurry fluctuated considerably with standard deviations from 5.2 to 11.6 and from 9.6 to 21.7g/l respectively (Tables A7, A8 and A9). These fluctuations and their effects are illustrated in Figs. 40 to 43. The largest deviations in COD were observed during Experiment 9, the data from which was therefore used to describe the effects of these variations on the characteristics of the mixed liquor.

Experiment 9

The TS of the input slurry varied between 52.4 and 84.6g/l and averaged 64.6g/l (Fig. 40). Such large variations were expected to be reflected in the quality of the treated slurry (ML) particularly since the treatment time of 5.3 days was relatively short. However variations of ML were dampened by the treatment effect and the ML volume, so that the difference between the minimum of 45.6 and the maximum of 58.4g/l was only 12.8g/l compared with a difference of 32.2g/l in the

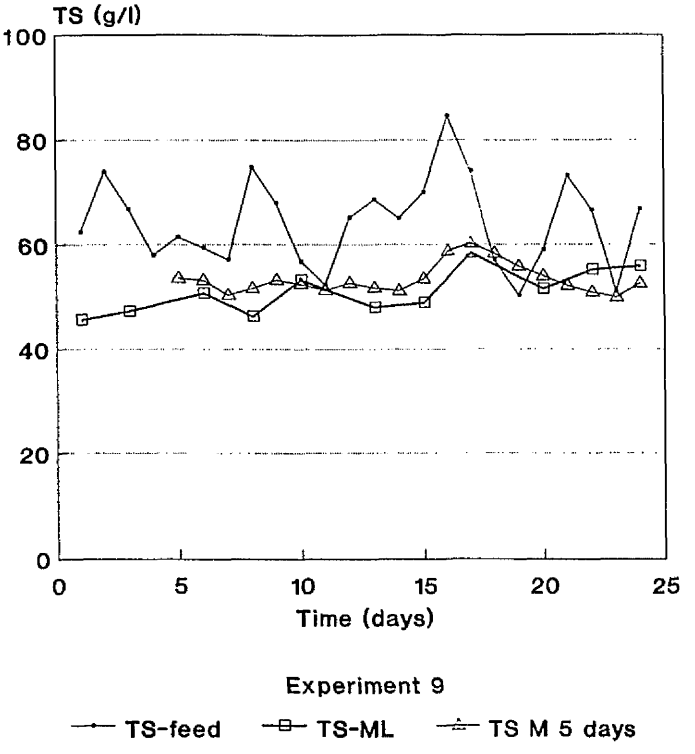

Fig.40 Effect of input slurry TS on the ML TS and predicted values (M) for 5 day running mean TS of input slurry.

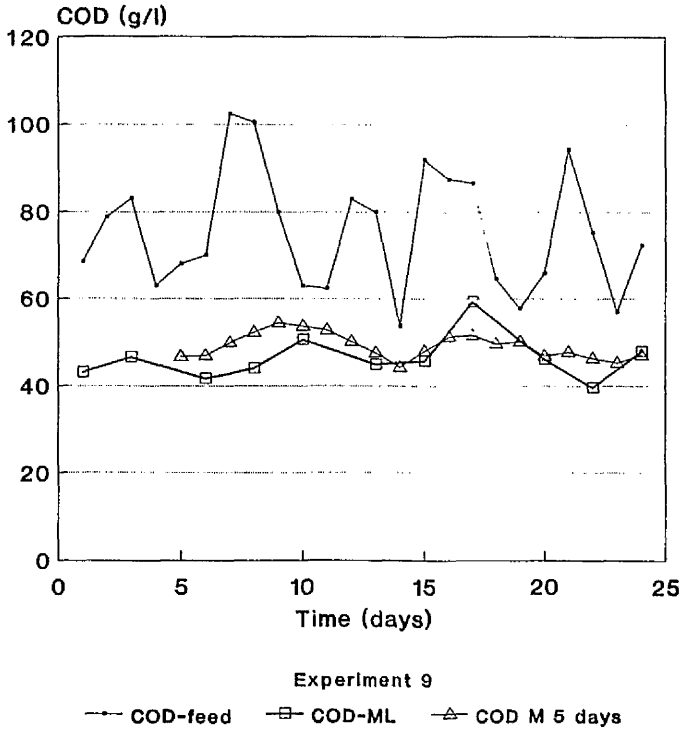

Fig.41 Effect of input slurry COD on the ML COD and predicted values (M) for 5 day running mean COD of input slurry.

input slurry.

The values of TS in the ML were predicted using equation (5). The value for TS of input slurry used in this equation was a running mean of TS of the previous five days (Sneath *et al.*, 1992). The predicted values generally agreed well with the observed values in TS of the ML. However, the predicted values, except for the last 4 days of the experiment, were approximately 6% higher than those of the ML.

The changes in COD of the input slurry during Experiment 9 were the largest observed in all the experiments. The minimum and maximum values of 55 and 102.5g/l respectively were reflected in the standard deviation which was 21.7g/l (Table A9). Variations affected the COD of the ML so that the difference between the minimum and maximum COD concentrations of 20g/l resulted from a difference in COD concentrations of 34.2g/l in the input slurry. The effects of a sudden increase or decrease of COD in the input slurry on the COD of the ML were usually apparent 2 to 3 days later, suggesting that the COD values of the ML could be predicted using a 3-day running mean value of the COD in the input slurry. However, the predicted values which best fitted COD of the ML were those where a five day-running mean value of the input COD was used for the calculations (Fig. 41).

Kjeldahl and ammoniacal nitrogen in the input

slurry varied between 6.9 and 9.3g/l and 4.2 and 7.1g/l respectively (Fig. 42). The concentrations in the ML followed those in the input very closely with little or no time delay.

The overall losses of total nitrogen (3.4%) and ammoniacal nitrogen (7%) during treatment in Experiment 9 were small and resulted from some ammonia stripping during aeration when the pH value was relatively high at 8.8.

The concentrations of TOA in the ML were largely unaffected by the variations in TOA concentration in the input slurry despite the wide range of values with a difference of 4.2g/l between maximum and minimum (Fig. 43) over 14 days. Only a small increase of 0.3gTOA/l in the ML was measured three days after the TOA increased by 2.5g/l in the input slurry.

9.3.3. Treatment at thermophilic temperature, 50^{o}C

Six treatment experiments were run at a thermophilic temperature averaging 50^{o}C (Table 29). The treatment time was increased from 4.7 in Experiment 10 to 8.6 days in Experiment 15.

The dissolved oxygen concentration in the ML was controlled by a DO probe at 40% of saturation which established the mean values of DO concentration between 5 and 35% and/or by the redox potential at between -10 and -160 mV E_{cal} (Table 30).

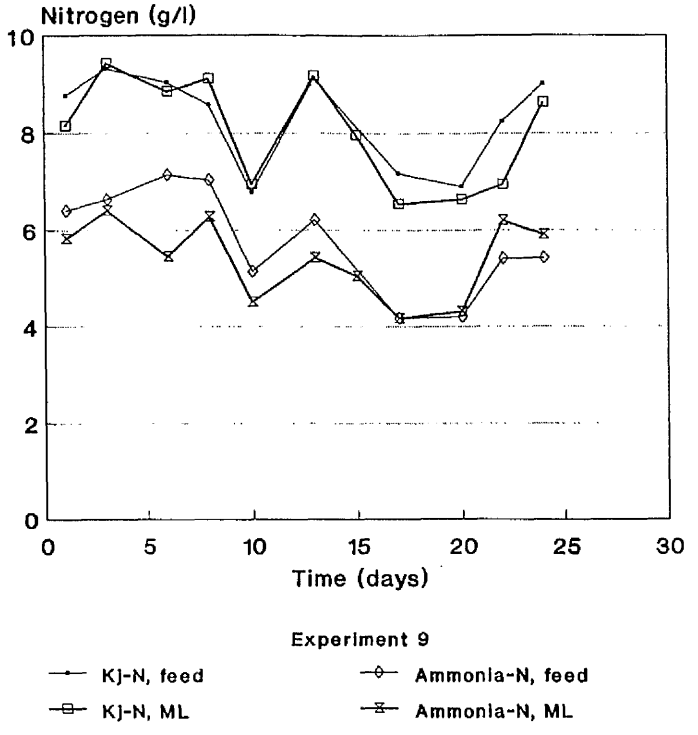

Fig.42 Effect of input slurry total and ammoniacal nitrogen on the total and ammoniacal nitrogen of the ML.

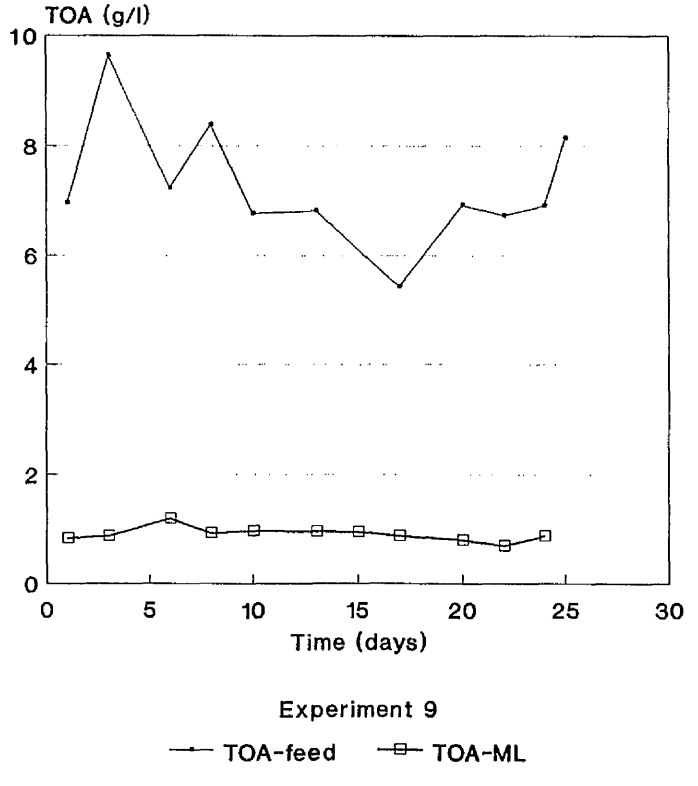

Fig.43 Effect of input slurry TOA an TOA of the ML.

Table 29. Treatment time and ML temperature during Experiments 10 to 15.

Experiment	TT (days)	ML Temp. (^{o}C) Range	Mean
10	4.7	50.0 to 53.3	50.1
11	5.6	49.0 to 54.0	50.5
12	6.6	47.3 to 53.9	49.6
13	7.1	49.1 to 51.9	50.1
14	8.4	49.0 to 55.4	50.2
15	8.6	45.0 to 50.9	48.7

Table 30. DO and redox potential during Experiments 10 to 15.

Experiment	DO (%) Range	Mean	Redox potential (mV E_{cal}) Range	Mean
10	0 to 40	10	-440 to -90	-140
11	0 to 40	10	-220 to -130	-160
12	0 to 45	15	-340 to 100	- 50
13	0 to 30	10	-210 to 80	- 20
14	30 to 40	35	-110 to 0	- 10
15	0 to 20	5	-330 to 0	- 60

The lowest values of DO concentration or redox potential occurred after feeding slurry into the reactor and were dependent on the concentration of the components in the intake slurry and on the level of foam which affected the aerator performance. A thick layer of foam was always present during all experiments with low levels of aeration and resultant low concentrations of DO.

Values of residual TS, TSS, COD, BOD_5 and BOD_{5s} were predicted using the model equations for continuous aerobic treatment at 50^{o}C (Evans *et al.*, 1983). These

were then compared with observed data (Tables A10 to A15) (Chapter 9.3.1.).

The DO level during Experiment 14 was maintained at a high level (35% of saturation), keeping the redox potential at the highest level for this series of experiments, in order to compare the results with those of experiment 15, with reference to losses of nitrogen and to any effects on the quality of the ML.

9.3.3.1. Characteristics of treated slurry and correlation with modelled data

Total solids

Values of predicted TS of treated slurry were calculated from the equation (9)

$$TS = [0.45/(1+0.7*R)+0.579]*TS_f$$

The observed values varied between 94.5% and 118.6% of the predicted values (Table 31) and are illustrated in Fig. 26.

Table 31. Observed and predicted values of total solids in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
10	45.2	46.4	- 2.7
11	33.5	31.7	+5.7
12	45.7	43.1	+10.2
13	56.0	47.2	+18.6
14	42.2	44.7	- 5.5
15	53.5	46.7	+14.6

The intake slurry for all these experiments except

Experiment 11 was more than twice as concentrated as that used in laboratory experiments (Evans *et al.*, 1983). This together with fluctuations in concentration of TS expressed as a standard deviation of up to 10.1g/l could account for less TS being biodegraded than expected.

Total suspended solids

Predicted values of residual TSS after treatment were calculated from the equation (10)

$$TSS = [0.45/(1+0.7*R)+0.563]*TSS_f$$

and compared with observed data in Fig. 28 and together with the differences in Table 32.

Table 32. Observed and predicted values of total suspended solids in treated slurry and their percentage differences expressed as a percentage of the predicted values.

Experiment	Observed g/l	Predicted g/l	Difference %
10	33.4	36.5	- 8.4
11	23.5	24.2	- 2.3
12	30.8	36.2	-15.0
13	43.8	41.1	+ 6.6
14	32.5	35.0	- 7.2
15	44.7	36.5	+22.4

The much lower value than that predicted in Experiment 12 was probably due to sedimentation on the base of reactor, while the large increase of TSS over that predicted in Experiment 15 defies explanation in the absence of an extension of this rather short experiment

which only lasted 12 days.

Chemical oxygen demand

Values of residual COD for experiments 10 to 15 were predicted using the equation (11)

$$COD = [0.429/(1+0.7*R)+0.445]*COD_f$$

and compared with observed data in Fig. 25 and together with the differences in Table 33.

Table 33. Observed and predicted values of COD in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
10	45.2	46.5	- 2.8
11	28.2	30.1	- 6.3
12	55.8	44.4	+25.7
13	60.3	48.9	+23.3
14	42.4	44.1	- 3.9
15	44.1	40.2	+9.7

Except for Experiments 12 and 13 the differences from predicted values were small and within the expected tolerance of 10%.

During experiment 12 the input COD of 85.1g/l (Table A 12) was more than twice the COD of input slurry used in laboratory experiments (Evans *et al.*, 1983) and this together with the low DO concentration of the ML must have influenced the effect of treatment. The mean value of treated slurry was 55.8gCOD/l and the standard deviation 24.5gCOD/l, showed some instability of treatment during this experiment.

In Experiment 13 the COD of the ML was obviously affected by the extremely high COD of the input slurry which averaged 94.5 g/l and by the large variations in the intake COD (SD=15.4gCOD/l).

Evans *et al.*, (1986a) demonstrated that, at treatment for 7 days at 50^{o}C and at redox potentials from 0 to -500mV E_{cal}, there was a linear relationship between the redox potential and the difference between the residual COD at these minimal rates of aeration and those at high rates of aeration. At about -50mV degradation actually increased by 2.0g COD/l whereas at -400mV there was a decrease by 6.0g COD/l compared to values obtained at high aeration rates. These results suggest that more COD should be degraded in Experiment 13 at redox potential -20mV than in Experiment 12 at -50mV, but no such effect was observed. At the lowest redox potentials reached, -340mV in Experiment 12 and -210mV in Experiment 13 (Table 33), the difference between the lower predicted values and the observed values would be expected to be 2 to 3 gCOD/l but the observed difference of 11.4g/l in both cases was far greater. The only possible explanation of such a deterioration in COD removal appears to be the increased concentrations of COD in the intake slurry.

Biochemical oxygen demand

The residual BOD_5 in Experiments 10 to 15 was predicted from the equation (12)

$$BOD_5 = 1.568/R + 0.152*BOD_{5f}$$

and compared with observed data in Fig. 26 and, together with the differences, in Table 34.

Table 34. Observed and predicted values of BOD_5 in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
10	4.00	3.26	+22.7
11	4.20	2.12	+98.1
12	3.40	3.52	- 3.4
13	7.40	4.75	+55.8
14	4.53	3.56	+27.2
15	3.60	3.48	+ 3.4

The differences between the predicted values and those observed show large variations and were reflected in the absolute removal effect. BOD_5 was decreased by only 66.1% during Experiment 11 whereas the maximum BOD_5 removal of 84.3% was achieved during Experiment 12.

A decrease in BOD removal during treatment at low redox potential was predicted from observations by Evans *et al*. (1986a). If a similar decrease of biodegradation to that occurring in 7 days at minimal aeration rate could be expected for other treatment times, then the percentage difference for Experiment 11 would decrease to only +16% but in Experiment 13 the low redox potential would only influence the percentage difference slightly to +43.7%. These large differences were probably due to the very wide fluctuations in redox potential.

The average BOD_5 removal was lower than that expected and obtained by treatment at high rates of aeration.

Biochemical oxygen demand of supernatant

Values of BOD_5 of supernatants for Experiments 10 to 15 were predicted using the equation (14)

$$BOD_{5s} = 0.0427/R + 0.007*BOD_{5f}$$

and compared with observed data in Fig. 27 and together with the differences in Table 35.

