Manuals of British Practice
in Water Pollution Control

Unit Processes

SEWAGE SLUDGE I: PRODUCTION, PRELIMINARY TREATMENT AND DIGESTION

The Institute of
Water Pollution Control
Ledson House, 53 London Road,
Maidstone, Kent. ME16 8JH
1979

THE INSTITUTE OF WATER POLLUTION CONTROL

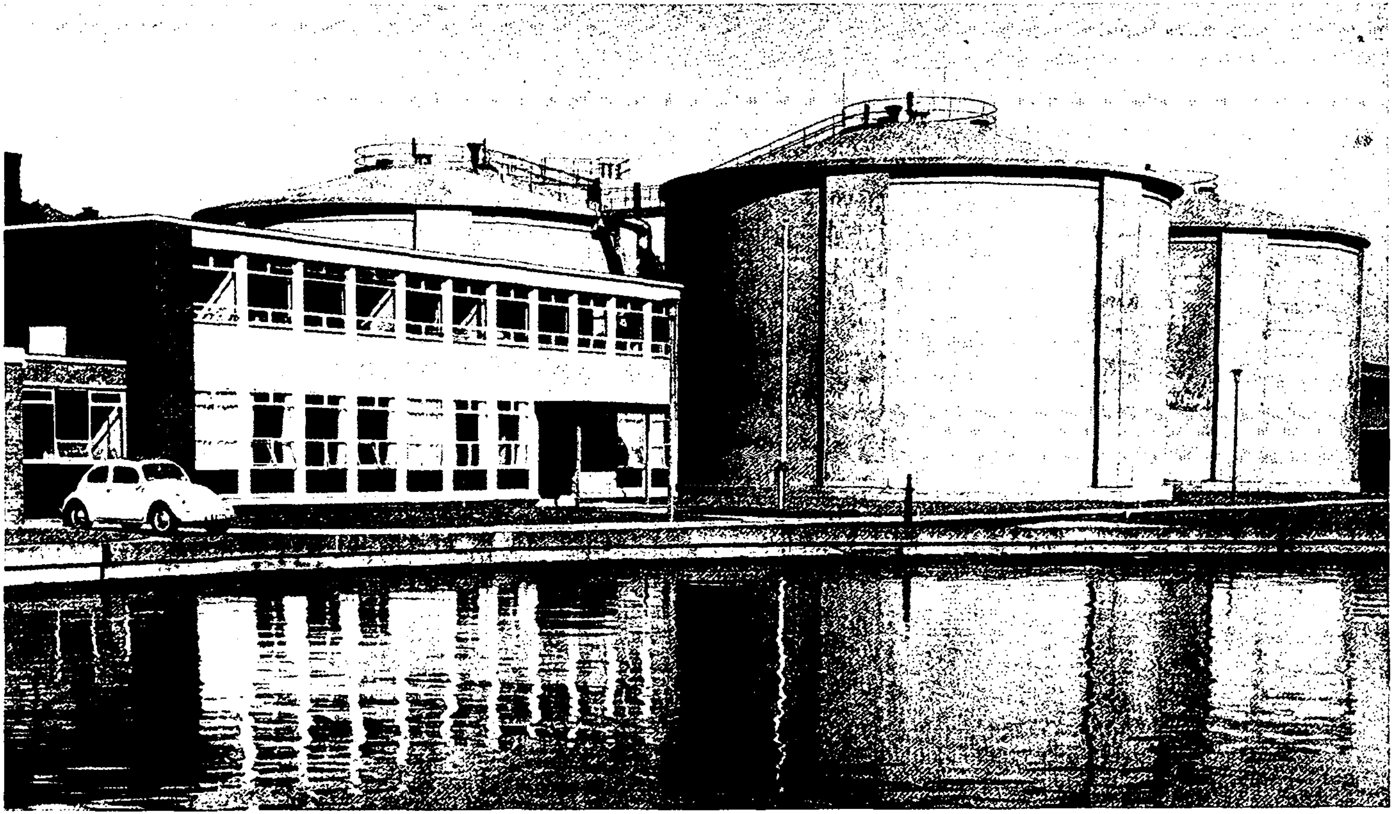
MANUALS OF BRITISH PRACTICE IN WATER POLLUTION CONTROL

Sewage Sludge I: Production, Preliminary Treatment and Digestion.

Correction:

Page 82, Appendix 1, Column headed "Dry Matter (%)"

In line 2: delete "2,34"
insert " - "



Mesophilic digestion plant and administration block at Ringley Fold sewage-treatment works

Manuals of British Practice
in Water Pollution Control

Unit Processes

SEWAGE SLUDGE I: PRODUCTION, PRELIMINARY TREATMENT AND DIGESTION

The Institute of
Water Pollution Control
1979

THE INSTITUTE OF WATER POLLUTION CONTROL

1979

Price £4·00

PREFACE

In 1970 the Council of the Institute of Water Pollution Control discussed the question of the publication of definitive manuals on the subject of British Practice in Water Pollution Control and concluded that such publications would generally be welcomed.

The Institute's publication An Introduction to Sewage Treatment *will continue to serve as a general guide to the layman interested in the subject, whilst the manuals will, it is hoped, cover the subject in sufficient depth to become accepted as a reference source both to those already actively engaged in this particular field as well as to students seeking authoritative guidance when preparing for professional qualifications.*

Throughout the manuals of unit processes of waste-water treatment it will be seen that there is often a variety of equipment available for any particular purpose, and different modes of operation are described. Wherever possible, an indication is given of circumstances which favour the use of any particular type of equipment or method of operation which past experience has shown to be advantageous. The variable nature of sewage and sludge means, however, that such an indication can usually only be given with qualifications.

The preparation of this Manual has included a lot of work on the part of a number of persons, and the Sub-Committee of the Institute's Publications Committee which has been responsible for its production wish to thank those members of the Council of the Institute who have made comments and suggestions for its improvement, and especially do they wish to thank the staff of the Water Research Centre, Stevenage Laboratory.

The initial draft of this manual was first prepared by Mr. H. H. Stanbridge, former editor of the Manuals Sub-Committee; the Sub-Committee wish to record their appreciation of his efforts in doing so. At the time of his death in 1977 the draft was still in an early stage of processing and credit is due to Mr. Malcolm D. F. Haigh who took over the duties of co-ordinator and editor at this difficult time.

H. A. Hawkes
Chairman

ACKNOWLEDGMENTS

The Institute wishes to make grateful acknowledgment to the following for permission to reproduce illustrations:

Mr. G. Ainsworth, Director of Scientific Services, North-West Water Authority (Frontispiece).

Mr. G. T. Calder, Division Director, Southern Division, Yorkshire Water Authority (Plates 1 and 5).

Mr. L. H. Thompson, Divisional Manager, Metropolitan Public Health Division, Thames Water Authority (Plates 6, 7 and 8).

Ames Crosta Babcock Ltd. (Fig. 4 and Plate 1).

Dorr-Oliver Co. Ltd. (Figs. 5 and 8 and Plates 2, 3 and 6).

Jones and Attwood Ltd. (Fig. 9 and Plate 4).

Simon-Hartley Ltd. (Fig. 10 and Plate 5).

SEWAGE SLUDGE I: PRODUCTION, PRELIMINARY TREATMENT AND DIGESTION

CONTENTS

PLATES

(Between pages 50 and 51)

FIGURES

1. Sludge Production

1.1 Introduction

Sludge is defined[1] as being 'a mixture of solids and water produced during the treatment of waste water'.

Although the volume of liquid sludge which is produced at a sewage-treatment works usually represents only 1–2 per cent of the total flow of sewage, its treatment and disposal is generally a major operation accounting for as much as 50 per cent of the total running costs of the works. The various stages of treatment to which sludge may be subjected before final disposal, and the alternative forms of disposal, are depicted in Fig. 1. All the stages of treatment shown are not required in every case and the combination of unit processes which are actually employed before disposal will depend upon many factors.

The basic objectives of the selection and operation of a sludge treatment and disposal system are (a) to reduce any potential detrimental effect on the environment to an acceptable level, (b) to maximize any beneficial effect, and (c) to achieve these objectives at an acceptable cost. The purpose of sludge treatment is to render the sludge more amenable to disposal by the various methods which are available and to minimize the cost of disposal. Treatment may be carried out specifically to achieve one or more of the following aims:

(i) To render the sludge less offensive and reduce any potential hazard to health, e.g. by anaerobic digestion or lime conditioning;

(ii) To convert the sludge to a form which is more suitable for use in agriculture, e.g. by anaerobic digestion;

(iii) To reduce the volume of sludge, hence the cost of transportation to the disposal site, or to reduce the volume prior to further treatment;

(iv) To change the nature of the sludge so that it is more amenable to dewatering (conditioning).

1.2 Sludge Production

At most sewage-treatment works about 60–70 per cent of the suspended solids (SS) and 25–40 per cent of the biochemical oxygen demand (BOD) in

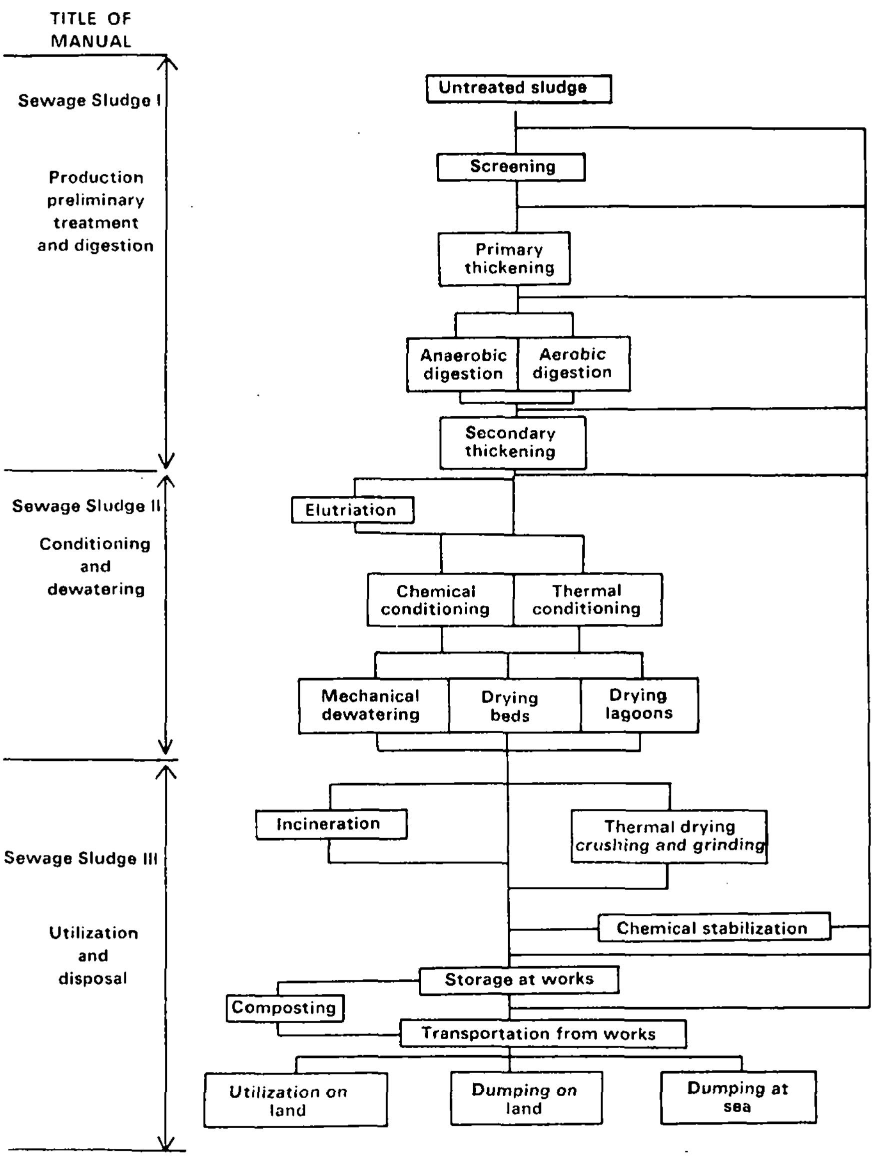


Fig. 1. Unit processes and operations employed in treatment, utilization and disposal of sewage sludge.