Table 35. Observed and predicted values of BOD_{5s} in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
10	0.28	0.14	+100
11	0.26	0.09	+189
12	0.47	0.16	+193
13	0.43	0.21	+105
14	0.28	0.16	+75
15	0.23	0.16	+43

The differences between observed and predicted values ranged from 43% to 193% (Table 35) and were larger than those expected and obtained at high rates of aeration. For minimal aeration rates an equation correlating BOD_{5s} and redox potential during a treatment time of 7 days (Evans *et al.*, 1986a) was used.

$$\log BOD_{5s} = -3.769*Redox-1.49 \quad (g/l)$$

where BOD_{5s} is the difference between the observed value

and the BOD_{5s} expected after treatment at a high rate of aeration and Redox is the redox potential in Volts. Using this equation, the predicted values increased by 40mg/l in Experiment 12 and 50mg/l in Experiment 13. These values decreased the differences between predicted and actual values from 193% to 123% in Experiment 12 and from 105% to 72% in Experiment 13. When the same equation was used for Experiment 11 the difference was 171%. These calculations suggest that, although always higher than expected, these differences were within the tolerance of variations in measured data (Evans *et al.*, 1979).

Total organic acids

The concentration of TOA in the treated slurry was independent of the treatment time in Experiments 10 to 15 (Table 36) and averaged 1.5g/l compared to the maximum concentration of TOA in the treated slurry of 0.3g/l calculated from the equation

$$\text{LogTOA} = -2.224*\text{Redox} - 0.884 \qquad (g/l)$$

(Evans *et al.*, 1986b).

Such a high concentration of residual TOA is a consequence of higher concentrations of TOA in the intake slurry of 5.5 to 12.3g/l than the 2.3g/l in the feed slurry reported by Deans and Evans (1987) and of anaerobic activity in the sediment, which would be increased by the high temperature of treatment.

Table 36. Concentration of TOA of intake and treated slurry and percentage removal during treatment.

Experiment	Intake g/l	Treated g/l	Removal %
10	7.6	1.4	81.6
11	6.6	1.5	77.3
12	5.5	1.3	76.4
13	6.1	1.6	73.8
14	12.3	1.5	87.8
15	7.3	1.6	78.1

Odour offensiveness calculated from the equation (Thacker and Evans, 1985) was 2.7 , i.e. "faintly to definitely offensive" . This indicates that treatment at 50^{o}C is less effective in reducing odour offensiveness than treatment within the mezophilic temperature range.

Nitrogen

Nitrifying microorganisms do not survive at thermophilic temperatures (Painter, 1986). Therefore the nitrogen content of the mixed liquor in these experiments is composed of ammoniacal and organic nitrogen.

Ammonification of part of the organic nitrogen in the intake slurry occurred, including mostly the dissolved (supernatant) nitrogen together with some of the nitrogenous solids. Loss of nitrogen could only occur by ammonia stripping which was encouraged by the high pH value and the air flow rate. Losses of total and ammoniacal nitrogen together with changes of organic nitrogen are shown in Table 37.

Table 37. Changes in total, ammoniacal, organic and supernatant organic nitrogen of ML as percentages of values in intake slurry.

Exp.	Tot.N %	Ammon.N %	Org.N %	$Org.N_S$ %	pH -
10	-24.2	-23.5	-25.0	0.0	9.2
11	- 6.9	- 9.4	+3.5	+8.3	8.7
12	-19.0	-13.3	-25.0	-24.1	8.8
13	-15.5	-10.0	-20.9	-24.1	8.8
14	-17.9	-30.0	0.0	-2.2	8.7
15	- 7.9	- 7.9	-7.9	-200.0	8.8

9.3.3.2. Effect of variation in the characteristics of the input slurry on those of the treated slurry

The treatment times increased progressively from 4.7 to 8.6 days in Experiments 10 to 15. The effect of variable feed slurry concentration on the quality of the treated slurry should be most pronounced in the shortest treatment time in Experiment 10 which also had the highest standard deviation of COD in this series of experiments.

The total solids of the intake slurry, with a mean value of 67.9g/l and a standard deviation of 7.9g/l (Table A10) reached a minimum value of 55.2g/l on day four and a maximum value of 81.6g/l on day 13 of the experiment. The effect on the TS of the ML was smoothed out by biodegradation and by buffering by volume, so that its mean TS was 45.2g/l with a standard deviation of only 3.9g/l (Table A10). The response of TS in the ML to the lowest value of TS in the intake slurry was negligible, while the highest value of intake TS showed an effect after two days when the TS of the ML reached a

maximum value of 51.2g/l.

The TS of the ML was predicted using the equation (9). In the equation, TS_f was substituted by 1 to 5-day running mean values of intake TS. The best fit with the observed values was with the 5-day running mean of the intake slurry (Fig. 44). Therefore the TS of the fifth day was calculated as follows:

$$TS_{5d}=[0.450/(1+0.7R)+0.579]*(TS_1+TS_2+TS_3+TS_4+TS_5)/5$$

The COD of the intake slurry varied from 54.8g/l to 115.8g/l with a mean value of 85.4g/l (Table A10). This affected the COD of the ML so that one day after the lowest COD of the intake feed, the lowest ML COD of 29.6g/l was observed. The highest intake COD occurred at the end of the experiment and the effect on COD of the ML was not observed but the cumulative effect of high intake COD of up to 105g/l was indicated by the highest value of 64.8gCOD/l in the ML which had a mean value of 45.2g/l.

Values of the ML COD were predicted from the equation (11) using one to five day mean COD_f values of the preceding days. The one-day COD_f gave the best fit with the observed data except on day 3 when the predicted value was too high and on day 17 when it was too low. Predictions using a 5-day running mean smoothed the data unrealistically and were, on average, approximately 15 to 20% higher than observed data (Fig. 45).

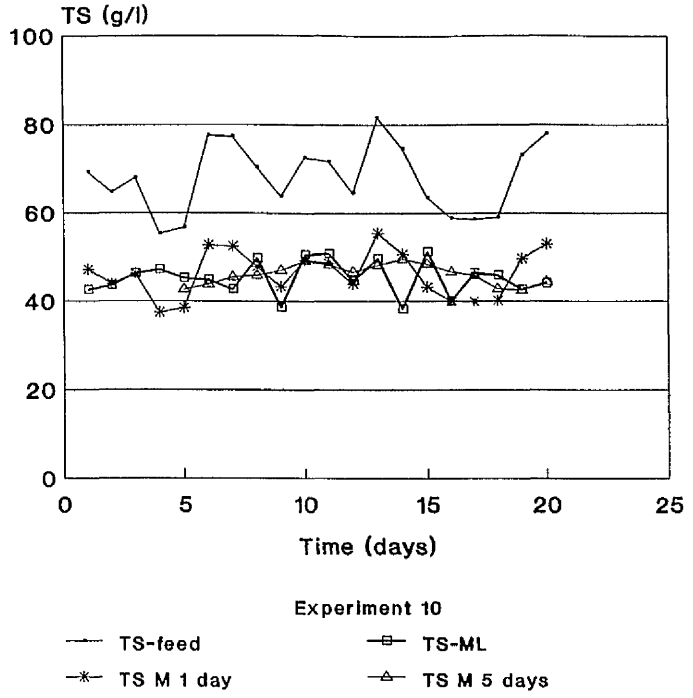

Fig.44 Effect of input slurry TS on the ML TS and predicted values (M) for 5 day running mean TS of input slurry.

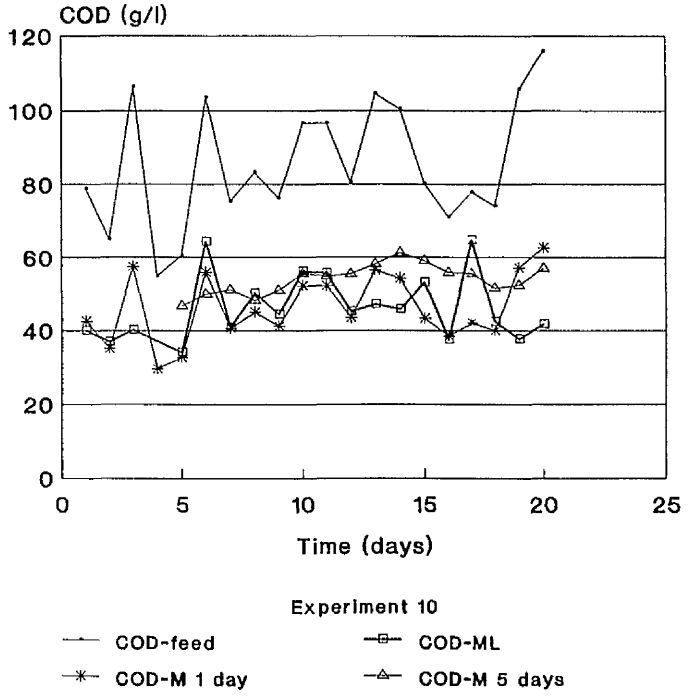

Fig.45 Effect of input slurry COD on the ML COD and predicted values (M) for 1 and 5 day running mean COD of input slurry.

The total nitrogen in the intake slurry varied from 5.6 to 9.16g/l but the wide range of 3.5g/l had very little impact on the total nitrogen in the ML which changed by only 1g/l during the course of the experiment (Fig. 46).

There was closer correlation between ammonia nitrogen in the feed slurry and in the ML but, even so, a change of 2.0g/l in the intake slurry resulted in a change of only 1.0g/l of ammonia nitrogen in the ML.

The concentration of total organic acids in the ML remained nearly constant with a mean value of 1.4g/l (Table A10) during Experiment 10 and did not respond to variations in the intake TOA of up to 2.4g/l (Fig. 47).

9.3.4. Treatment at thermophilic temperature, 55°C

Thermophilic treatment provides extractable heat that can be utilised more efficiently and without the need for upgrading by heat pump (Hughes, 1984; Svoboda and Evans, 1987). The temperature required is in excess of 45°C (Hamer and Bayers, 1985), with the optimum between 50 and 65°C. These findings have been mostly observed in the treatment of sewage sludge (Wollinski and Bruce, 1982; Paulsrud and Langeland, 1983; Wollinski, 1985; Deeny *et al.*, 1985; Morgan *et al.*, 1986; Morgan and Gunson, 1987).

Treatment of piggery slurry at this temperature was reported by Lock *et al.* (1982) on two experiments in a 200 litre reactor.

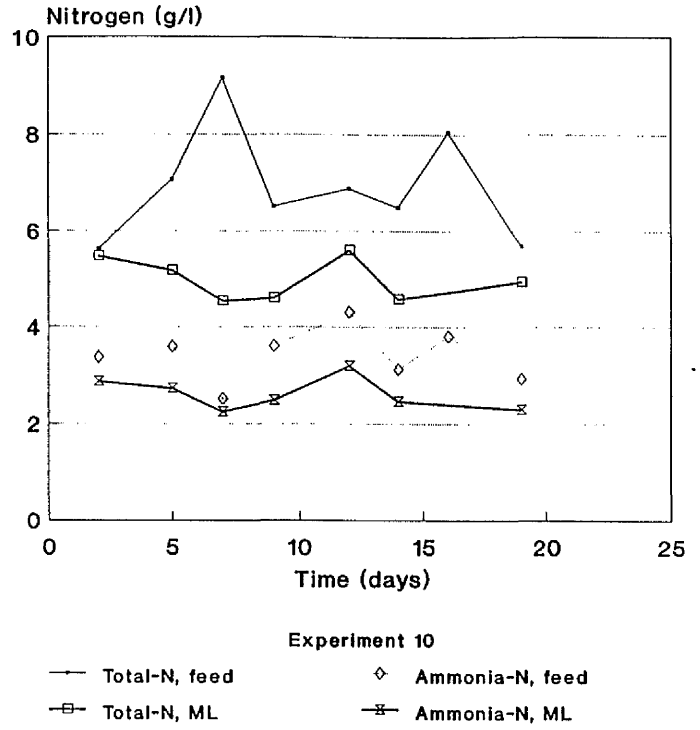

Fig.46 Effect of input slurry total and ammoniacal nitrogen on the total and ammoniacal nitrogen of the ML.

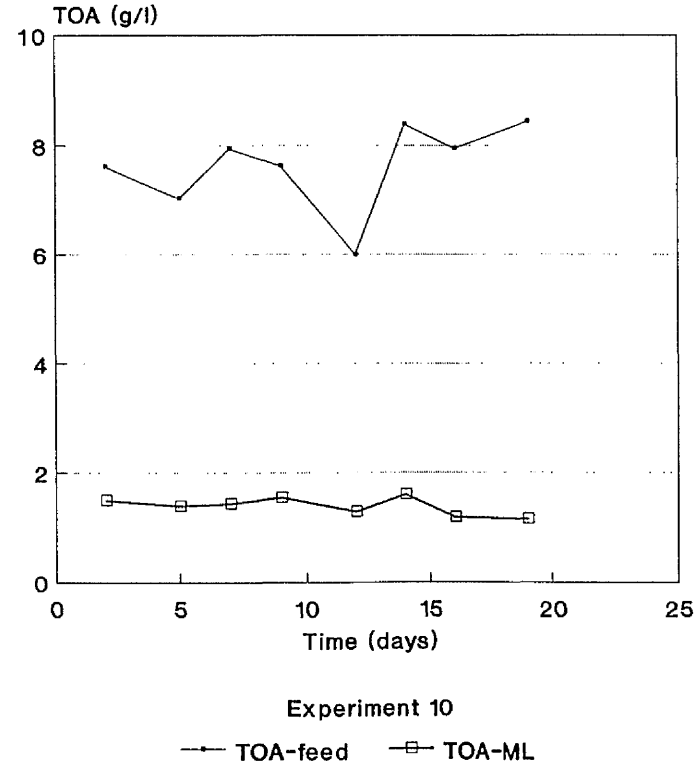

Fig.47 Effect of input slurry TOA an TOA of the ML.

The temperature of the ML during Experiments 16 to 20 was controlled at a nominal temperature of 55°C and the treatment time was progressively increased from 4.7 to 9.1 days (Table 38).

Table 38. Treatment time and ML temperature during Experiments 16 to 20.

Experiment	TT (days)	ML Temp. (°C) Range	Mean
16	4.7	45.0 to 61.3	53.0
17	5.7	53.0 to 57.7	55.8
18	7.1	49.5 to 55.7	54.2
19	7.5	50.0 to 55.8	54.8
20	9.1	50.0 to 55.7	54.5

The DO concentration control was set to a level of 30%. Since the DO level always decreased after the reactor was fed and stayed near 0% for most of the time between feeds its overall mean values were between 3 and 15% of saturation (Table 39). The fluctuations in DO level influenced the redox potential which varied widely between -440 and 120mV E_{cal}.

Table 39. DO and redox potential during Experiments 16 to 20.

Experiment	DO (%) Range	Mean	Redox potential (mV E_{cal}) Range	Mean
16	0 to 20	3	-440 to 30	-60
17	0 to 33	4	-440 to 20	-110
18	0 to 33	12	-150 to 120	30
19	0 to 30	15	-180 to 30	-10
20	0 to 35	15	-160 to -10	-40

9.3.4.1. Characteristics of treated slurry and correlation with modelled data

The concentrations of the various components in the ML were predicted from the same equations used in Experiments 10-15 and derived for a treatment temperature of 50°C by Evans *et al.* (1983). The predicted values were compared with the observed analytical data listed in Tables A16 to A20.

Total solids

The concentrations of total solids in the ML were consistently higher than those predicted by equation (9) at 50°C. (Table 40, Fig. 26).

Table 40. Observed and predicted values of total solids in treated slurry and their percentage difference.

Exp.	Observed	Predicted		Difference	
	55°C g/l	50°C g/l	35°C g/l	50°C %	35°C %
16	55.9	47.4	57.9	+17.9	-3.4
17	52.1	47.4	58.3	+10.0	-10.7
18	53.1	41.6	51.7	+27.6	-2.8
19	55.0	41.9	52.1	+31.3	+5.8
20	58.0	43.6	54.6	+33.0	+6.2

The minimum increase to 110% of the predicted value in Experiment 17 can still be considered to be within the tolerance of error and variability of the treatment system as was observed previously (Evans *et al.*, 1979). The TS values in the remaining experiments were therefore 7.9 to 23% higher than would be expected even allowing for acceptable errors and variability.

The effect of minimal aeration can be considered as a factor in these extremely variable results. It was suggested by Evans *et al.* (1986a) that degradation of TS at low redox potential and at high aeration rate would be similar at 50°C.

In Experiments 16 to 20 the concentrations of TS in the ML were much nearer to the concentrations expected from treatment at mezophilic temperatures. Predicted values were therefore recalculated from the equation (5) for mezophilic temperature and produced results which were much nearer to those observed (Table 40).

Total suspended solids

The concentration of TSS in the ML also showed much closer correlation with TSS concentration predicted from treatment at mezophilic temperature than from treatment at thermophilic temperature (Table 41, Fig. 28).

Table 41. Observed and predicted values of total suspended solids in treated slurry and their percentage difference.

Exp.	Observed	Predicted		Difference	
	55°C g/l	50°C g/l	35°C g/l	50°C %	35°C %
16	45.5	40.3	48.8	+12.9	-6.8
17	45.3	39.3	47.7	+15.2	-5.0
18	43.1	36.1	44.0	+19.4	-2.0
19	46.7	35.7	43.5	+30.8	+7.4
20	47.2	36.2	44.3	+30.3	+6.5

This suggests that the effect of low redox potential is significant in relation to the removal of

TSS and that a more accurate prediction is obtained by using the equation for residual TSS after mezophilic rather than thermophilic treatment.

Chemical oxygen demand

The values of residual COD were predicted from equations (11) and (7) for thermophilic and mezophilic treatments (Fig. 29) and the differences are shown in Table 42.

Table 42. Observed and predicted values of COD in treated slurry and their percentage difference.

Exp.	Observed	Predicted		Difference	
	55°C g/l	50°C g/l	35°C g/l	50°C %	35°C %
16	54.8	42.6	50.9	+28.6	+7.7
17	58.8	52.6	63.1	+11.8	-6.8
18	56.6	42.8	51.5	+32.2	+9.9
19	61.0	40.0	48.2	+52.5	+26.5
20	65.6	42.7	51.5	+53.6	+27.3

The observed values were much closer to the predictions from mezophilic than from thermophilic treatment. Although the performance in respect of COD removal during Experiment 17 was slightly better than might be expected, the concentrations of residual COD in the ML in Experiments 19 and 20 were much higher than predicted from equation (11).

According to Evans *et al.* (1986a), there is a linear relationship between redox potential and residual COD for 50°C treatment and 7 day treatment time. When this finding was applied to the results from Experiments 16 to 20 the observed large increases of the residual

COD over those predicted by the equation (11) could not be justified. Therefore the most accurate predictions of residual COD were obtained from calculations using the 35°C equation (7).

Biochemical oxygen demand

The BOD_5 of the whole treated slurry varied widely from that predicted from the equation (12)

$$BOD_5 = 1.568/R + 0.152 * BOD_{5f} \quad (g/l)$$

which can be applied for both mezophilic and thermophilic treatment temperatures.

The predicted values are compared with the observed values in Table 43 and Fig. 30.

Table 43. Observed and predicted values of BOD_5 in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
16	6.81	4.01	+69.8
17	3.85	4.34	-11.3
18	-	-	-
19	4.1	3.31	+23.9
20	5.12	3.79	+35.1

Although some improvement in the fit of the observed values to those predicted would be achieved by considering the decrease of BOD_5 removal as being due to low redox potential (Evans *et al.*, 1986a), the difference in Experiment 17 which represents an increase in BOD_5 removal over the predicted value should be even larger.

It may be that the relatively high pH in the other experiments have rendered the treatment less effective in terms of BOD_5 removal than in Experiment 17.

Biochemical oxygen demand of supernatant

Observed and predicted values of BOD_{5s} are given in Table 44 and Fig. 31.

Table 44. Observed and predicted values of BOD_{5s} in treated slurry and their percentage difference.

Experiment	Observed g/l	Predicted g/l	Difference %
16	0.45	0.18	+150
17	0.28	0.14	+100
18	0.30	0.15	+100
19	0.71	0.15	+370
20	0.58	0.17	+240

The decreased effect of treatment compared with that predicted in terms of removal of BOD_{5s} is consistent with results obtained with the other characteristics, namely TS, TSS, COD and BOD_5. The less effective treatment is probably caused by:

i) the high pH value of 9.4 allowing free ammonia to be present in the ML and suppressing microbiological activity (Painter, 1986)

ii) low redox potential, especially after feeding the reactor (Evans *et al.*, 1986a).

Total organic acids

The concentrations of TOA in the treated slurry remained relatively high (Table 45) averaging 1.6g/l.

Table 45. Concentration of TOA of raw and treated slurry and percentage of their removal after treatment.

Experiment	Input g/l	Treated g/l	Removal %
16	7.1	1.5	78.9
17	7.8	1.7	78.3
18	6.0	1.4	76.7
19	5.7	1.7	70.2
20	5.5	1.7	69.1

These values were independent of the treatment time between 4.7 and 9.1 days. The amount of TOA removed was between 69.1 and 78.9% and was only influenced by the initial concentration of TOA in the input slurry.

The odour offensiveness rating of 2.8 ("faintly to definitely offensive"), derived from equation (16) would render this particular treatment unacceptable as a means of odour control (Williams *et al.*, 1989).

Nitrogen

The ammonification of nitrogenous compounds in the input slurry was similar to that at 50^{o}C. Relatively very high pH values (Table 46) encouraged the stripping of ammonia by air flow and the losses of total nitrogen increased to 12.2% as treatment time was extended. Losses of ammonia were partially masked by growth of biomass, thus increasing the total content of organic nitrogen. Increases of organic nitrogen in the supernatant may have further resulted from solubilisation by aerobic activity in the ML or by anaerobic activity in the tank sediment.

Table 46. pH of ML and changes in total, ammoniacal, organic and supernatant organic nitrogen as percentages of initial concentrations in the input slurry

Exp.	Tot.N %	Ammon.N %	Org.N %	$Org.N_S$ %	pH -
16	-6.9	-8.0	+9.1	-23.5	9.3
17	-8.0	-9.7	-9.3	+14.3	9.3
18	-11.6	-10.8	-17.2	+16.7	9.4
19	-11.0	-20.9	+6.9	+ 9.1	9.4
20	-12.2	-17.9	-5.4	0.0	9.5

9.3.4.2. Effect of variation in the characteristics of the input slurry on those of the treated slurry

The effect of varying feed concentrations of components in the input slurry on the characteristics of the ML during treatment at 55°C was examined at the shortest treatment time in Experiment 16.

The total solids of the input slurry varied during the 31 days of Experiment 16 from a minimum of 57.9g/l to a maximum of 79.4g/l (Fig. 48) with a mean value of 69.3g/l and a standard deviation of 7.4g/l (Table A16). The effect of these variations was reflected in the ML by a smooth decreasing trend of TS concentration during the first 15 days followed by an increase with virtually no effect from a decrease of 20g/l in the TS of the intake slurry. Predictions from equations (9) and (5) for treatment at 50 and 35°C were obtained for comparison with observed analytical data.

In view of the assessment of results and their correlation with predicted values of the various components in the ML in Chapter 9.3.3.1. it was

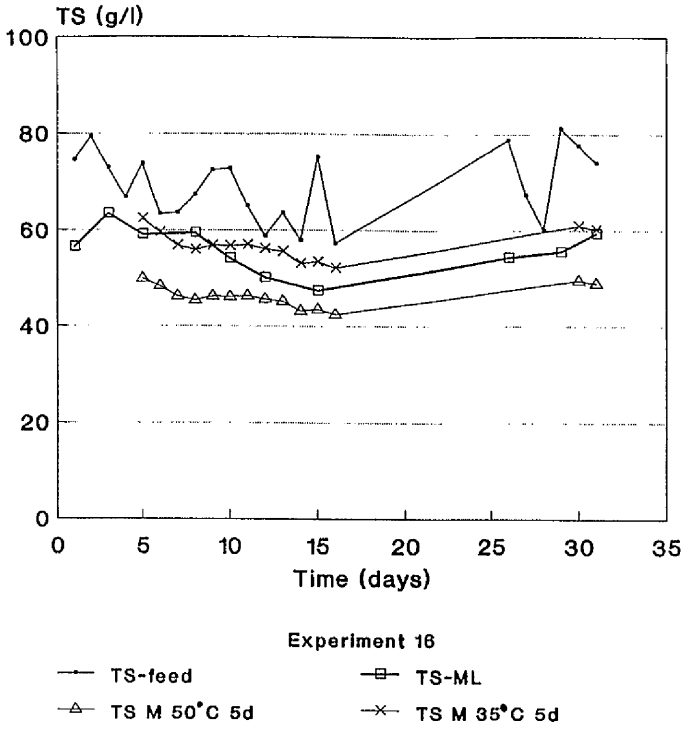

Fig.48 Effect of input slurry TS on the ML TS and predicted values (M) calculated for 35 and 50°C equations for 5 day running mean TS of input slurry.

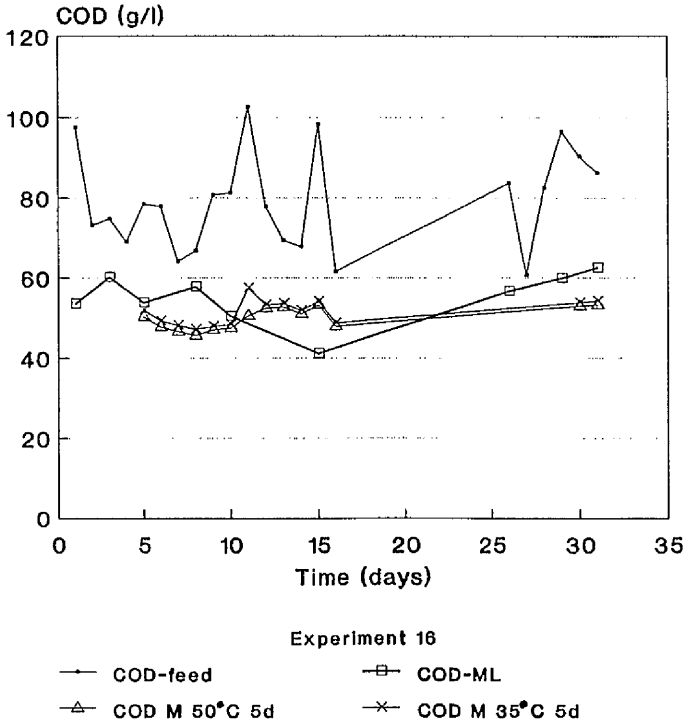

Fig.49 Effect of input slurry COD on the ML TS and predicted values (M) calculated for 35 and 50°C equations for 5 day running mean COD of input slurry.

decided to use predictive values from the 35°C equation (5). Data predicted from this equation were much nearer to the observed values than those derived from the 50°C equation (9) and this view was supported by predicting the daily changes as shown in Fig. 48. These predicted values show a less effective treatment than that observed and would therefore be more advantageous for the design of a treatment system since an underestimation of the effectiveness would allow for sub-optimal performance.

The input slurry contained from 61.6gCOD/l to 102.7gCOD/l with a mean value of 78.2g/l (Table A16). The effect of this variation on the COD concentration in the ML was minimal, as with TS, and showed a slowly declining trend during the first 15 days followed by an increase which was not affected by a fall of more than 25gCOD/l in the input slurry (Fig. 49).

Data predicted from equations (7) and (11) for treatment at 35°C and 50°C, were similar on average to the observed data. The predictions from equation (7) were only marginally higher than those from equation (11), but they did not follow exactly the trend of the observed values of ML COD.

Changes in the total nitrogen in the input slurry directly affected the total nitrogen in the ML (Fig. 50). On the contrary the ammonia nitrogen in the ML remained fairly constant at around 3g/l, despite a

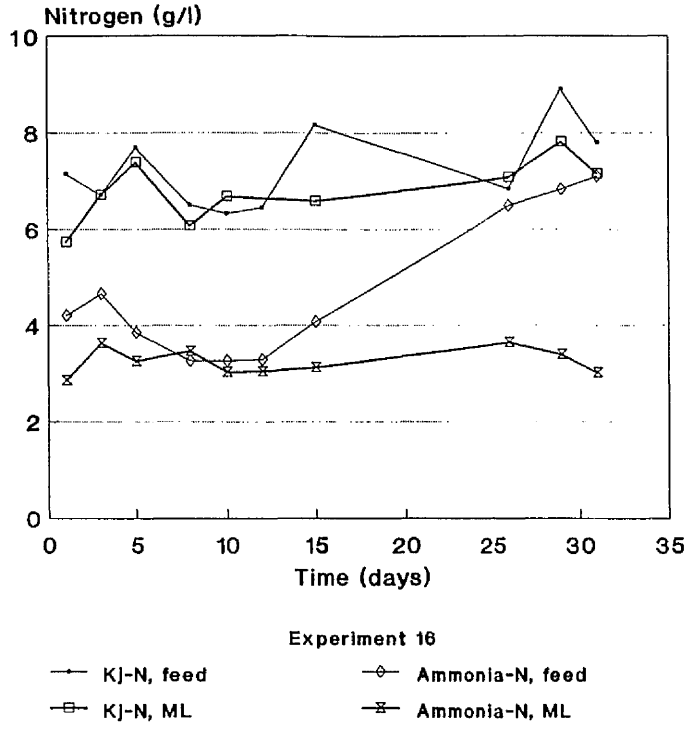

Fig.50 Effect of input slurry total and ammoniacal nitrogen on the total and ammoniacal nitrogen of the ML.

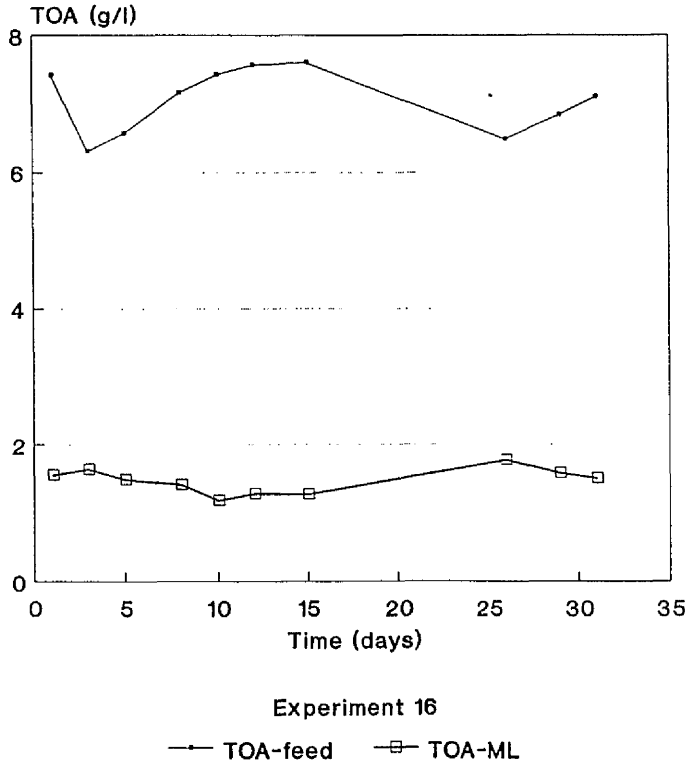

Fig.51 Effect of input slurry TOA an TOA of the ML.

large increase of ammonia nitrogen in the input slurry from 3.2g/l to 7.1g/l.

Concentrations of TOA in the ML were largely unaffected by variations in TOA in the feed slurry (Fig. 51). Total organic acids in the ML remained relatively low varying only between 1.2g/l and 1.8g/l while TOA of the input slurry varied between 6.3g/l and 7.6g/l.

9.4. Capillarity suction time of treated slurry

The effect of treatment on dewaterability of pig slurry was assessed by comparing the CST of input slurry and treated slurry (ML).

The mean value of CST of the input slurry containing between 58.8 and 91.8gTS/l was 2235 seconds which is approximately 10 times higher than the CST of sludges from sewage works (Smollen, 1986a,b; Vesilind, 1988).

The results in Table 47 conclusively show the positive improvement in slurry dewaterability by aerobic treatment at mezophilic temperatures with either ammonification or nitrification (Experiments 1, 3, 5 and 9). On the contrary, thermophilic treatment at 55^{o}C did not improve the dewaterability and the CST remained close to the value of untreated slurry (Experiments 16 and 17).

Table 47. CST values of mixed liquors during the treatment of piggery slurry.

Experiment	1	3	5	9	16	17
CST (sec.)	235	176	174	244	2428	2764

9.5. Experimental measurement of the heat loss from the reactor

Measurements of heat losses from the reactor by transmission through the reactor surfaces were based on temperature differences between the inner and outer surfaces of the walls of the reactor and 'U' values were calculated from the thermal conductivity of the walls, materials comprising the base and lid, and the insulation used. To ensure that these calculations were correct, two direct measurements of heat losses from the reactor surfaces were performed.

On the first occasion, the reactor contained tap water and the heat loss was calculated from the heat energy input and the rise in the temperature of the water. Since these measurements were undertaken during the period before the start of slurry treatment, steady state of the heat flux in the system was not established and the heat losses were unrealistically high. Therefore, a second assessment of heat losses was obtained when steady state had been established in the ML.

In the second measurement, a 6kW electrical heater was placed into the reactor which was closed and rendered air tight. The temperature of the ML was

50°C. After two days of continuous aeration and mixing, the oxygen in the air pocket above the ML was exhausted and anaerobic conditions existed in the ML. It was assumed that heat evolution during anaerobic metabolism was relatively very small, approximately 4.5% of that of aerobic metabolism, according to Weast (1980) and within the range of errors of measurement. The heater was switched on and the electricity input for this heater and the aerator, which mixed the ML and therefore prevented local overheating around the heater and maintained similar conditions to those during aeration, was monitored. The quantity of heat extracted together with the ambient temperature and the temperatures of the reactor surface and of the soil adjoining the reactor were continuously monitored for the duration of experiment which was exactly 2 days. The measured values were:

Heat from the aerator	219 kWh
Heat from the heater	282 kWh
Total heat input	501 kWh
Total heat extracted	424 kWh
Total heat loss	77 kWh

The calculated surface heat losses, using the computer program "Hepcal", were:

Loss to ambient temperature	76.3 kWh
Loss to the reactor surface	74.2 kWh

Thus the calculated heat losses varied by 1% to 4% of the measured value and were within the range of acceptable error.

9.6. Heat evolution and comparison with predicted data

The reactor was built as a commercial system within an uncontrolled environment. Energy flow and energy balance within the reactor were therefore functions of many uncontrolled variables.

The energy input was measured as COD and oxidisable nitrogen in slurry, the mechanical energy derived from electric energy and the heat inputs in streams of slurry and air, and the heat from the environment (Fig. 13). The energy output from the reactor was the total of extracted heat, heat in the streams of treated slurry and of exhaust gas and heat loss from the reactor surfaces (Chapter 8.2). Comparisons of these inputs and outputs of heat were made on the bases of relationships of the following measured variables:

1. Extracted heat
2. Ambient temperature
3. Intake slurry temperature
4. Soil temperature beside the reactor
5. Exhaust air temperature
6. Reactor surface temperature
7. Feed volume
8. Feed strength (Carbon as COD, nitrogen)
9. Air volume
10. Air humidity
11. Electrical heat energy input
12. Treatment temperature

Some of these parameters are functions of some of the others, thus:

(1) Extracted heat = F(2 to 12)
(3) Intake slurry temperature = F(2)
(4) Soil temperature = F(2, 12)
(5) Exhaust air temperature = F(2, 9, 10, 12)
(6) Reactor surface temperature = F(2, 12)

Correlations between measured values from all the experiments were used to obtain more credible relationships between the parameters.