the sewage entering the works are removed by primary sedimentation. Up to 80 per cent of the BOD remaining in the sewage after primary sedimentation may be converted into an equivalent weight of solids during the secondary biological treatment stage and removed during secondary settlement to form a secondary sludge. Therefore the total quantity of sludge formed at the works may comprise a considerable proportion of secondary biological sludge. When a tertiary treatment process is employed, a further quantity of solids may be removed and form a sludge which requires disposal.

1.3 Character of Sewage Sludges

1.3.1 Types of sludge

Sludges from conventional sewage-treatment plants originate from primary, secondary and tertiary treatment processes and are known as (i) primary sludge, including storm tank sludge, (ii) secondary sludge, and (iii) tertiary sludge, respectively.

Raw sludge has been defined[1] as 'primary sludge or secondary sludge or a mixture of the two, prior to modification of its nature by anaerobic digestion, thermal or other treatment'. Digested sludge has been defined[1] as 'sludge which has been subjected to either aerobic or anaerobic digestion'.

Where primary and secondary sludges are combined the mixture is referred to as *mixed* sludge or, when settled together in primary sedimentation tanks, a *co-settled* sludge.

Some small plants which treat sewage without primary treatment produce only a single sludge.

1.3.2 Primary sludge

Primary sludge normally comprises the major proportion (in terms of dry solids) of the sludges which are produced by a sewage-treatment works. The actual proportion of solids removed depends to a great extent on the composition of the sewage, the efficiency of primary sedimentation, and whether any aids to sedimentation have been employed, e.g. the addition of flocculating agents.

A typical domestic primary sludge is normally greyish black, has an offensive odour and contains about 5 per cent dry solids of which 70–80 per cent is organic and volatile matter. The organic matter includes fats and grease, food residues, faeces, paper, and detergents, and the inorganic matter mainly consists of siliceous grit.

The presence of industrial effluents may have a marked influence on the characteristics of the primary sludge, which will depend upon the types of industry involved.

1.3.3 Secondary sludge

The biological treatment of sewage results in the production of further organic solid material termed secondary sludge. This is either: (a) humus sludge or (b) surplus activated sludge.

1.3.4 Humus sludge

Humus sludge is the product of the settlement of effluents from biological filters. Fresh humus sludge is brown in colour and has a characteristic earthy smell. A typical sludge contains 0·5–2·0 per cent dry solids of which 65–75 per cent is organic matter, the dry solid matter comprising biological residues including insects and worms. The rate of production of humus sludge varies seasonally because of the temperature dependency of the grazing fauna in the filters.

On most sewage-treatment works the practice is to return humus sludge to the primary sedimentation tanks for co-settlement with the primary sludge.

A rotating-disc filter produces a sludge which is similar to humus sludge but without fly larvae or larger worms.

1.3.5 Surplus activated sludge

In the operation of an activated-sludge plant a proportion of the mixed liquor suspended solids (MLSS) has to be removed from the plant at regular intervals, and this is known as surplus activated sludge. It consists of flocculated and synthesized solids and micro-organisms, varies in colour from grey to dark brown, and normally has an earthy smell; the solids are in the form of flocs. Depending upon the rate of recycling and other factors surplus activated sludge normally contains less than 1·0 per cent dry solids of which 70–85 per cent is organic matter; if allowed to stand without aeration it normally becomes black and offensive after a period of about 24 h. As with humus sludge, surplus activated sludge is frequently returned to the primary sedimentation tanks and co-settled with primary sludge, although recent trends have been towards separate thickening of surplus activated sludge.

1.3.6 Tertiary sludge

Tertiary sludge is derived from a tertiary treatment (or effluent polishing) process. It comprises that fraction of the secondary sludge which remains in the effluent from the secondary settlement tank and is removed in the tertiary treatment stage. As with secondary sludges this sludge is usually returned to the primary sedimentation tanks for co-settlement. 'Chemical' sludges, which are produced during physico-chemical treatment for the removal of nutrients from secondary effluent, may be included in this category.

1.3.7 Digested sludge

There are two types of digested sludge, which are products of anaerobic and aerobic digestion respectively, of which the former is more common. Anaerobically digested sludge is black, is generally considered to be inoffensive and has a characteristic 'tarry' odour, whereas aerobically digested sludge is usually dark brown in colour with an inoffensive, mildly earthy odour. A comparison of analysis of raw sludge with anaerobically digested sludge is given in Table 1.

TABLE 1. COMPARISON OF TYPICAL PRIMARY AND ANAEROBICALLY DIGESTED SLUDGES

	Primary sludge	Anaerobically digested sludge
pH	6·3	7·2
Alkalinity (mg/l)	1200	4400
Volatile acids (mg/l)	2900	<200
Dry solids (per cent)	5·0	3·0
Petroleum extractable (per cent)	20	10
Organic and volatile matter (per cent)	70	60
Mineral matter (per cent)	30	40
Nitrogen (as N) (per cent)	4·3	3·2

1.4 Calculation of Sludge Quantity (Gravimetric)

1.4.1 Primary sludge

The amount of dry solids in primary sludge will depend upon the concentration of SS in the incoming sewage, the settleability of those solids, the 'efficiency' of the sedimentation tank and whether works' liquors are returned to the inlet. Primary sludge production is normally calculated from:

(i) Measurement of the quantity of SS in the primary tank inflow and outflow,

(ii) The SS loading multiplied by the proportion settling in the primary sedimentation tanks, or

(iii) An assumed *per capita* SS figure and an assumed percentage reduction of SS in the primary sedimentation tanks. (In the absence of specific data a design figure of 65 per cent reduction may be used).