Fig. 52 shows the dependence of the input slurry temperature on the ambient temperature. During the experiments, the mean ambient temperature varied between 0 and 18.1°C with a total mean value of 9.1°. The temperature of the input slurry never fell below 11°C and the mean temperature was 14.4°C. The correlation equation between input slurry temperature and ambient temperature

$$T_{input} = 10.27 + 0.41T_{amb} \qquad (^{o}C)$$

$R^2(adj)=0.76$

demonstrates that at ambient temperatures around 0°C, when the heat from aerobic treatment would be most useful (Evans *et al.*, 1982), the input slurry would still be warm and only at extremely low temperatures below -25°C (extrapolated value), would the slurry be expected to freeze. Such a situation is unlikely to occur in the UK.

The temperature of the exhaust gas together with

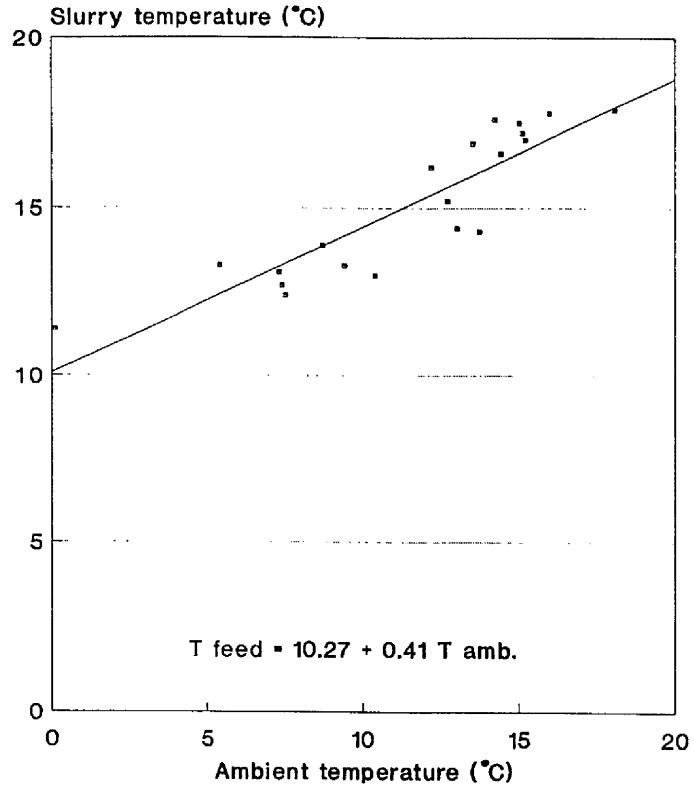

Fig.52 Effect of ambient temperature on temperature of input slurry.

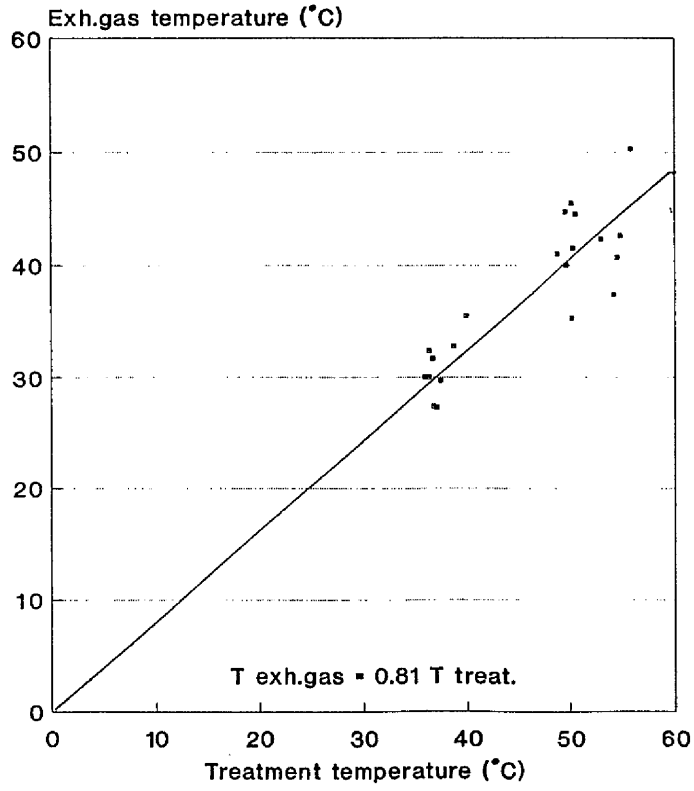

Fig.53 Effect of treatment temperature on the temperature of exhaust gas.

the 100% humidity had the largest influence on the heat lost during aeration. The greatest effect on the temperature of the exhaust gas was the temperature of treatment (Fig. 53).

$$T_{exh.gas} = 0.81\ T_{treat.} \qquad (^{o}C)$$

$R^2=0.77$

The correlation line extended through the origin shows that the exhaust gas temperature was 81% of the temperature of treatment. When the ambient temperature, which can also influence the exhaust gas temperature, was included in the correlation (treatment minus ambient temperature) the value of the correlation coefficient decreased from 0.77 to 0.45. The variations of ambient temperature were therefore larger than the changes in exhaust air temperature and their inclusion in the correlation would describe the dependence of the exhaust air temperature much less accurately. There is no significant correlation between the exhaust air temperature and either the air flow rate or the oxygen concentration in the exhaust air.

The temperature of the soil in the proximity of the reactor next to the layer of the polystyrene insulation was used for the calculation of heat loss from the surface of the reactor at the subsoil level (Chapter 8.2.3.). The soil temperature was largely affected by the treatment temperature (Fig. 54) and, although the correlation coefficient was low ($R^2=0.26$) the

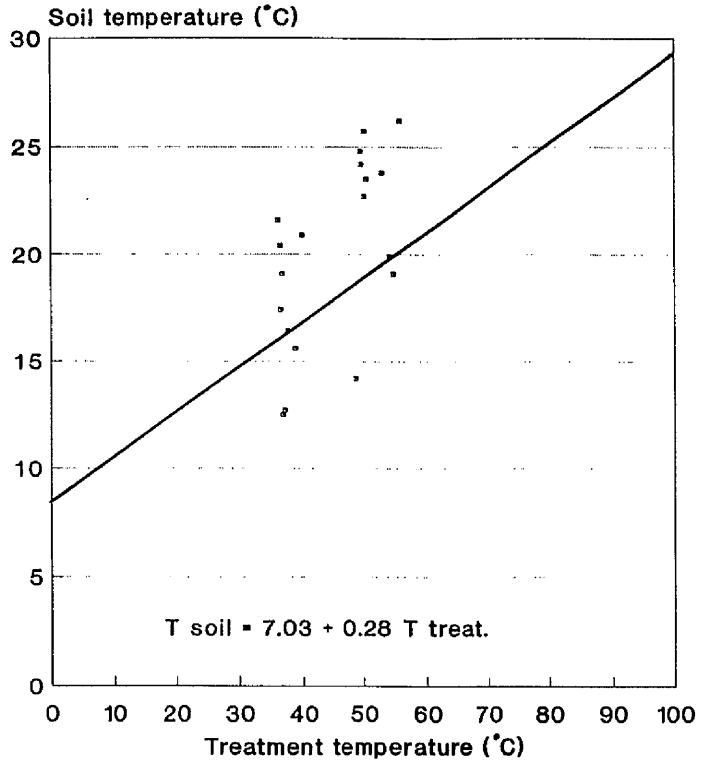

Fig.54 Effect of treatment temperature on the temperature of soil in proximity of the reactor.

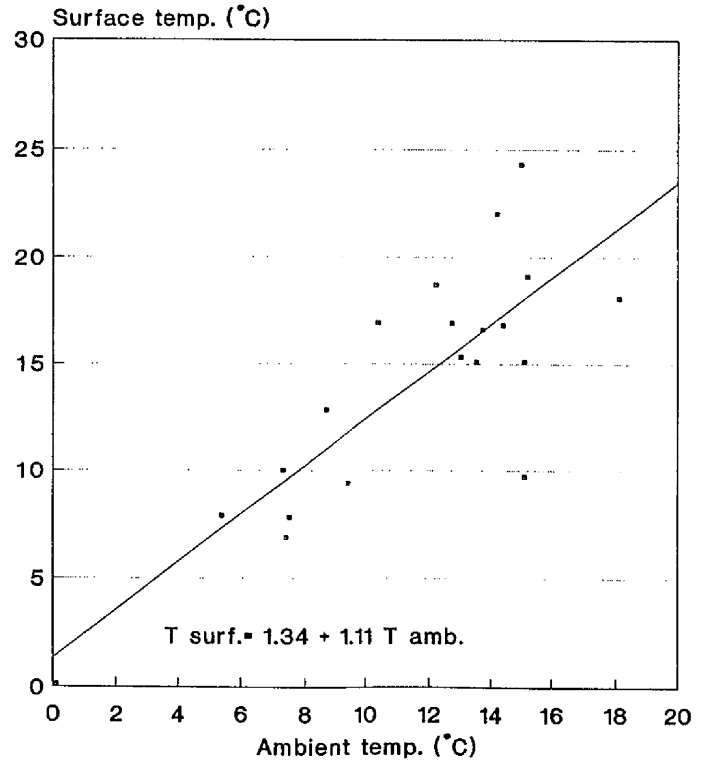

Fig.55 Effect of ambient temperature on the temperature of the reactor surface.

relationship was expressed as a linear regression:

$T_{soil} = 7.03 + 0.28\ T_{treat.}$ (^{o}C)

$R^2 = 0.26$

The temperature of the reactor surface, measured as a mean value of three temperature probes positioned on the surface of the reactor (Chapter 7.1.19.), was used for calculations of the surface heat losses and was directly influenced by the ambient temperature (Fig. 55).

$T_{surf.} = 1.34 + 1.11\ T_{amb.}$ (^{o}C)

$R^2=0.67$

However, other factors, in particular radiation from the sun, rain and wind, were responsible for variations in the reactor surface temperature in addition to those related to ambient temperature.

Electrical energy input

Electrical energy driving the aerator was absorbed as heat within the reactor. The aerator was running continuously during the experiments, therefore the energy input was not directly related to the oxygen requirement but rather to the concentration of TS in the ML as was observed by Cumby (1987a,b,c), to foam ingress in the aerator cone and most of all to the size of the aerator turbine. The mean daily rate of electrical energy input for the first 6 experiments

varied and was lower, (about 60kWh), for Experiments 1, 5 and 6, due to the decreased depth of submergence of the aerator by approximately 150mm, compared with Experiments 2, 3 and 4. During Experiments 7, 8, 9, 15 and 16 the rate was increased by changing the aerator turbine from 2kW size to 4kW, and the effect on oxygen transfer is shown in Table 50. Thus, the daily input of energy for aeration varied from 44.1kWh for Experiment 20 to a maximum value of 97.6 kWh for Experiment 8.

The specific power input for aeration and mixing (aeration/mixing power density) was relatively very high at 562W/m^3 for Experiment 16 in which the working volume of the reactor was 6.8m^3 and 243W/m^3 for Experiments 2,3 and 4 with a working volume of 13m^3 (Table B13 and B16). The minimum specific power input of 184W/m^3 was measured in Experiment 20. Despite such a high mixing power density the sedimentation of slurry particles was not prevented (Chapter 9.3.). The high mixing power density was approximately 10 to 20 times larger than that generally applied for slurry mixing and aeration (Vasseur and Laigneau, 1975) although 200 to 300W/m^3 were used to fully homogenise cattle slurry containing 60kgTS/m^3 (Heduit, 1980).

Gobel (1981) experimented with a similar but batch treatment system where the energy density was 70W/m^3.

The mean volume of slurry processed daily was 1.38m^3 varying from 0.84 to 1.86m^3 in Experiments 6 and

10 respectively (Table B9 to B12, Appendix B). The mean value of specific aeration energy per m^3 of slurry for all 20 experiments was therefore 44.4kWh/d with a minimum value of 34.0kWh/d in Experiment 12 and a maximum value of 70.6kWh/d in Experiment 2.

The mean value of specific aeration energy required for each pig place each day was 380W and varied from a minimum value of 240W in Experiment 12 to 670W in Experiment 4.

Heat losses

The temperatures of the input slurry, soil, exhaust air and reactor surface directly influence the heat losses from the system (Chapter 8.2.).

Heat losses from the reactor in the effluent mixed liquor (effluent heat loss) increased progressively as the temperature selected for treatment was raised. This relationship expressed by the equation

$$\text{Eff.heat loss} = -37.7 + 1.9 * \text{Tr.Temp (kWh/d)}$$

$$R^2 = 0.74$$

is illustrated in Fig. 56.

The heat loss in the effluent represented 24-63% of the total heat loss and was the highest proportion of all the sources of heat loss, except during nitrification at mesophilic temperatures when the effluent heat loss was 30% of the total and was exceeded by surface losses which were 50% of the total heat loss.

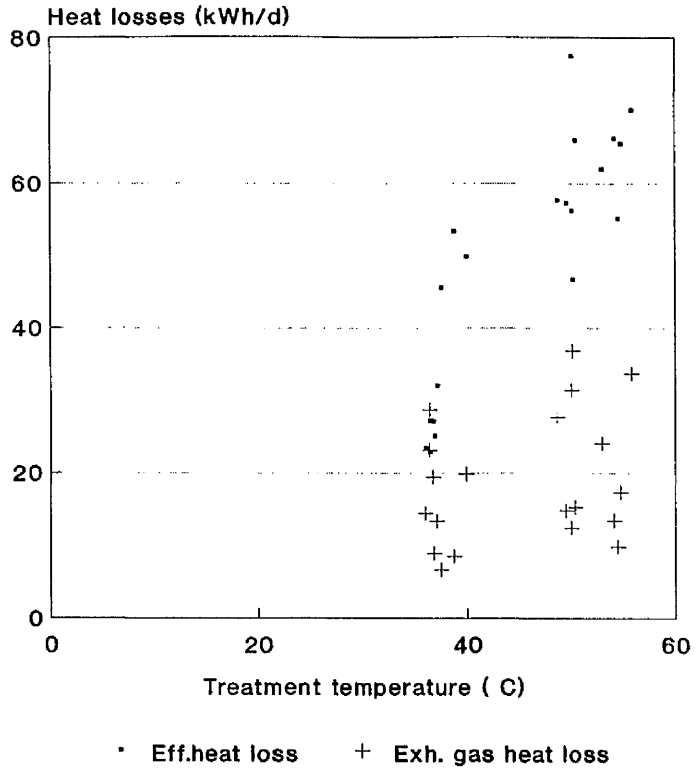

Fig.56 Effect of treatment temperature on effluent and exhaust gas heat loss.

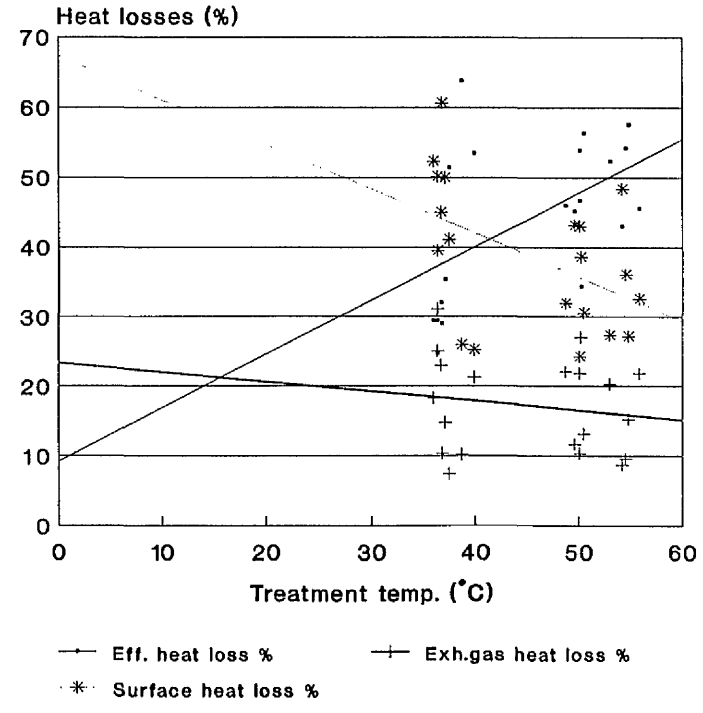

Fig.57 Effect of treatment temperature on effluent, exhaust gas and surface heat losses as a percentage of the total heat losses.

As the treatment temperature increased, the proportion of heat loss in the effluent increased in relation to total heat losses whereas the losses from other sources relatively decreased (Fig. 57).

Comparison of the observed results with the data predicted from the program "Farm Waste Management", described in Chapter 7.3.3., showed minimal differences of between 1 and 3% (Tables C1 to C4, Appendix C and Fig. 58). The "Farm Waste Management" program therefore provided correct predictions of the effluent heat losses.

Heat losses from the reactor in the exhaust gases (exhaust gas loss), represented the lowest proportion of the total heat losses and averaged 13 to 20%. They increased slightly as the treatment temperature was raised (Fig. 59) but the correlation was poor with R^2=0.2.

A comparison with model data (Table C1 to C4, Appendix C and Fig. 58) showed heat losses in the exhaust gases which were generally lower than predicted. The mean differences from predicted values were 12% and 15% for mezophilic treatment with nitrification and ammonification respectively and were within the range of error. The predicted losses during thermophilic treatment were much higher: 31% at 50^{o}C and 63% at 55^{o}C than the heat losses measured in the experiments. These large differences reflected a lower

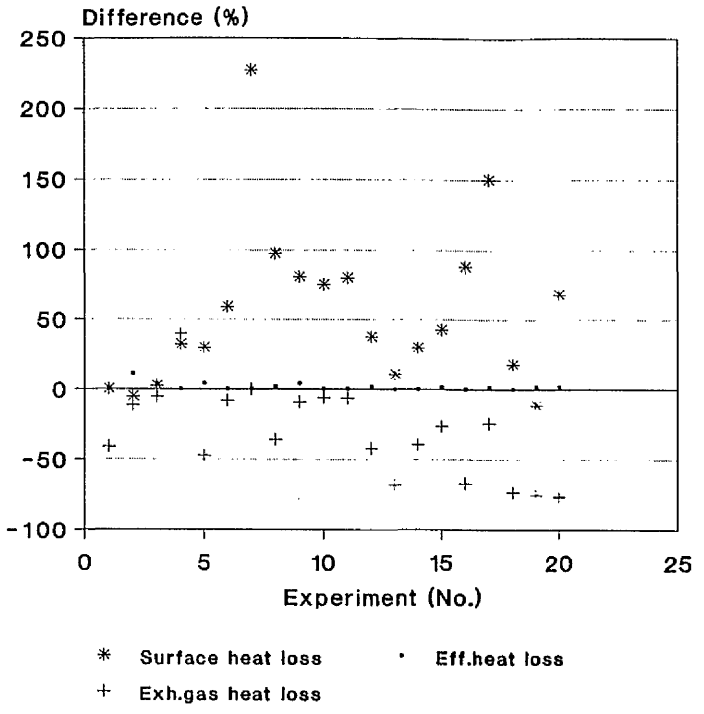

Fig.58 Percents of variation of heat losses from the values predicted by the model.

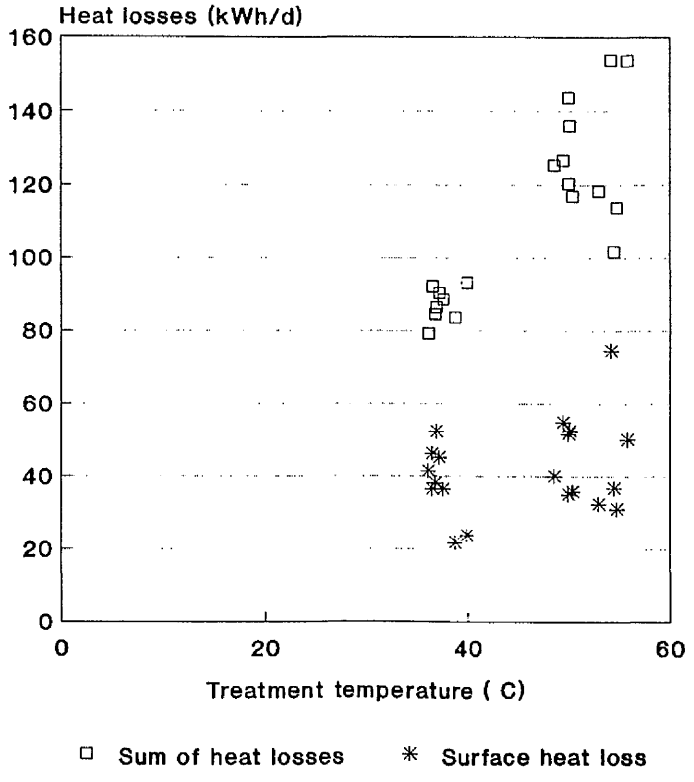

Fig.59 Effect of treatment temperature on sum of heat losses and surface heat loss.

level of aerobic microbial activity than that predicted and therefore the demand for oxygen was lower and less air was required for aeration as described in Chapter 9.3.3. and 9.3.4. The use of equation (7) for COD removal at 35^{o}C to calculate microbial activity at a treatment temperature of 55^{o}C reduces the predicted heat losses in the exhaust gases to give better agreement with the observed results at 55^{o}C.

Heat loss by transmission from the reactor surfaces varied according to the reactor surface temperature, treatment temperature, depth of ML in the reactor and the degree of surface insulation (Chapter 8.2.3.). Due to the wide changes in the ambient and treatment temperatures these losses therefore varied between 21.7kWh/d (Experiment 8) and 74.4kWh/d (Experiment 18) (Table B5 to B8, Appendix B, and Fig. 59). However, these surface losses remained fairly constant as a proportion of the total heat losses. The mean values of these losses for mezophilic and thermophilic ammonification experiments were 30 to 35% of total losses. A higher proportion of total losses was measured for mezophilic nitrification experiments (Experiments 1 to 6) where the mean value represented 49.6% of total losses.

Comparison of the measured surface heat losses with the modelled data showed large discrepancies, the measured data being up to 227% higher than predicted.

These large differences, mainly in the experiments at thermophilic treatment temperatures, were a reflection of the different methods of calculating the surface losses. The predictive program used an ideal reactor size, the height was equal to the diameter and there was no freeboard whereas in the calculations from the experimental data, account was taken of surfaces with different insulation, inside and outside temperatures and variable levels of the ML in the reactor. Amendments to the program are therefore necessary otherwise the predicted losses from reactor surfaces will be approximately 50% of those measured in actual practical situations.

Extracted heat

The heat recovered from the reactor in the form of hot water was measured directly by a heat meter (Chapter 7.3.2.). The mean daily recovered heat for each of the 20 experiments is shown in Tables B5 to B8 (Appendix B). The measured quantity of heat was compared with the theoretically extractable heat calculated from the difference between the heat input (electrical energy and theoretical metabolic heat) and the sum of heat losses using the computer program Hepcal described in Chapter 8.2. These measured heat values were also compared with the values predicted using the program "Farm Waste Management".

The quantity of extracted heat from the treatment

process decreased as the treatment temperature and the heat losses increased (Fig. 60 and Fig. 61).

The heat extracted from the reactor during Experiments 1 to 20 (Table B1 to B4, Appendix B) was compared with values predicted by the model program "Farm Waste Management" (Table C1 to C4, Appendix C). For the first six experiments with nitrification, the variations were within the range of the 20% difference which might be expected. During Experiments 7 to 9 the quantity of extracted heat was 31 to 51% less than that expected and this gap widened to 40 to 68% in Experiments 10 to 15. For Experiments 16 to 20 the difference from predicted values was even greater and reached 63 to 87%.

The reasons for such large differences are two-fold. Firstly the predicted surface heat losses, discussed above, were too low. With a program amended to take account of the reactor design, the differences between measured and predicted values for extracted heat would decrease by an average of approximately 10%.

Secondly, the observed biological activity (Chapters 9.3.2.1., 9.3.3.1 and 9.3.4.1.) was lower than that predicted. The treated slurry had considerably higher COD values than those predicted, especially during experiments at a treatment temperature of 55^{o}C (Fig. 62). The use of the 35^{o}C instead of the 50^{o}C equation for the calculation of oxygen requirement

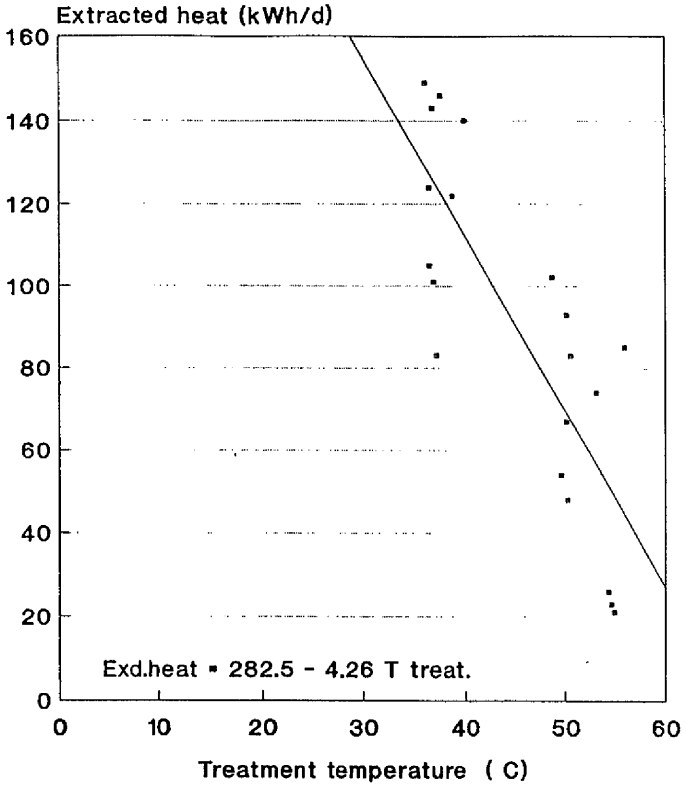

Fig.60 Effect of treatment temperature on extracted heat.

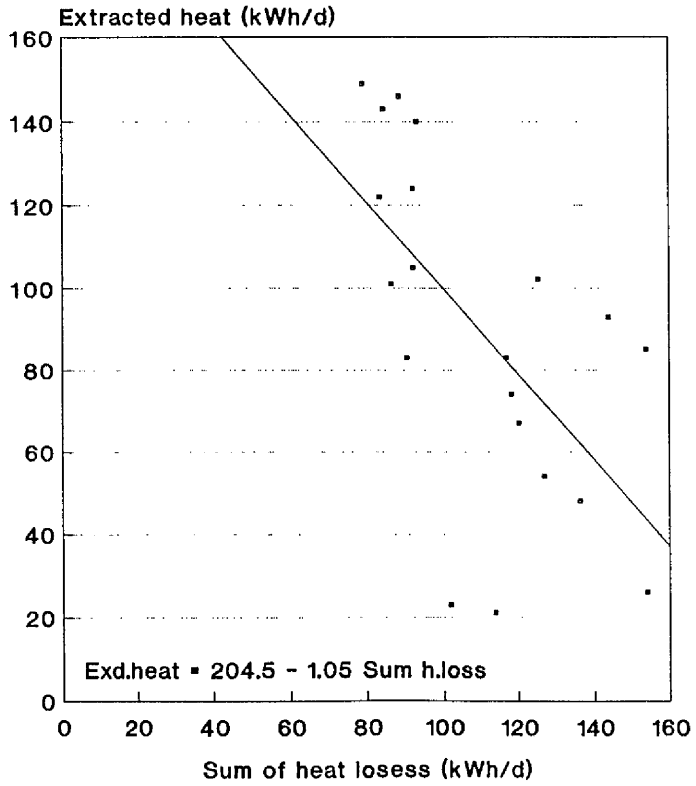

Fig.61 Effect of the sum of heat losses on extracted heat.

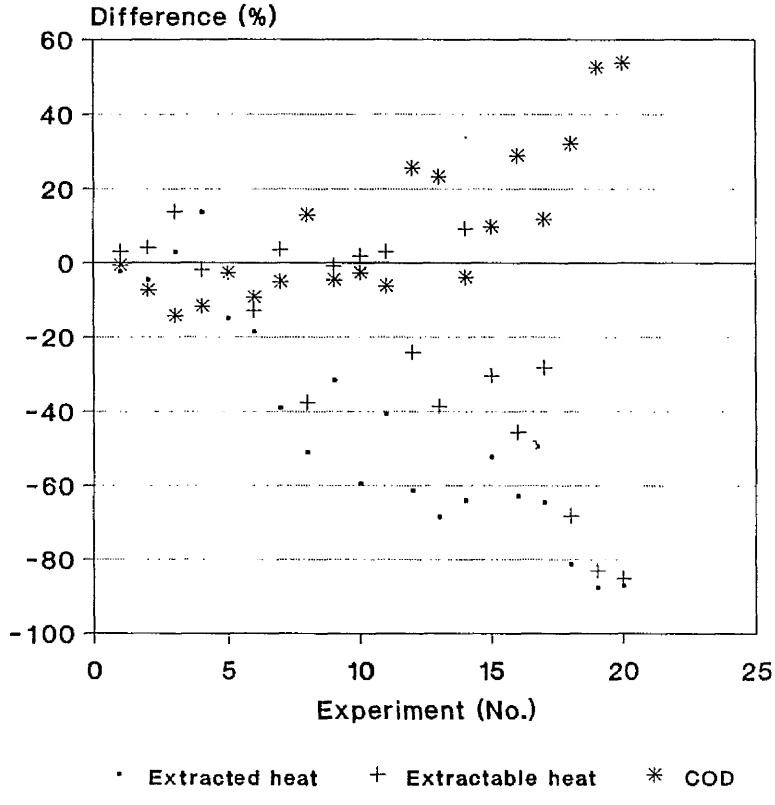

Fig.62 Percents of variation of extracted and extractable heat and residual COD from the values predicted by the model.

improves the relationship between the predicted and actual quantities of extracted heat.

The electrical energy required for aeration, mixing and foam control represented 52 to 79% of extracted heat (Table B13 to B16, Appendix B) for the experiments at mezophilic temperature (1-9). The quantity of heat extracted decreased in the experiments at thermophilic temperatures, therefore the ratio of electrical energy to extracted heat increased and was 87 to 145% for Experiments 10-14 and 98 to 240% for Experiments 15 to 20. The specific extracted energy for each pig place varied from 0.11kWh/day to 1.3kWh/day for Experiments 19 and 4 respectively (Table B13 to B16, Appendix B).

Metabolic heat

Metabolic heat was expressed as an analytical value and as an experimental value. The analytical value was calculated assuming 4kWh/kgO_2 for heterotrophic metabolism and 1.2kWh/kgO_2 for autotrophic metabolism during nitrification (Evans *et al.*, 1982). Experimental metabolic heat was the difference between the sum of measured recovered heat and heat losses and the sum of heat input measured as electrical energy. Specific experimental metabolic heat varied from 1.9 to 4.52kWh/kgO_2, (Tables B13 to B16, Appendix B) and, except in Experiments 7 and 22 when the specific metabolic heat was 4.25 and 4.52kWh/kgO_2 respectively, the average was lower than values observed by others.

For example Cooney *et al.*, (1968) measured the heat evolution of pure microorganism culture as 4kWh/kgO_2 (Chapter 4.2.). From the aerobic stabilisation at 50^oC of sewage sludge, Loll (1984) derived the metabolic heat as 4.1 to 4.7kWh/kgO_2 of COD removed. Aerobic treatment of pig slurry at a thermophilic temperature of 55^oC produced metabolic heat of 4.47kWh/kgO_2 (Lock *et al.*, 1982).

During the first six experiments the analytical and experimental metabolic heat measurements were similar as assessed by the ratio of analytical to experimental heat values which ranged from 0.82 to 1.12 (Table B13 to B16, Appendix B). During Experiments 7 to 20 this ratio increased to 2.15 in Experiment 10, i.e. the experimental metabolic heat was less than 50% of analytical metabolic heat.

These differences suggest two possible explanations. Firstly, the sedimentation occurring during experiments increased the apparent removal rate of COD (although not the actual removal rate) and therefore gave misleading high values for the analytical metabolic heat. Some anaerobic activity (documented by analyses of exhaust gas containing methane gas) in the vicinity of the sediments on the reactor base would decrease COD but the heat evolution would be only approximately 4.5% of that expected from aerobic degradation. Secondly, the other rather more prosaic explanation is that these differences

in the values of measured metabolic heat from those observed by other researchers were caused by errors in measurement of heat losses which were dependent on uncontrollable environmental factors. The heat losses were apparently higher than those calculated, (this discrepancy increased with increase of treatment temperature), and therefore the measured metabolic heat appeared to be smaller than expected.

Metabolic energy is sometimes related to the removed VS. This specific heat was found to vary during these 20 experiments between 5.6 and 12.2kWh/kgVS removed. This was a very large variation. No relationship between treatment time and this specific heat was found, so the mean values for experiments with mezophilic nitrification, mezophilic ammonification, thermophilic ammonification at 50^{o}C and 55^{o}C were calculated. They were 10.4, 7.9, 5.5 and 9.2kWh/kgVS removed. These values were similar to or higher than those found by Sobel and Muck (1983) (Table 48)

Table 48. The ultimate energy of some manures and other materials (Sobel and Muck, 1983).

Material	VS (%TS)	Ultimate energy kWh/kgVS
Dairy cow manure	82.5	5.55
Chicken manure	76.0	4.68
Sewage sludge (digested)	56.0	6.36
Sewage sludge (fresh)	76.0	7.63
Wood (air dried)	99.0	4.31
Anthracite coal	88.0	9.76

who compared the energy in animal manures and

particularly in cow manure. The ultimate energy released by combustion of volatile solids from cow manure was 5.55kWh/kgVS.

9.7. Aerator performance

The floating subsurface aerator (BRV 040, Chapter 6.5.) (Fig. 8) was used with a 2kW impeller for all experiments except 7, 8, 9, 15 and 16 in which a 4kW impeller was substituted. The air inlet was through a cone which was 0.52m deep and the impeller was approximately 0.4m below the surface of the liquid. The height of the top of the cone above the surface of the liquid was designed to contain foam in a layer approximately 150mm in depth. Foam which overspilled into the cone was sucked into the liquid. Any foam in the cone displaced air and the oxygenation capacity of the aerator was therefore reduced. This was overcome by the installation of a flexible pipe (diameter 75mm) from the outflow of a fan, supplying an average of $50m^3$ of air per hour, through the aerator platform to the base of the cone near the impeller. Although there was no foam during the trials with tap water to measure oxygenation capacity, the arrangement of the aerator with the flexible hose and air supply was maintained.