The average concentration of SS can be assessed accurately only by taking continuous or frequent periodic (e.g. hourly) samples over a number of 24–h periods, taking account of any seasonal variations due to holidays and weekends, and variations due to intermittent industrial operations.

The SS loading may be determined using the following relationship:

$$L = Q(S_c - S_s) \times 3600 \times 24 \times 10^{-6}$$
$$= 0{\cdot}0864\, Q(S_c - S_s)$$

where L = daily SS loading (kg)

Q = average rate of flow of sewage (l/s)

S_c = average conc. of SS (mg/l) in crude sewage

S_s = average conc. of SS (mg/l) in settled sewage

Where analytical data are unavailable, a *per capita* estimate of domestic sludge production may be made by reference to experience in the area concerned, and a generally acceptable figure for the amount of dry suspended matter in domestic sewage is 0·06–0·07 kg/hd d. The industrial proportion should be calculated by the sampling and analysis of industrial effluents and consultation with factory management to determine any future change in sludge production. Any proposed industrial development must also be taken into account, particularly with regard to the types of processes involved and the limitations which may be imposed by the receiving authority.

1.4.2 Humus sludge

A difficulty in estimating the sludge yield from biological filters arises from the marked seasonal variation in biological activity and hence sludge production. For example, it has been shown[2] that for a low-rate filter treating domestic sewage, the rate of humus sludge production in the spring was 6 times greater than in the summer months.

The yield also depends upon the type of plant; for example, low-rate filters produce less humus sludge than high-rate filters. The average sludge yield from low-rate biological filters in normally 0·25–0·50 kg dry solids per kg BOD removed less the dry mass of SS in the humus tank effluent, whereas the average yield from high-rate filters may be as high as 1·0 kg dry sludge solids per kg BOD removed.

1.4.3 Surplus activated sludge

1.4.3.1 High-rate activated sludge (less than 5 h aeration[1]). For a typical high-rate activated-sludge process the total surplus sludge dry solids yield may be as high as 0·8–1·0 kg solids per kg BOD applied in the settled sewage, less the dry mass of SS in the secondary settlement tank effluent. In the absence of other data, a reduction of 30 per cent in BOD as a result of primary sedimentation may be assumed.

1.4.3.2 Conventional (intermediate-rate) activated sludge (5–16 h aeration[1]). Typically a surplus sludge dry solids yield would be 0·6 kg dry sludge solids per kg BOD applied in the settled sewage, less the dry mass of SS in the secondary settlement tank effluent.

1.4.3.3 Extended-aeration activated sludge (more than 20 h aeration[1]). Primary sedimentation is not normally used before extended aeration. Sludge production from this process may be assumed to be about 0·6 kg dry sludge solids per kg BOD applied in the crude sewage, less the dry mass of SS in the secondary tank effluent.

1.4.4 Tertiary sludge

Where tertiary treatment is practised, the dry mass of solids captured by this process and returned for treatment and disposal should be added to the quantity of humus or surplus activated sludge.

1.4.5 Digested sludge

When primary or mixed sludge undergoes anaerobic digestion, the organic and volatile matter is normally reduced by about 50 per cent with a consequent overall reduction in the mass of total solids of 35–40 per cent, although the volume of sludge is virtually unchanged.

1.5 Calculation of Sludge Quantity (Volumetric)

In determining the quantity of sludge, it is convenient to express the sludge solids content on a weight/volume basis, i.e. assuming that the sludge has a specific gravity of 1·0.

$$\text{Thus the percentage solids (w/v)} = \frac{\text{mass of solid (kg)}}{\text{volume of sludge (l)}} \times 100$$

1.5.1 Primary sludge

This normally contains 4–8 per cent dry solids, depending upon the character of the sewage, the period of storage in the primary sedimentation tank, and the method of sludge draw-off.

1.5.2 Secondary sludge

The volume of surplus activated sludge depends upon the method of plant operation, and its dry solids content is usually within the range 0·5–1·0 per cent; lower concentrations are normally associated with abnormalities such as bulking.

Depending upon the actual BOD loading and type of sewage, the rate of humus sludge production over a year by a low-rate biological filter may range from 0·25–0·50 kg dry solids/kg BOD removed less the dry mass of SS discharged in the humus-tank effluent. It has been reported[2] that the seasonal rate of humus sludge production varied in the case of one low-rate filter from 0·5 kg/kg BOD removed during the spring to as low as 0·08 kg/kg BOD removed during the summer. The overall yearly average rate was 0·22 kg/kg BOD removed.

The rate of production of humus sludge by high-rate filters will depend upon the loading but may be as high as 1·0 kg/kg BOD removed[2].

1.5.3 Mixed sludge

When, as is frequently the case, secondary sludges are returned to the inlet of the primary sedimentation tanks the co-settled mixed sludge typically contains about 5 per cent dry solids.

2. Preliminary Sludge Treatment

2.1 Introduction

The term 'preliminary' treatment when applied to sewage sludge refers to the following processes: (a) screening or disintegration to remove coarse solids, particularly fibrous material, and (b) thickening (or consolidation)[1] to reduce the volume of liquid sludge for subsequent treatment or disposal.

2.2 Screening

On arrival at the sewage-treatment works, sewage is usually screened (see Manual '*Preliminary Processes*') or comminuted. However, since the screening of sewage is never completely effective and because shredded rags tend to 'ball up' and cause blockages in sludge pipelines and in treatment equipment, sludge is also sometimes screened prior to treatment, using screens having about 19-mm spacings between the bars. The screens may be cleaned manually or mechanically and the screenings should be disposed of separately. Alternatively all the sludge should be macerated prior to dewatering.