Oxygenation capacity in tap water was measured on four occasions. Sodium sulphite and a catalyst, cobalt chloride, were used to deoxygenate tap water in the reactor. The level of DO was continuously monitored

with a DO probe.

The results indicated large variations in the rate of oxygen transfer and in oxygenation efficiency (Table 49).

Table 49. Aeration conditions and oxygenation capacity of aerator with 2kW impeller.

Parameter/ No. of trial		1	2	3	4
Water volume	m^3	20.0	20.0	7.1	8.6
Depth of water	m	2.2	2.2	0.78	0.95
Temperature of water	^oC	12.0	34.5	6.0	10.0
K_{La}	h^{-1}	5.75	10.6	7.67	14.2
Oxygenation capacity	kgO_2/d	29.8	54.6	16.2	33.1
Oxygenation efficiency	kgO_2/kWh	0.62	1.14	0.34	0.69
Oxygen utilisation	%	6.5	11.8	4.1	8.3

Although Heduit and Racault (1983) showed that the oxygenation capacity and oxygen transfer efficiency of similar aerators were virtually independent of the water depth, the extremely low depth in trial no.3 could explain together with the low temperature of the water, the low oxygenation capacity and efficiency. The oxygenation efficiencies found in these trials are similar to the average values of 0.3 to $1kgO_2/kWh$ found for subsurface aerators (Cumby, 1987c).

Aerator performance during the experiments was assessed on the bases of (A) daily oxygen requirement to reduce the COD of the feed slurry to that of the treated slurry, and to oxidise nitrogen in the case of the first six experiments and (B) the daily electrical energy requirement of the aerator. By dividing (A) by (B) an oxygenation efficiency (OE1) was calculated, but

was incorrect by definition, because the concentration of oxygen in the ML was not zero and the "normal" atmospheric conditions of air containing 21% oxygen did not exist in the headspace (oxygen was replaced by CO_2).

To include the effect of the DO concentration in the ML and the decreased oxygen content in the headspace above the ML, an assessed value (OE2) for oxygenation efficiency was calculated according to the equation

$$OE2 = A/B * 21/C * (1+DO/100) \quad (kgO_2/kWh)$$

where A and B are described above as (A) and (B) and the units are kgO_2/d and kWh/d respectively; C is percentage concentration of O_2 in the headspace gas and DO is DO concentration in the ML. The value of OE1 and OE2 for all the experiments are included in Table 50.

Table 50. Oxygen used for COD removal, concentration of O_2 in the headspace gas and "oxygenation efficiency" of the aerator.

Exp.	O_2 used(A) kg/d	Headsp.O_2(C) %	OE1 kgO_2/kWh	OE2 kgO_2/kWh
1	36.6	16.5	0.56	0.83
2	42.6	18.5	0.49	0.75
3	46.9	16.5	0.62	1.06
4	37.4	15.0	0.49	0.92
5	37.9	15.8	0.65	1.08
6	40.0	17.2	0.77	1.42
7*	57.0	4.3	0.58	2.91
8*	35.8	11.0	0.37	0.76
9*	50.6	14.7	0.54	0.88
10	73.6	10.0	1.04	2.36
11	44.0	8.2	0.61	1.76
12	44.6	11.3	0.85	1.82
13	48.4	11.3	0.83	1.78
14	52.9	16.0	1.06	1.91
15*	48.6	14.4	0.51	0.78
16*	33.7	15.7	0.37	0.51
17	62.0	10.0	0.86	1.88
18	36.8	12.6	0.71	1.33
19	22.1	15.0	0.44	0.71
20	21.1	12.2	0.48	0.95

* 4kW aerator

10. DISCUSSION AND CONCLUSIONS

The slurry from a large scale piggery can be treated aerobically in an integrated collection and treatment system and the treated product presents fewer problems in disposal or utilisation. The characteristics of the treated slurry can be predicted by an existing computerised mathematical model (Farm Waste Management Program) although some changes in the model are required. The quantity of heat energy recovered from the treatment can also be predicted but further changes in the model are necessary to improve accuracy.

This piggery unit with approximately 300 fattening pigs and 100 weaning pigs produced raw slurry of variable concentration caused by dilution with wash water and rain. From the standard dry diet a similar slurry will be produced in other piggeries. The correlations between various analytical parameters in slurry, which are discussed in Chapter 4 have further implications for future assessment of more complex analytical values (COD, BOD, TOA, total nitrogen, filterability) by using more simple analyses such as TS, TSS and ammonia.

A continuous aerobic treatment process can be achieved by the aeration of tap water into which slurry is dosed in hourly intervals, thereby promoting the gradual development of a microbial flora. Carbonaceous degradation and ammonification of nitrogenous compounds

will be achieved but oxidation of nitrogen to nitrite and nitrate will require inoculation with nitrifying bacteria, which are not present in sufficient numbers, if at all, in the input slurry. This can be accomplished with small regular doses of nitrified slurry or by a large dose of nitrifying activated sludge from a nearby sewage works. Treatment at mezophilic temperature and high DO level produces slurry with the most acceptable environmental characteristics. Slurry treated in this way has approximately ten times better dewatering ability than the raw slurry and the supernatant, a dark brown clear liquid, has the lowest BOD_5 of all the slurries treated at mezophilic or thermophilic temperatures at low DO concentration with ammonification of the nitrogeneous compounds , but no nitrification. Although the concentrations of BOD_5 in the supernatant were much higher than predicted from the model, it should be recognised that the predicted values were derived from a model based on a diluted slurry which was ideally mixed and aerated. On a large scale, the sedimentation of solids from the undiluted slurry with a high TS concentration creates conditions for anaerobic activity which is a major cause of deterioration in the characteristics of the treated slurry. Another important factor was the fluctuating concentration of DO in the ML caused by dosing the reactor with raw slurry every hour. The minimum values of BOD_{5s} which were observed

were rather more than 30mg/l and are nearer to the minimum values of 50mg/l observed on filtrates of treated pig slurry from large treatment plants in Czechoslovakia than to the predicted value of 10mg/l.

Mezophilic aerobic treatment has another huge advantage over all other treatment processes which is the possibility of using "environment friendly" manipulation of nitrogen. Oxidised nitrogen contained in treated slurry is used as an electron acceptor instead of oxygen during anoxic storage, thus preventing odour regeneration. However, contrary to the laboratory experiments and hence the model predictions, only a small percentage of oxidised nitrogen remained in the treated slurry from the large-scale plant. Simultaneous nitrification and denitrification occurred during treatment and could not be prevented even by high mixing/aeration density and by maintaining a high DO concentration for most of the treatment time. An advantage of the simultaneous process is that the pH value is maintained in the optimum range so that the treatment effect is maximised which is reflected in the quality of the treated slurry.

The loss of nitrogen in the form of dinitrogen gas is a safe method for decreasing the concentration of immediately available nitrogen in slurries for disposal or for application to land in "nitrogen sensitive areas" such as those usually found in regions of

intensive pig farming. This method would not be recommended if slurry nitrogen is to be effectively used as fertiliser, although in cases when a large proportion of nitrogen is lost by ammonia stripping to the atmosphere because of incorrect application, loss as dinitrogen gas is preferable for reasons of environmental protection.

Treatment incorporating nitrification, with or without denitrification, facilitates the control of foam. During steady state treatment conditions with nitrification, the production of foam is minimal, thus the subsurface aerator is not throttled by excess foam and can be operated most efficiently.

In an air-tight enclosed reactor, such as that used in these experiments, where the DO concentration in the ML and the concentration of oxygen in the head space can be controlled, the oxygen in the air is utilised to a high degree and is replaced by carbon dioxide as the gas is circulated. The exhaust gas could therefore be utilised for enriching the atmosphere in greenhouses or could be dissolved in an algal pond to increase biomass production. Headspace gas from a process in which nitrification takes place is especially suitable since it is free from ammonia which may be harmful to plant growth.

The nitrification process, once established, can be easily switched to ammonification and back to

nitrification by decreasing or increasing the DO concentration of the ML (Fig. 63). The process is therefore flexible and attractive since it can produce slurry with a high concentration of ammonia for fertilising purposes or remove nitrogen when it is not required in the discharged slurry because of environmental factors.

Both mezophilic treatment with ammonification only and thermophilic treatment at 50^{o}C produce slurry which has slightly worse characteristics than those predicted by the Farm Waste Management Program. This is to be expected because of the very low redox potential values which were experienced after the reactor was dosed with raw slurry and the pH value of the ML which was on average higher than in the pH-controlled laboratory experiments from which the model and program were derived.

Treatment at 55^{o}C produced slurry with characteristics which were not comparable with slurry treated at 50^{o}C. A temperature of 55^{o}C, classified by many researchers as a true thermophilic temperature, caused a large increase in pH value to 9.5 which must be the reason for the decrease in the degradation of organic matter. Although the predicted values calculated from equations for treatment at 50^{o}C were too low in comparison with those observed in slurry treated at 55^{o}C, much closer and more acceptable predictions can

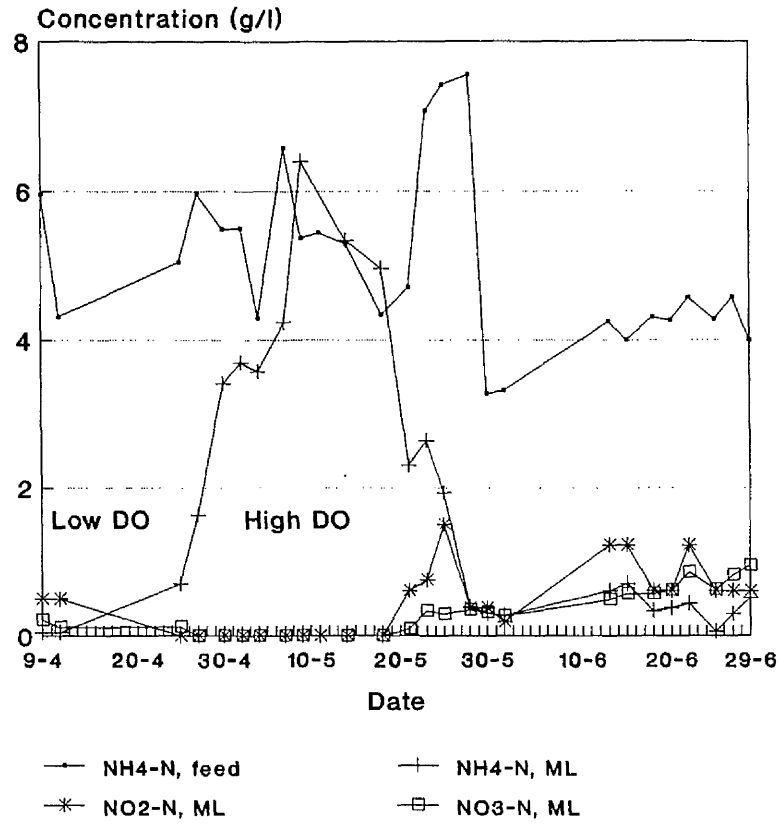

Fig.63 Control of ammonification and nitrification by changes of DO level.

be obtained by use of the equations derived from treatment at mezophilic temperatures.

Variations in the composition of slurries, which can be expected on farms, influence the slurry characteristics (TS, COD and nitrogen) after treatment for short periods, but there is little influence at long treatment times. To model and predict this influence, running mean analytical values from the analyses over a number of preceding days corresponding approximately to the treatment time, should be substituted for the single analytical values of input slurry in the predictive equations.

Sedimentation of particles, of which more than 90% are smaller than 2mm, cannot be prevented by high density mixing/aeration energy input. Mechanical separation of slurry with 2mm screen apertures, which is the standard size normally used, will not prevent sedimentation. Only separation by centrifugation, suggested by Sneath (1988) would remove these small and heavy particles. Such a process adds considerably to the overall cost of treatment.

The rate of degradation of organic matter increases as the temperature of treatment increases, although the rate decreased at a treatment temperature of 55^{o}C to the level of that at a treatment temperature of 35^{o}C. At all temperatures, any heat which is extracted to provide temperature control and which can be utilised can offset

the cost of treatment.

The quantity of heat recovered from the reactor decreased as the treatment temperature was increased, but it might be argued that water extracted at a higher temperature is a more valuable heat source than water at a low temperature, especially as the use of a heat pump can be avoided with a consequent saving in capital and running costs.

The highest proportion of the total heat losses were in the liquid effluent except during mezophilic treatment with nitrification, when the insulation of the reactor was not yet complete and the surface losses were the highest proportion. The proportion of heat lost in the effluent increased as the treatment temperature increased. Total heat losses varied from 53% of extracted heat at mezophilic temperatures to 590% of extracted heat at a thermophilic temperature of 55^{o}C. It may therefore be suggested that minimising the effluent heat loss would be attractive. Cross flow heat exchangers, in which the effluent slurry heated the input slurry, have been constructed, but the rapid wear, caused by the abrasiveness of slurry, and the relatively high cost of the exchangers does not justify their use. The input of electrical energy for mixing and aeration in this reactor was high in relation to larger-scale systems. Despite this it accounted for only 50 to 80% of extracted energy during mezophilic

treatment, averaged 100% during treatment at 50°C and 170% during treatment at 55°C. This was to be expected since the aerator, despite being the smallest commercial size available, was oversized for the reactor volume and for the volume of slurry available for treatment.

Metabolic heat generated by heterotrophic biomass has been frequently quoted as approximately 4kWh/kgO_2, but some large variations have been observed mostly for pure cultures. With mixed cultures and a mixed substrate, as is the case in the aerobic treatment of piggery slurry, relatively small variations are to be expected. Therefore the values, which were calculated from observed quantities of recovered heat, and which varied from 2.2 to 4.5kWh/kgO_2, might have been affected by errors in the assessment of heat balance in this complicated farm-scale system.

The increased demand for long-term storage of slurry as required by new regulations, may render continuous aerobic treatment unsuitable on economic grounds in some cases. Therefore new systems, designed for odour removal only, are being developed. Based on fed-batch systems, with intermittent aeration, they could provide a satisfactory treatment for slurry, but odour emissions might be experienced after long intervals without aeration.

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A P P E N D I X A

CHARACTERISTICS OF RAW AND TREATED SLURRY DURING EXPERIMENTS 1 TO 20

Table A1. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 1.

	Raw slurry g/l			Treated slurry g/l	
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	19	52.6		10	41.8	5.5
VS	19	38.0		10	27.6	4.5
TSS	18	38.4		10	28.4	2.6
VSS	18	29.1		10	18.7	3.2
COD	20	57.6		10	35.4	4.4
NH_4-N	10	2.6		10	0.01	0.01
Kj.-N	10	5.0		10	1.6	0.18
Org.-N	10	2.4		10	1.6	0.18
Nitrate-N	-	-		10	0.4	0.15
BOD_5	2	18.0		3	1.6	0.13
TS_s	18	12.1		10	8.3	0.70
VS_s	18	5.2		10	1.9	0.49
TOA_s	15	4.7		10	0.21	0.07
NH_4-N_s	10	2.0		10	0.01	0.01
Kj.-N_s	10	3.1		10	0.07	0.01
Org.-N_s	10	1.0		10	0.06	0.02
BOD_{5s}	5	7.1		8	0.07	0.05

Table A2. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 2.