2.3 Sludge Thickening/Consolidation

The thickening or consolidation of sludge comprises the separation and removal of liquor in order to reduce the volume of liquid sludge to be subsequently treated. The process is to be distinguished from 'dewatering' or 'drying' which removes a much higher proportion of liquor and leaves the sludge in a solid (cake) form.

Thickening is aided by stirring, gas flotation or centrifugation.

It should be appreciated that, for a unit weight of solids, a sludge containing 98 per cent water occupies only half the volume of a sludge containing 99 per cent water. Fig. 2. demonstrates the significant relationship of the dry solids content to the volume of sludge.

2.3.1 Purpose

The provision of a 'thickening' facility has the following potential advantages:

(i) It reduces the volume of sludge requiring subsequent treatment thereby reducing operational costs,

(ii) It enables sludge to be withdrawn from sedimentation or separating tanks more frequently so that their performance can be improved,

(iii) It facilitates the blending of sludges and equalization of their rate of flow to the treatment plant.

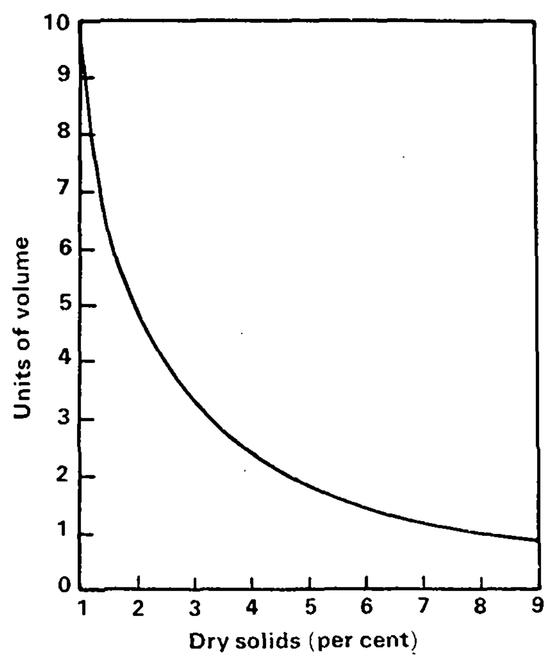


Fig. 2. Relationship between dry solids content and volume of sludge.

On the other hand, the thickening or consolidation of raw sludge may give rise to odour nuisance and, since the sludge could become stale, the chemical requirement for conditioning may be increased. Also there is a limit to the extent to which sludge should be concentrated, depending upon the subsequent method of treatment and disposal. The point at which it becomes too thick to flow by gravity or to be pumped varies with the type of sludge, but with primary sludge this point is reached when it contains about 12 per cent dry solids.

During consolidation or thickening a liquor is produced which is usually returned to mix with the incoming sewage, and this liquor will impose an additional load on the sewage-treatment plant.

When sludge enters a continuous-flow tank at the surface the particles of solid matter gravitate towards the floor; accordingly the concentration of solids in the liquor increases until settlement is hindered by their collision with other particles. Eventually, however, they reach a level at which further concentration takes place by compression.

2.3.2 Gravity separation

2.3.2.1 Thickening tanks. Tanks in which continuous-flow thickening takes place are usually circular with a sludge outlet at either the centre or the periphery.

TABLE 2. EFFECT OF 'THICKENING' ON SOLIDS CONCENTRATION OF SLUDGES PRODUCED IN SEWAGE TREATMENT

Type of sludge	Range of SS concentration before thickening (per cent)	Average SS concentration before thickening (per cent)	Average SS concentration after thickening (per cent)
Primary	5 – 7	6	9
Mixed primary and activated	3 – 6	4·5	7
Mixed primary and humus	3·5–7	5·5	8
Activated	0·3–0·6	0·5	3
Humus	2 – 4	2·5	4
Anaerobically digested	2·5–6·5	3·5	5

A rotating thickening device, called a 'picket fence thickener' comprising a series of picket rods at about 100-mm spacings, extends down into the tank from a central, fixed bridge. Although the optimum peripheral speed is 1–2 m/min, the drive mechanism may be designed to allow for operation at differing speeds ranging between 0·5 and 3·0 m/min. The sludge is agitated by the moving picket fence which serves to: (a) release entrained gas bubbles,

(b) prevent bridging of the sludge solids, (c) minimize scum formation, and (d) form void channels through which water is displaced upwards.

The effect of thickening of sludges produced in sewage treatment is shown in Table 2, and particulars of installations using thickening tanks are given in Table 3.

TABLE 3. PERFORMANCE OF THICKENING TANKS

Works	Year commissioned	Sludge	Number	Diameter (m)	Side wall depth (m)	Depth at centre (m)	Combined capacity (m^3)	Solids content of sludge increased from (per cent)	Liquor: Suspended solids (mg/l)	BOD (mg/l)	Reference
Coventry	c. 1966	H	2	6·70	3·20	4·70	308	0·14 to 1·90	340	212	3
Manchester	c. 1935	A	1	12·19		8·53	909				4
Manchester		PA		30·5	3·82	5·18	3360	2·1 to 7·83	6 700	4180	4
Manchester		A		30·5	3·82	5·18	3360	1·98 to 6·5	11 200	7350	5
Oxford	1969	A	2	12·19	2·59		846	3·0			

2.3.2.2 Consolidation tanks (Fig. 3). Consolidation tanks are either rectangular or circular and supernatant liquor is withdrawn by (a) a floating arm, (b) a swivel arm, (c) a telescopic weir, or (d) a series of valve-controlled outlets spaced at regular intervals vertically. It has been suggested that there is

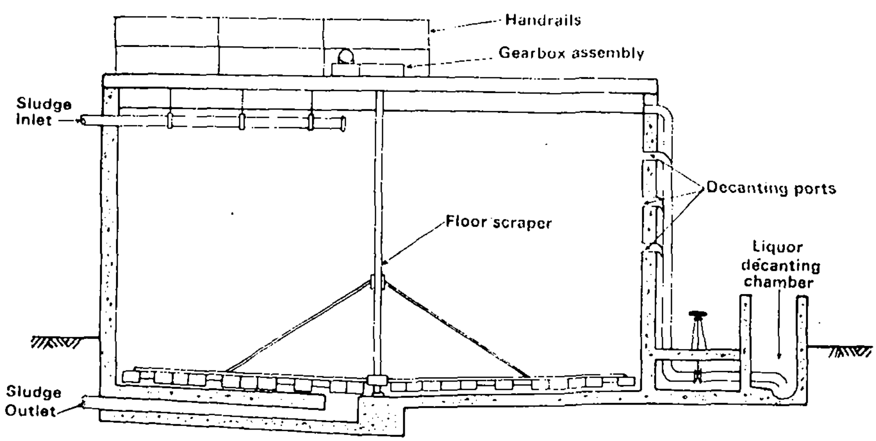


Fig. 3. Cross-section of circular sludge consolidation tank.

little additional benefit in increasing the depth of the sludge, after consolidation, above 1 m; however, a sidewall depth of 3 m allows flexibility of operation and increases the chance of achieving the optimum consolidation on different types of sludges. The daily sludge production varies widely according to the nature of the sewage and the degree of the consolidation which is required. Particulars of installations of consolidation tanks are given in Table 4.

TABLE 4. PERFORMANCE OF CONSOLIDATION TANKS

Works	Year commissioned	Sludge	Number	Dimensions (m)	Combined capacity (m^3)	Settlement period (h)	Solids content of sludge increased from (per cent)	Reference
Barnsley	1961	PH	2	12·19 × 6·10 × 2·08	290	24	to 4·8	7, 8
Colchester	1970	P	3	7·8 square × 2·13, pyramidal bottom	620	24		9
Coventry	1953	PH	2	13·71 × 7·62 × 4·27	1335	4	5·0 to 6·5	3
Maple Lodge	1962	PA	2	15·24 square, four hoppers			to 6·7	10
Norwich	1963	PH	4	7.62 square × 6·55, pyramidal bottom	1227	48	5·3 to 6·1	11
Walsall	1966	PH	2	25·91 × 25·60 × 2·59	1727		to 6·5	12

Sludge: P, primary; A, activated; H, humus.

2.3.2.3 Operation and performance of consolidation and thickening tanks. It is common practice to operate these tanks as a batch process and to provide three tanks having a combined capacity equal to three days' production of sludge, operating with one tank filling, a second emptying and a third providing quiescent settlement. However, they can be operated continuously and may also serve as storage tanks.

The performance of thickening and consolidation tanks is affected by the type of sludge and its solids content. A sludge which is affected to a considerable extent by ageing is unsuitable for concentration, consequently secondary sludges from high-rate treatment processes, e.g. a high-rate activated-sludge plant, and humus sludge are normally unsuitable. Co-settled primary/activated sludge and digested sludge are less affected by ageing and are therefore more amenable to consolidation.

With some activated-sludge plants the surplus sludge is consolidated by allowing it to accumulate in one or more of the secondary settlement tanks. At Manchester[13], for example, when sludge was allowed to accumulate in a final tank for 5 h its dry solids content increased from 0·8 per cent to 2·0 per cent.

2.3.3 Gas flotation

The earliest attempts at sludge thickening by flotation relied on natural gas evolution[14] or gases evolved by the addition of chemicals[15] to promote buoyancy of the sludge solids by the attachment of bubbles. These processes were not economically viable and were successful only with primary sludges which can normally be thickened adequately by sedimentation. Activated sludges, however, are difficult to concentrate by gravity alone but flotation thickening due to gas release brought about by denitrification can sometimes be observed when these sludges are held under quiescent conditions, e.g. in secondary settlement tanks.

Flotation of particles by gas bubble attachment is a proven technique in the mineral processing industry and it is well established that very small bubbles give the best results. Owing to the nature of sewage sludges, and in particular activated sludges to which flotation techniques have chiefly been applied, bubble generation for this application is accomplished by methods producing a minimum of agitation. Either air is dissolved in water (or effluent) under pressure which is subsequently released, or an electrolytic method is adopted.

Polyelectrolytes are usually added in the dissolved-air process but may not always be beneficial. Charge neutralization effects which are associated with the electrolytic process appear to make polyelectrolyte addition unnecessary. The first dissolved-air flotation unit in the UK was installed at Newton Aycliffe in 1969 and several similar units are now in operation. Development of the electrolytic process has been less rapid and has centred on surplus activated sludge thickening.

2.3.3.1 Operation and performance. Dissolved-air flotation is carried out by mixing a stream of liquid containing dissolved air under pressure with the sludge and introducing the mixture near the bottom of a flotation tank (Fig. 4). The associated release of pressure generates very small gas bubbles and the gas/sludge mixture rises to the surface of the tank and may be further buoyed up by subsequent release of gas. Thickened sludge is removed continuously or intermittently by the action of a flight scraper, and the liquid underflow may be returned either to the main treatment plant or to a recycle stream for subsequent saturation with air prior to re-use. Common methods of dissolving air are (a) injection into the suction side of the water pump, (b) use of an air eductor, (c) a packed column device, or (d) a bubble dispersion generator.

2.3.3.2 Electrolytic flotation is achieved by passing the sludge between a grid of inert electrodes (often platinized titanium) across which a DC potential is applied. Electrolysis takes place which produces very small gas bubbles and in some cases sludge flocculation. The subsequent thickening effect and method of sludge removal are similar to those for dissolved-air systems.