	Raw slurry g/l			Treated slurry g/l	
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	28	50.2		12	38.6	3.1
VS	28	34.7		12	26.0	2.6
TSS	27	41.6		12	25.6	3.7
VSS	27	30.0		12	18.9	3.0
COD	27	56.3		12	31.2	4.4
NH_4-N	13	2.3		12	0.24	0.14
Kj.-N	13	4.2		12	1.5	0.27
Org.-N	13	1.9		12	1.2	0.29
Nitrate-N	-	-		10	1.4	0.37
BOD_5	7	14.9		4	1.6	0.82
TS_s	28	11.0		12	14.0	1.51
VS_s	28	4.8		12	5.4	1.26
TOA_s	24	4.2		11	0.31	0.08
NH_4-N_s	13	2.0		11	0.24	0.14
Kj.-N_s	13	2.7		11	0.34	0.16
Org.-N_s	13	0.7		11	0.10	0.04
BOD_{5s}	7	6.1		12	0.11	0.07

Table A3. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 3.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	17	48.0		9	35.1	1.9
VS	17	35.9		9	23.3	1.4
TSS	17	39.5		9	25.7	2.8
VSS	17	35.9		9	17.1	2.4
COD	17	67.4		8	34.4	3.5
NH_4-N	12	2.2		7	0.004	0.004
Kj.-N	12	4.4		7	1.4	0.14
Org.-N	12	2.1		7	1.4	0.14
Nitrate-N	-	-		7	0.38	0.15
BOD_5	5	12.4		3	1.1	0.32
TS_s	17	10.7		8	7.4	0.35
VS_s	17	5.4		8	1.9	0.26
TOA_s	14	4.6		8	0.26	0.07
NH_4-N_s	12	1.8		8	0.003	0.003
Kj.-N_s	12	2.6		8	0.07	0.02
Org.-N_s	12	0.75		8	0.06	0.02
BOD_{5s}	5	6.2		5	0.12	0.08

Table A4. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 4.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	23	45.9		12	34.4	3.5
VS	23	31.5		12	20.3	2.3
TSS	23	37.6		12	26.4	2.1
VSS	23	28.1		12	18.5	3.6
COD	23	55.4		12	29.0	3.3
NH_4-N	13	2.4		10	0.003	0.001
Kj.-N	13	4.0		10	1.3	0.20
Org.-N	13	1.7		10	1.3	0.16
Nitrate-N	-	-		10	0.51	0.22
BOD_5	7	16.3		7	1.7	0.16
TS_s	20	11.1		10	7.2	0.66
VS_s	20	4.5		10	1.4	0.32
TOA_s	15	4.0		10	0.26	0.09
NH_4-N_s	18	1.9		10	0.003	0.001
Kj.-N_s	18	2.5		10	0.56	0.02
Org.-N_s	18	0.64		10	0.07	0.02
BOD_{5s}	12	5.5		8	0.04	0.02

Table A5. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 5.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	30	74.1	7.4	13	57.3	2.3
VS	30	52.3	6.9	13	37.7	2.0
TSS	21	56.7	5.4	13	38.9	3.4
VSS	21	43.0	4.2	13	27.3	4.1
COD	25	84.6	12.4	13	48.8	4.4
NH_4-N	18	3.4	0.32	13	0.03	0.01
Kj.-N	18	6.4	0.39	13	2.0	0.33
Org.-N	18	3.0	0.22	13	2.0	0.33
Nitrate-N	-	-	-	13	0.44	0.11
BOD_5	3	22.8	2.1	4	2.5	0.54
TS_s	21	18.3	1.2	12	11.7	0.41
VS_s	21	9.2	0.8	12	3.0	0.44
TOA_s	21	7.1	1.0	13	0.26	0.04
NH_4-N_s	18	2.8	0.33	13	0.02	0.01
Kj.-N_s	18	4.0	0.39	13	0.10	0.01
Org.-N_s	18	1.2	0.33	13	0.08	0.05
BOD_{5s}	3	10.1	0.67	13	0.03	0.02

Table A6. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 6.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	25	75.6	11.0	10	58.6	7.3
VS	25	54.2	8.8	10	37.1	4.8
TSS	23	60.8	9.4	10	42.1	5.6
VSS	23	45.2	6.5	10	29.1	3.6
COD	25	89.7	14.8	10	48.1	6.7
NH_4-N	23	3.3	0.33	10	0.02	0.01
Kj.-N	23	6.1	0.77	10	2.1	0.01
Org.-N	23	2.7	0.65	10	2.1	0.10
Nitrate-N	-	-	-	10	0.34	0.19
BOD_5	3	22.7	6.5	3	1.7	0.67
TS_s	25	17.7	2.1	9	10.5	0.44
VS_s	25	8.5	1.2	9	2.6	0.32
TOA_s	24	7.7	1.8	10	0.35	0.05
NH_4-N_s	23	2.7	0.24	10	0.02	0.01
Kj.-N_s	23	3.7	0.55	10	0.13	0.02
Org.-N_s	23	1.1	0.06	10	0.10	0.02
BOD_{5s}	3	9.0	0.96	9	0.002	0.002

Table A7. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 7.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	30	64.6	5.2	29	54.2	5.9
VS	30	47.4	4.0	29	38.6	5.4
TSS	13	57.6	5.7	12	46.6	6.0
VSS	13	45.9	4.3	12	34.9	6.7
COD	28	91.9	9.6	29	55.7	7.7
NH_4-N	13	3.9	0.51	12	3.7	0.46
Kj.-N	13	8.3	0.65	12	7.9	0.44
Org.-N	13	4.4	0.36	12	4.2	0.48
BOD_5	4	20.2	1.0	4	7.4	0.76
TS_s	13	14.8	0.92	12	12.8	1.0
VS_s	13	7.2	0.94	12	5.3	1.0
TOA_s	13	7.3	0.38	12	1.1	0.36
NH_4-N_s	13	3.4	0.45	12	3.2	0.26
Kj.-N_s	13	5.7	0.41	12	5.4	0.38
Org.-N_s	13	2.3	0.51	12	2.3	0.50
BOD_{5s}	13	9.1	1.0	10	0.58	0.28

Table A8. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 8.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	20	63.0	11.6	8	51.9	1.7
VS	20	44.5	9.7	8	36.5	1.8
TSS	6	55.4	3.4	8	42.1	3.8
VSS	6	41.6	2.3	8	33.1	3.8
COD	21	75.3	13.3	13	54.7	11.5
NH_4-N	6	5.0	0.59	8	4.6	0.37
Kj.-N	5	8.0	0.77	8	7.1	0.68
Org.-N	5	3.0	0.73	7	2.5	0.48
BOD_5	2	22.4	1.1	3	10.0	1.5
TS_s	6	13.4	0.81	7	12.4	0.99
VS_s	6	6.0	0.75	7	5.2	0.88
TOA_s	6	6.3	0.58	8	0.89	0.13
NH_4-N_s	5	4.6	0.59	6	4.5	0.35
Kj.-N_s	6	5.6	0.46	7	5.3	0.19
Org.-N_s	5	0.96	0.82	6	0.73	0.40
BOD_{5s}	3	8.7	1.2	8	0.76	0.29

Table A9. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 9.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	22	64.6	8.3	11	51.0	4.3
VS	22	45.1	6.2	11	35.2	3.6
TSS	10	54.6	6.0	11	39.1	5.2
VSS	10	41.3	4.8	11	29.8	4.0
COD	23	75.8	21.7	11	46.3	5.2
NH_4-N	10	5.8	1.1	11	5.4	0.81
Kj.-N	10	8.3	0.98	11	8.0	1.1
Org.-N	10	2.5	0.65	11	2.6	0.77
BOD_5	3	16.0	5.8	4	5.5	1.1
TS_s	10	13.6	0.63	11	11.4	0.60
VS_s	10	6.2	0.61	11	4.2	0.44
TOA_s	10	7.2	1.1	11	0.91	0.13
NH_4-N_s	10	5.0	0.47	11	4.4	0.49
Kj.-N_s	10	6.4	0.69	11	6.3	0.95
Org.-N_s	7	1.5	0.40	11	1.9	0.93
BOD_{5s}	10	8.3	1.4	11	0.33	0.12

Table A10. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 10.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	20	67.9	7.9	20	45.2	3.9
VS	20	48.6	6.1	20	30.6	3.5
TSS	8	55.5	6.6	8	33.4	2.6
VSS	8	42.1	5.0	8	24.2	2.3
COD	20	85.4	17.2	19	45.2	10.3
NH_4-N	8	3.4	0.56	7	2.6	0.34
Kj.-N	8	6.6	0.79	7	5.0	0.44
Org.-N	8	3.2	0.65	7	2.4	0.21
BOD_5	2	19.3	4.8	2	4.0	1.45
TS_s	8	14.1	0.60	8	13.5	0.45
VS_s	8	6.6	0.58	8	6.2	0.63
TOA_s	8	7.6	0.80	8	1.4	0.16
NH_4-N_s	7	3.0	0.35	6	2.5	0.30
Kj.-N_s	7	4.0	0.51	6	3.5	0.52
Org.-N_s	7	1.0	0.44	6	1.0	0.33
BOD_{5s}	6	8.3	0.64	7	0.28	0.16

Table A11. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 11.

	Raw slurry g/l			Treated slurry g/l	
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	7	47.2	11.4	7	33.5	4.0
VS	7	32.3	8.6	7	20.8	3.6
TSS	5	37.4	4.9	5	23.5	4.6
VSS	5	28.2	3.9	5	16.7	4.2
COD	7	56.5	12.6	7	28.2	5.1
NH_4-N	5	3.2	0.85	5	2.9	0.36
Kj.-N	5	5.8	1.2	5	5.4	0.74
Org.-N	5	2.6	0.69	5	2.69	0.69
BOD_5	1	12.1	0.00	1	4.1	0.00
TS_s	5	13.1	1.9	5	13.0	0.97
VS_s	5	6.4	1.1	5	6.1	0.72
TOA_s	5	6.6	0.6	5	1.5	0.32
NH_4-N_s	5	3.0	0.60	4	2.7	0.22
Kj.-N_s	5	4.2	0.53	4	4.0	0.63
Org.-N_s	5	1.2	0.20	4	1.3	0.48
BOD_{5s}	2	6.9	0.66	2	0.26	0.13

Table A12. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 12.

	Raw slurry g/l			Treated slurry g/l	
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	21	65.4	7.7	9	47.5	13.4
VS	21	49.2	6.3	9	34.5	13.1
TSS	10	57.0	4.9	9	30.8	8.9
VSS	10	45.6	4.7	9	22.5	7.6
COD	21	85.1	11.5	9	55.8	24.5
NH_4-N	10	3.0	0.26	9	2.6	0.27
Kj.-N	10	5.8	0.28	9	4.7	0.31
Org.-N	10	2.8	0.31	9	2.1	0.12
BOD_5	2	21.6	3.9	3	3.4	0.71
TS_s	10	12.8	0.81	9	12.9	1.2
VS_s	10	5.6	0.47	9	6.0	1.3
TOA_s	9	5.5	0.41	9	1.3	0.21
NH_4-N_s	10	2.8	0.46	9	2.4	0.24
Kj.-N_s	10	3.4	0.56	9	2.9	0.26
Org.-N_s	9	0.79	0.46	8	0.60	0.20
BOD_{5s}	10	7.0	1.4	7	0.47	0.38

Table A13. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 13.

	Raw slurry g/l			Treated slurry g/l	
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	30	72.1	10.1	12	56.0	10.2
VS	30	54.4	8.1	12	42.0	8.8
TSS	10	65.1	10.4	11	43.8	7.5
VSS	10	51.2	8.1	11	33.8	5.5
COD	30	94.5	15.4	13	60.3	14.0
NH_4-N	11	3.0	0.26	11	2.7	0.23
Kj.-N	11	5.8	0.62	11	4.9	0.38
Org.-N	11	2.7	0.46	11	2.2	0.29
BOD_5	3	29.7	14.4	2	7.4	2.3
TS_s	11	14.0	1.8	8	14.3	3.0
VS_s	11	6.8	1.4	8	7.7	2.9
TOA_s	11	6.1	0.78	12	1.6	0.53
NH_4-N_s	11	2.5	0.21	10	2.1	0.76
Kj.-N_s	11	3.4	0.21	10	3.1	0.19
Org.-N_s	11	0.83	0.15	10	0.63	0.28
BOD_{5s}	9	9.2	1.67	5	0.43	0.25

Table A14. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 14.

	Raw slurry g/l			Treated slurry g/l	
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	16	69.3	5.5	9	42.2	3.6
VS	16	49.3	4.6	8	27.3	3.8
TSS	9	56.3	5.6	9	32.5	5.0
VSS	9	42.8	3.9	9	22.7	5.7
COD	16	86.9	13.9	9	42.4	5.6
NH_4-N	9	2.9	0.29	9	2.0	0.47
Kj.-N	9	5.6	0.61	9	4.6	0.22
Org.-N	9	2.6	0.51	9	2.6	0.64
BOD_5	3	22.2	7.4	4	4.5	0.84
TS_s	9	15.1	0.92	9	14.6	0.86
VS_s	9	6.8	0.79	9	6.4	0.89
TOA_s	9	12.3	2.6	9	1.5	0.39
NH_4-N_s	9	2.5	0.39	9	1.7	0.37
Kj.-N_s	9	3.1	0.69	9	2.6	0.48
Org.-N_s	7	0.91	0.39	9	0.89	0.48
BOD_{5s}	4	9.0	1.2	9	0.28	0.05

Table A15. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 15.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	13	72.6	3.2	6	53.5	5.1
VS	13	52.7	3.4	6	38.0	4.6
TSS	6	58.8	8.3	6	44.7	6.4
VSS	6	49.9	3.0	6	34.7	5.3
COD	13	79.5	8.7	6	44.1	9.0
NH_4-N	6	3.8	0.44	6	3.5	0.42
Kj.-N	6	7.6	0.53	6	7.0	1.3
Org.-N	4	3.8	0.81	6	3.5	1.1
BOD_5	2	21.7	3.6	1	3.6	0.00
TS_s	6	15.4	0.73	6	15.1	1.5
VS_s	6	7.0	1.0	6	7.1	1.2
TOA_s	5	7.3	0.77	2	1.6	0.06
NH_4-N_s	6	4.0	0.36	6	3.2	0.69
Kj.-N_s	6	5.6	0.40	6	6.6	1.3
Org.-N_s	4	1.7	0.52	6	3.4	1.1
BOD_{5s}	6	7.8	0.64	4	0.23	0.08

Table A16. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 16.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	22	69.3	7.4	10	55.9	4.7
VS	22	50.9	5.6	10	39.5	3.7
TSS	10	61.4	7.4	10	45.5	5.1
VSS	10	47.7	5.3	10	34.4	4.4
COD	22	78.2	14.0	9	54.8	6.3
NH_4-N	10	3.9	0.57	10	3.2	0.28
Kj.-N	10	7.3	0.85	9	6.8	0.64
Org.-N	10	3.3	0.79	9	3.6	0.67
BOD_5	3	24.2	2.6	3	6.8	0.73
TS_s	10	13.5	0.94	10	13.6	0.57
VS_s	10	6.6	0.76	10	6.5	0.40
TOA_s	10	7.1	0.47	10	1.5	0.18
NH_4-N_s	10	3.1	0.75	10	2.8	0.19
Kj.-N_s	10	4.8	0.59	10	4.1	0.41
Org.-N_s	10	1.7	0.70	10	1.3	0.39
BOD_{5s}	10	7.7	2.4	10	0.45	0.27

Table A17. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 17.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	22	70.8	6.7	21	52.0	7.4
VS	22	50.5	11.3	21	37.0	6.1
TSS	10	61.0	5.5	10	45.3	6.1
VSS	10	49.0	4.6	10	35.2	5.5
COD	22	99.1	9.3	21	58.8	7.3
NH_4-N	10	3.1	0.56	10	2.8	0.46
Kj.-N	10	7.4	0.62	10	6.8	0.50
Org.-N	10	4.3	0.52	10	3.9	0.33
BOD_5	2	26.8	12.4	2	3.8	3.1
TS_s	10	14.5	0.59	10	15.1	0.83
VS_s	10	7.0	0.54	10	6.6	1.27
TOA_s	10	7.8	0.64	10	1.7	0.14
NH_4-N_s	10	2.8	0.43	10	2.3	0.48
Kj.-N_s	10	4.9	0.67	10	4.8	0.45
Org.-N_s	10	2.1	0.71	10	2.4	0.32
BOD_{5s}	7	10.7	1.5	7	0.55	0.11

Table A18. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 18.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	30	63.6	7.9	13	53.1	5.7
VS	30	47.7	6.1	13	39.7	4.8
TSS	8	57.2	8.5	11	43.1	4.2
VSS	8	46.1	6.1	11	34.4	3.6
COD	30	82.9	13.2	13	56.6	9.8
NH_4-N	11	3.7	0.47	11	3.3	0.41
Kj.-N	11	6.6	0.89	11	5.8	0.36
Org.-N	11	2.9	5.6	11	2.4	0.41
BOD_5	2	10.3	10.7	-	-	-
TS_s	11	12.0	0.75	11	13.5	1.6
VS_s	11	5.7	0.53	11	7.4	1.6
TOA_s	4	6.0	0.25	5	1.4	0.20
NH_4-N_s	11	3.2	0.28	11	2.7	0.28
Kj.-N_s	12	4.6	0.65	11	4.1	0.44
Org.-N_s	11	1.2	0.30	11	1.4	0.44
BOD_{5s}	4	7.2	2.9	2	0.27	0.07

Table A19. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 19.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	29	64.3	6.4	13	55.0	4.6
VS	29	47.4	4.5	13	41.7	4.2
TSS	13	56.9	3.3	13	46.7	6.5
VSS	13	44.5	2.7	13	37.7	5.8
COD	29	77.9	15.7	13	61.0	10.7
NH_4-N	13	4.3	0.52	13	3.4	0.18
Kj.-N	12	7.3	0.82	13	6.5	0.66
Org.-N	11	2.9	0.60	13	3.1	0.57
BOD_5	4	11.5	10.5	4	4.1	1.4
TS_s	13	13.1	0.82	13	14.6	1.6
VS_s	13	6.6	0.70	13	8.1	1.4
TOA_s	12	5.7	1.1	13	1.7	0.58
NH_4-N_s	13	3.5	1.1	13	3.1	0.32
Kj.-N_s	13	4.6	0.74	13	4.2	0.41
Org.-N_s	12	1.1	0.52	13	1.2	0.39
BOD_{5s}	12	7.1	1.5	11	0.71	0.34

Table A20. Number of analyses (N.val.) and mean and standard deviations of characteristics of raw and treated slurry of Experiment 20.

	Raw slurry g/l			Treated slurry g/l		
Char.	N.val.	Mean	S.D.	N.val.	Mean	S.D.
TS	16	68.2	10.1	7	58.0	1.9
VS	16	49.6	7.8	7	43.0	1.9
TSS	7	58.6	10.1	7	47.2	3.1
VSS	7	46.0	8.0	7	37.7	2.3
COD	16	84.9	17.9	7	65.6	6.1
NH_4-N	7	4.4	0.32	7	3.7	0.37
Kj.-N	7	8.2	0.58	7	7.2	0.73
Org.-N	7	3.7	0.43	7	3.5	0.49
BOD_5	3	23.8	9.2	3	5.1	1.2
TS_s	7	13.9	0.91	7	14.8	0.59
VS_s	7	7.0	0.73	7	8.0	0.75
TOA_s	7	5.5	1.5	7	1.7	0.08
NH_4-N_s	7	3.6	0.73	7	3.3	0.32
Kj.-N_s	7	4.9	0.41	7	4.6	0.24
Org.-N_s	7	1.3	1.0	7	1.3	0.36
BOD_{5s}	5	7.1	2.1	5	0.58	0.23

A P P E N D I X B

MONITORED PARAMETERS AND ENERGY BALANCE

Table B1. Mean values of monitored parameters used for calculation of heat balance of the reactor, Experiments 1 to 6.