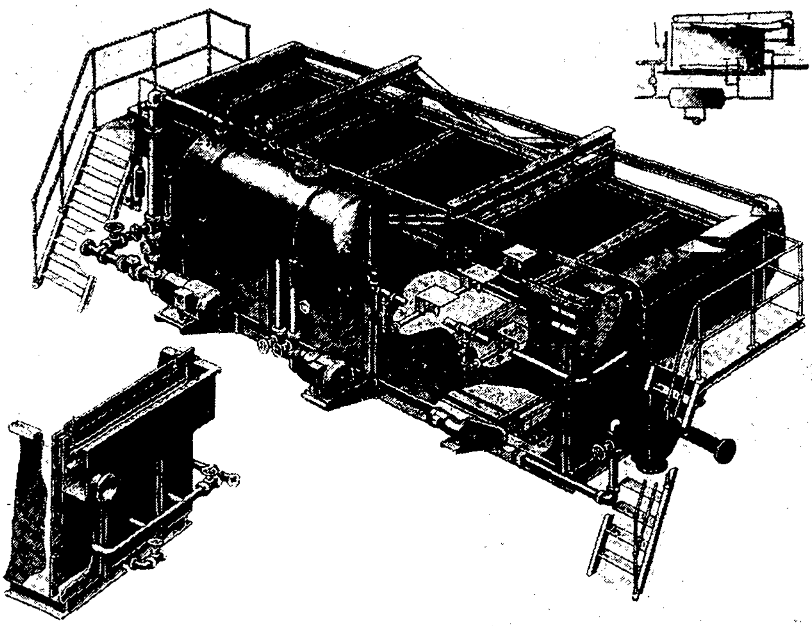


Fig. 4. 'Exploded' view of gas flotation unit.

The design of both systems is based on a solids loading per unit area of flotation tank per hour. A figure of 10 kg/m^2 h has been quoted for design purposes[16] but individual sludges may give better or worse solid fluxes. A production of 15–20 kg/m^2 h has been achieved in some plants and 11 kg/m^2 h was achieved at Bolton with a feed activated sludge containing 0·5 per cent dry solids giving a concentration of 4·5 per cent solids at a polyelectrolyte dose of 0·27 kg active material per tonne sludge solids[17]. A balance is normally achieved between the degree of thickening required, acceptable underflow quality, air and polyelectrolyte amounts, and frequency of scraper operation. Gas flotation units are intended to operate without continuous surveillance but care is needed in setting the operating parameters. Prolonged storage of sludge can adversely affect thickening and there appears to be a relationship between the degree of thickening which can be achieved by settlement and flotation[18].

Flotation of surplus activated sludge in general will produce concentrations of 4–5 per cent DS from a feed containing 0·5–1·0 per cent DS. Polyelectrolyte doses of 0·5–2·5 kg/tonne sludge solids are commonly used for dissolved-air flotation, the effect being chiefly to permit an increase of solids flux rather than increasing thickening.

Thickening of activated sludge to facilitate subsequent sludge handling or improve digester efficiency by reducing water input are the principal current applications. It has been suggested that flotation could replace primary or secondary sedimentation but full-scale operating information is not available at present for this application.

2.3.4 Centrifugation

A centrifuge is a mechanical device which is used for employing centrifugal force on the particles of sludge in order to increase the rate of separation and hence settling. Lighter particles are discharged with the centrate; the heavy particles pass to a thickening zone of the machine and are then discharged either as a cake or a thickened 'slurry'.

Fundamentally there are two types of centrifuge: (a) the nozzle bowl or disc-stack type which is used for thickening surplus sludge, and (b) the solid bowl scroll type which may be used for thickening either activated sludge or mixed co-settled sludges. Both types of centrifuge are operated continuously, rotating at a speed of 900–3300 rev/min, the speed depending upon the type of centrifuge and the sludge being treated. For further information on the theory and practice of centrifugation, see *Sewage Sludge II: Conditioning and Dewatering*.

2.3.4.1 Nozzle bowl or disc-stack centrifuge (Fig. 5). This is a vertical-spindle machine with a bowl of stainless steel. The bowl contains a stack of conical discs which act in a manner similar to inclined plate separators to enhance the surface area and therefore the settling of the solid particles. Vertical bowl machines develop high centrifugal forces (5000–8000 G) within the bowl.

Operation and performance. In order to prevent excessive wear and the blockage of nozzles in this type of machine, the sludge needs to be screened upstream from the centrifuge.

On start-up, the feed sludge enters the centre of the bowl. High-speed revolution of the centrifuge (3000–3300 rev/min) throws the solid particles outwards through the nozzles. The supernatant liquor passes through the 'disc stack' where fine suspended solids agglomerate on the underside of the

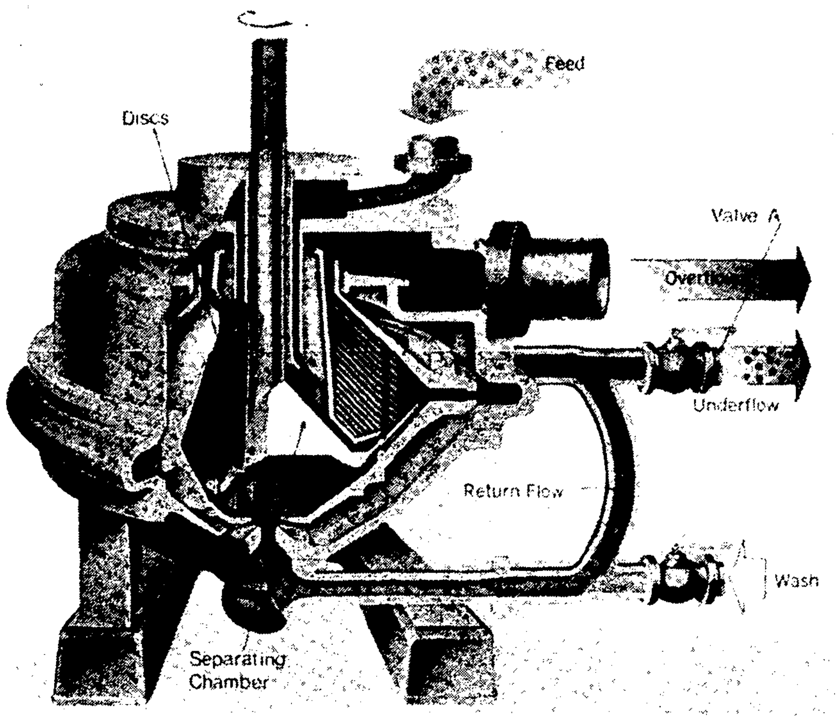


Fig. 5. 'Exploded' view of nozzle bowl or disc-stack centrifuge.

discs and as they increase in size and density are thrown outwards to join the thickened sludge passing from the machine. When the machine is operational, adjustment of valve (A) allows a proportion of the thickened sludge to be recycled and this enhances thickening of the incoming sludge.