Parameter / Experiment		1	2	3	4	5	6
ML temp.	°C	37.1	36.4	36.7	35.8	36.8	36.4
Ambient temp.	"	5.4	15.1	13.5	18.1	15.1	10.4
Raw slurry temp.	"	13.3	17.3	16.9	17.9	11.7	13.0
Soil temp.	"	12.7	20.4	19.1	21.6	12.5	17.4
Exhaust air temp.	"	27.3	31.0	31.7	36.6	27.4	32.4
3 probe temp.	"	7.9	15.1	15.1	18.1	9.7	16.9
Extracted heat	kWh/d	83.1	124.0	143.3	149.0	101.1	104.9
Aerator heat	"	62.1	86.8	75.8	76.9	57.9	52.2
Foam cutter heat	"	0.0	0.0	0.0	0.0	2.2	9.0

Table B2. Mean values of monitored parameters used for calculation of heat balance of the reactor, Experiments 7 to 9.

Parameter / Experiment		7	8	9
ML temp.	°C	37.5	38.7	39.9
Ambient temp.	"	7.4	7.5	12.7
Raw slurry temp.	"	12.7	12.4	15.2
Soil temp.	"	16.4	15.6	20.9
Exhaust air temp.	"	29.7	32.8	35.5
3 probe temp.	"	7.4	7.8	12.7
Extracted heat	kWh/d	146.0	124.0	140.0
Aerator heat	"	92.4	96.7	80.5
Foam cutter heat	"	11.4	0.0	0.0

Table B3. Mean values of monitored parameters used for calculation of heat balance of the reactor, Experiments 10 to 15.

Parameter / Experiment		10	11	12	13	14	15
ML temp.	°C	50.1	50.5	49.6	50.1	50.2	48.7
Ambient temp.	"	13.7	13.0	14.2	12.2	15.0	9.4
Raw slurry temp.	"	14.3	14.4	17.6	16.2	17.5	13.3
Soil temp.	"	25.7	23.5	24.2	22.7	25.7	14.2
Exhaust air temp.	"	45.5	44.5	40.0	35.3	41.5	41.0
Reactor surface	"	16.6	15.3	22.0	18.7	24.3	9.4
Extracted heat	kWh/d	92.7	83.1	53.8	67.4	47.6	101.8
Aerator heat	"	70.6	72.5	52.4	58.1	50.1	96.0
Foam cutter heat	"	12.9	13.0	1.4	0.0	19.3	0.0

Table B4. Mean values of monitored parameters used for calculation of heat balance of the reactor, Experiments 16 to 20.

Parameter / Experiment		16	17	18	19	20
ML temp.	°C	53.0	55.8	54.2	54.8	54.5
Ambient temp.	"	14.4	15.2	8.7	7.3	0.1
Raw slurry temp.	"	16.6	17.0	13.9	13.1	11.4
Soil temp.	"	23.8	26.2	19.9	19.1	16.3
Exhaust air temp.	"	42.3	50.3	37.4	42.6	40.7
Reactor surface t.	"	16.8	19.1	12.8	10.0	0.1
Extracted heat	kWh/d	73.8	85.4	26.4	21.1	23.0
Aerator heat	"	91.0	72.0	51.6	50.3	44.1
Foam cutter heat	"	0.8	11.2	0.0	0.0	0.0

Table B5. Mean daily values of calculated heat energies and heat losses, Experiments 1 to 6.

Parameter / Experiment		1	2	3	4	5	6
Heterotrophic heat	kWh	106.3	127.5	158.2	121.2	121.8	135.6
Autotrophic heat	"	9.6	12.9	8.8	8.6	20.3	7.3
Total metabolic heat	"	115.9	140.4	167.0	129.8	142.1	142.9
Liquid heat loss	"	31.9	27.1	27.0	23.4	25.0	22.8
Air heat loss	"	13.3	28.6	19.4	14.4	8.9	23.1
Surface heat loss	"	45.1	36.3	38.0	41.4	52.4	46.2
Sum heat losses	"	90.3	92.0	84.4	79.2	86.3	112.1
Extractable heat	"	87.6	135.2	158.4	127.5	115.8	112.0

Table B6. Mean daily values of calculated heat energies and heat losses, Experiments 7 to 9.

Parameter / Experiment		7	8	9
Total metabolic heat	kWh	228.1	143.2	202.5
Liquid heat loss	"	45.5	53.3	49.8
Air heat loss	"	6.6	8.5	19.8
Surface heat loss	"	36.4	31.7	23.5
Sum heat losses	"	88.5	83.5	93.1
Extractable heat	"	248.7	155.8	203.2

Table B7. Mean daily values of calculated heat energies and heat losses, Experiments 10 to 15.

Parameter / Experiment		10	11	12	13	14	15
Total metabolic heat	kWh	293.5	175.9	178.6	193.6	212.5	194.4
Liquid heat loss	"	77.4	65.8	57.2	56.2	46.7	57.6
Air heat loss	"	31.7	15.3	14.8	12.4	36.8	27.6
Surface heat loss	"	34.9	35.7	54.7	51.7	52.5	40.0
Sum heat losses	"	143.7	116.8	126.7	120.2	136.0	125.2
Extractable heat	"	234.3	144.4	106.1	130.9	146.3	165.6

Table B8. Mean daily values of calculated heat energies and heat losses, Experiments 16 to 20.

Parameter / Experiment		16	17	18	19	20
Total metabolic heat	kWh	134.7	243.9	167.3	92.3	84.3
Liquid heat loss	"	61.9	70.0	66.1	65.4	55.1
Air heat loss	"	24.0	33.6	13.4	17.3	9.8
Surface heat loss	"	32.3	50.1	74.4	30.9	36.7
Sum heat losses	"	118.2	153.7	153.9	113.7	101.7
Extractable heat	"	108.7	172.4	44.3	28.9	26.7

Table B9. Daily mass flow through the reactor, Experiments 1 to 6.

Parameter / Experiment		1	2	3	4	5	6
Raw slurry	kg	1160	1230	1170	1110	860	840
Evaporated water	"	10	30	20	20	10	20
Air	"	694	1540	943	564	658	952
Heterotrophic oxygen	"	26.6	31.9	39.6	30.3	30.4	33.9
Autotrophic oxygen	"	8.0	10.7	7.3	7.1	7.4	6.1

Table B10. Daily mass flow through the reactor, Experiments 7 to 9.

Parameter / Experiment		7	8	9
Raw slurry	kg	1580	1750	1740
Evaporated water	"	10	10	20
Air	"	309	323	727
Heterotrophic oxygen	"	57.0	35.8	50.6

Table B11. Daily mass flow through the reactor, Experiments 10 to 15.

Parameter / Experiment		10	11	12	13	14	15
Raw slurry	kg	1860	1570	1540	1430	1230	1400
Evaporated water	"	20	20	20	10	30	30
Air	"	603	311	416	452	957	666
Heterotrophic oxygen	"	73.4	44.0	44.6	48.4	52.9	48.6

Table B12. Daily mass flow through the reactor, Experiments 16 to 20.

Parameter / Experiment		6	17	18	19	20
Raw slurry	kg	1470	1560	1410	1350	1100
Evaporated water	"	30	30	10	20	10
Air	"	575	501	397	360	217
Heterotrophic oxygen	"	33.7	62.0	36.8	22.1	21.1

Table B13. Mean values of specific input electrical and extracted energy and metabolic heat, Experiments 1 to 6.

Parameter / Experiment		1	2	3	4	5	6
1.Spec.aeration en.1	W/m^3	259	278	243	246	250	255
2.Spec.aeration en.2	$kWh/m^3.d$	53.5	70.6	64.8	69.3	67.3	62.1
3.Spec.aeration en.3	Wh/p.d	480	610	600	670	410	370
4.El.en./extrd.heat	%	75	70	53	52	60	58
5.Spec.extrd.heat	Wh/p.d	640	880	1140	1300	710	750
6.Spec.met.heat 1	kWh/kgVS	9.2	10.8	9.9	12.2	9.8	10.3
7.Spec.met.heat 2	kWh/kgO_2	3.2	3.0	3.2	4.2	3.4	3.9
8.Met.an./met.exp.	%	105	109	94	82	112	90

Table B14. Mean values of specific input electrical and extracted energy and metabolic heat, Experiments 7 to 9.

Parameter / Experiment		7	8	9
1.Spec.aeration en.1	W/m^3	443	528	427
2.Spec.aeration en.2	$kWh/m^3.d$	55.2	61.8	53.6
3.Spec.aeration en.3	Wh/p.d	390	430	370
4.Aer.en./extrd.heat	%	79	75	67
5.Spec.extrd.heat	Wh/p.d	500	640	560
6.Spec.met.heat 1	kWh/kgVS	7.4	8.7	7.7
7.Spec.met.heat 2	kWh/kgO_2	3.0	2.2	2.8
8.Met.an./met.exp.	%	131	182	146

1, 2 and 3 are el.energy requirement for aeration of $1m^3$ of used reactor volume, $1m^3$ of slurry and per pig and day respectively

4 - el.energy input (aerator+foam cutter) as percentage of extracted heat

5 - extracted energy per pig and day

6, 7 - percentage of metabolic heat per 1kg of removed VS and COD resp.

8 - percentage of analytical metabolic heat as measured metabolic heat

Table B15. Mean values of specific input electrical and extracted energy and metabolic heat, Experiments 10 to 15.

Parameter / Experiment		10	11	12	13	14	15
1.Spec.aeration en.1	W/m^3	405	414	224	242	289	338
2.Spec.aeration en.2	$kWh/m^3.d$	38.0	46.2	34.0	40.6	40.7	68.6
3.Spec.aeration en.3	Wh/p.d	250	440	240	250	260	420
4.Aer.en./extrd.heat	%	90	103	100	87	145	94
5.Spec.extrd.heat	Wh/p.d	330	500	240	290	250	450
6.Spec.met.heat 1	kWh/kgVS	3.9	6.3	5.6	7.2	4.0	6.0
7.Spec.met.heat 2	kWh/kgO_2	1.9	2.6	2.9	2.7	2.2	2.7
8.Met.an./met.exp.	%	215	153	141	149	186	148

Table B16. Mean values of specific input electrical and extracted energy and metabolic heat, Experiments 16 to 20.

Parameter / Experiment		16	17	18	19	20
1.Spec.aeration en.1	W/m^3	562	403	215	210	184
2.Spec.aeration en.2	$kWh/m^3.d$	61.9	46.2	36.6	37.3	40.1
3.Spec.aeration en.3	Wh/p.d	400	290	260	260	260
4.Aer.en./extrd.heat	%	124	98	198	240	192
5.Spec.extrd.heat	Wh/p.d	330	350	130	110	140
6.Spec.met.heat 1	kWh/kgVS	5.6	7.0	11.4	11.9	10.2
7.Spec.met.heat 2	kWh/kgO_2	3.0	2.5	3.5	4.5	3.8
8.Met.an./met.exp.	%	135	156	114	92	104

1, 2 and 3 are el.energy requirement for aeration of $1m^3$ of used reactor volume, $1m^3$ of slurry and per pig and day respectively

4 - el.energy input (aerator+foam cutter) as percentage of extracted heat

5 - extracted energy per pig and day

6, 7 - percentage of meatabolic heat per 1kg of removed VS and COD resp.

8 - percentage of analytical metabolic heat as measured metabolic heat

A P P E N D I X C

COMPARISON OF MODELLED AND OBSERVED HEAT ENERGY

Fig.C1 Percent difference between modelled and observed data from Experiments 1 to 6.

Parameter/Experiment	1	2	3	4	5	6	Mean
				% difference			
O_2 demand	1.6	11.5	20.0	18.0	2.2	7.2	10.1
El.Energy - aerator	-12.7	-17.3	-11.8	-11.6	-18.5	-29.5	-16.9
Surface heat loss	0.0	-5.2	2.7	32.3	30.0	59.3	19.8
Effluent heat loss	0.0	11.1	3.8	0.0	4.2	0.0	3.2
Exh.gas heat loss	-40.9	-11.4	-5.0	40.0	-47.1	-8.0	-12.1
Extracted heat	-2.4	-4.6	2.9	13.7	-15.1	-18.6	-4.0
Extractable heat	3.0	4.0	13.8	-1.9	-2.8	-13.0	0.5
COD	-0.7	-7.3	-14.4	-11.9	-2.8	-9.4	-7.8

Fig.C2 Percent difference between modelled and observed data from Experiments 7 to 9.

Parameter/Experiment	7	8	9	Mean
		% difference		
O_2 demand	8.8	-23.8	7.0	-2.7
El.Energy - aerator	8.4	-29.4	-6.8	-9.3
Surface heat loss	227.3	97.3	80.8	135.1
Effluent heat loss	0.0	1.9	4.2	2.0
Exh.gas heat loss	0.0	-35.7	-9.1	-14.9
Extracted heat	-39.2	-51.2	-31.7	40.7
Extractable heat	3.6	-37.6	-0.9	-11.6
COD	-5.2	13.0	-4.7	1.0

Fig.C3 Percent difference between modelled and observed data from Experiments 10 to 15.

Parameter/Experiment	10	11	12	13	14	15	Mean
				% difference			
O_2 demand	1.5	6.0	-9.0	-25.9	0.4	-11.6	-6.4
El.Energy - aerator	-5.9	-5.8	-19.4	-35.4	0.6	-15.8	-13.6
Surface heat loss	75.0	80.0	37.5	10.6	30.0	42.9	46.0
Effluent heat loss	0.0	0.0	1.8	0.0	0.0	1.8	0.6
Exh.gas heat loss	-6.1	-6.3	-42.3	-67.6	-39.3	-26.3	-31.3
Extracted heat	-59.6	-40.7	-61.4	-68.5	-64.2	-52.3	-57.8
Extractable heat	1.9	3.1	-24.2	-38.6	9.2	-30.5	-13.2
COD	-2.8	-6.3	25.7	23.3	-3.9	9.7	-0.7

Fig.C4 Percent difference between modelled and observed data from Experiments 16 to 20.

Parameter/Experiment	16	17	18	19	20	Mean
				% difference		
O_2 demand	-35.9	-14.4	-34.8	-57.0	-54.5	-39.6
El.Energy - aerator	-37.6	-18.2	-42.0	-62.7	-60.3	-44.2
Surface heat loss	88.2	150.0	18.1	-11.4	68.2	62.6
Effluent heat loss	0.0	1.4	0.0	1.6	1.9	1.0
Exh.gas heat loss	-67.1	-24.4	-73.2	-75.0	-76.2	-63.1
Extracted heat	-63.0	-64.6	-81.4	-87.7	-87.2	-76.8
Extractable heat	-45.7	-28.2	-68.3	-83.1	-85.1	-62.1
COD	28.8	11.8	32.2	52.5	53.6	35.8

A P P E N D I X D

COMPUTER PROGRAM H E P C A L

```
10
20 REM ***** HEPISAT CALCULATIONS ***** "HEPDCAL"OFF *****UNDILUTED
30 REM Modified for all Runs after    and including RUN6 ****** 1.3.1991
40 VDU 12:VDU15:PRINT:PRINT"** HEPISAT CALCULATIONS **"
50 PRINT:INPUT "PRINTER ON (2) OFF (3)",print%:VDU print%
60 DIM N(50)
70 PROCreadata
80 no%=N(1)
90 PROCparams(no%)
100 num=N(2)
110 ts=N(3)
120 tss=N(4)
130 cod=N(5)
140 bod=N(6)
150 nt=N(7)
160 nte=N(8)
170 code=N(9)
180 no3e=N(10)
190 temp=N(11)
200 he=N(12)
210 ha=N(13)
220 hc=N(14)
230 t1=N(15)
240 t2=N(16)
250 t3=N(17)
260 t4=N(18)
270 t5=N(19)
280 ient=N(20)
290 eent=N(21)
300 av=N(22)
310 fh=N(23)
320 oc=N(24)
330 p=N(25)
340 pr=N(26)
350 eh=N(27)
360 iwc=N(28)
370 ewc=N(29)
380 v=N(30)
390 Htot = ha + hc
400 A=fh*av*p/760
410 AIR=A*1.293  :REM air total weight
420 OX=A*(21-oc)/100*1.429
430 LAIR = (eent-ient)*AIR/3600
440 LAIRR= LAIR-((21-oc)/360000*eent*AIR)
450 WATER = AIR*(ewc-iwc)/1000000
460 VEFF  = pr*0.06*eh
470 VRAW  = VEFF+WATER
480 AVRAW = VEFF
490 REPEAT:AVRAWO=AVRAW
500   DCOD=AVRAW*cod-VEFF*code
510   nloss=nt*AVRAW-nte*VEFF
520   nox=no3e*VEFF
530   NO=(nloss*.375+nox)*4.57
540   IF no3e=0 THEN NO=0
550   NOH=(nloss+nox)*4.57
560   IF no3e=0 THEN NOH=0
570   AAIR = ((DCOD+NO)/1.429)/(21-oc)*129.3
```

A P P E N D I X E

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