Centrifuges of this type are capable of thickening surplus activated sludge without the addition of polyelectrolytes. For example, at Knostrop (Leeds)[19], extended trials during 1975–6 demonstrated that a sludge containing up to 6 per cent dry solids could be achieved at a throughput of 0·80 m³/min giving a solids recovery of 90 per cent. On the basis of these results a permanent plant was installed in 1978 to thicken sludge before disposal to the North Sea.

2.3.4.2 Solid bowl, scroll centrifuge (Fig. 6). These machines are more fully described in *Sewage Sludge II: Conditioning and Dewatering.*

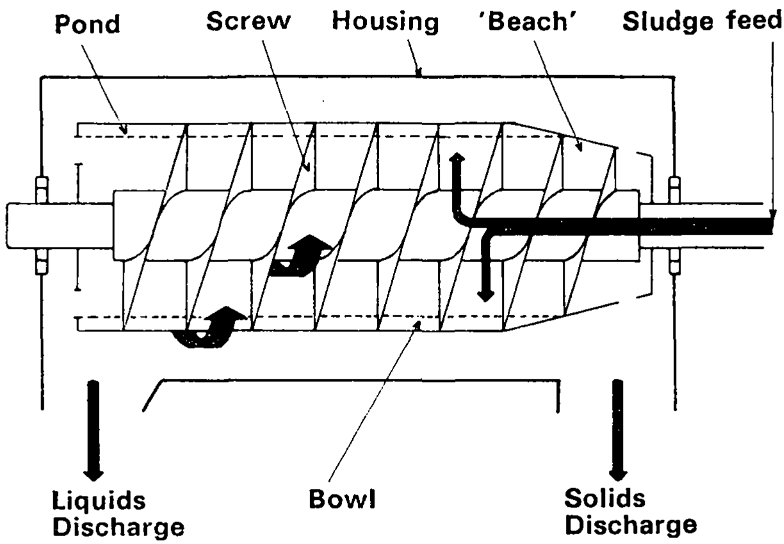


Fig. 6. Diagrammatic cross-section of solid bowl, scroll centrifuge.

The solid bowl consists of a horizontally-mounted tapered cylinder, the tapered section forming a 'beach' for the solids, up which they are conveyed by the scroll rotating at a speed slightly higher than that of the bowl.

Operation and performance. Sludge is introduced into the bowl where high-speed revolution separates the solids which collect on the periphery of the bowl from where the conveyor or scroll transports the thickened sludge to the 'beach' before final discharge from the machine. Operation of this type of centrifuge depends upon (a) the nature of the sludge being treated, (b) the type of polyelectrolyte being added, (c) the centrifugal bowl/screw conveyor speed differential, and (d) the level of the liquid maintained in the centrifuge.

In order to produce a thickened slurry rather than cake, the liquid level is maintained above the discharge port.

When used without polyelectrolytes, it is possible to thicken a surplus activated sludge to 6 per cent DS, but at a poor recovery and low throughput; however, the addition of a polyelectrolyte has enabled the throughput to be increased substantially at a better recovery rate for the same degree of thickening. For example, at Oxford[20], before the use of the polyelectrolytes, the average 'cake' solids were 4·5 per cent from a feed sludge containing 0·57 per cent DS, the solids recovery being 39·8 per cent due to the centrate containing 0·36 per cent DS. After the addition of 0·2 per cent Zetag 92 on a dry solids basis, the sludge was thickened to 4·9 per cent DS, the centrate containing only 150 mg/l SS, throughput also increased and further trials have improved upon these results.

Centrifuges of this type are also used for thickening surplus activated sludge at Saddleworth[21] where poor settling characteristics of the surplus activated sludge led to operational difficulties and odour problems. Experimental work was carried out on-site with a view to thickening the surplus sludge other than by co-settlement with the primary and humus sludges. This work led to the installation of a thickening process utilizing two centrifuges, each designed to treat 6 m^3 of surplus activated sludge per hour. The centrifuges operate continuously and are unattended outside normal daywork hours. From the experimental work the equipment was designed to process sludges at 1 per cent w/w solids and to produce a 'cake' containing 8–10 per cent w/w solids using a Zetag 92 polymer dosage of 3–5 kg/tonne dry solids. Under these conditions it was expected to maintain a SS concentration in the centrate of less than 1000 mg/l. Typical analyses are given in Table 5.

TABLE 5. TYPICAL RESULTS OF PERFORMANCE OF SADDLEWORTH CENTRIFUGE PLANT[21]

Feed rate (m^3/h)	Feed solids (per cent w/w)	Polymer dosage (kg/tonne DS)	'Cake' solids (per cent w/w)	Centrate solids (mg/l)
7	0·90	5·6	8·4	1078
6	1·31	4·9	10·8	314
6	1·06	4·6	7·5	499
6	1·02	4·9	8·9	320
6	1·16	4·2	7·7	428
7	1·24	4·5	9·0	814

Sludge feed rates up to 8 m^3/h have been used and a good cake has been produced; however, there is an indication that the percentage recovery may have decreased under these circumstances. Occasionally the solids concentration of the feed has fallen to 0·7–0·8 per cent w/w. Under these conditions it has not always been possible to achieve a good 'cake' and on one occasion only a 2–3 per cent w/w slurry was produced. Generally the centrifuges have performed as was originally predicted.

3. Aerobic Digestion of Sewage Sludge

3.1 Introduction

Aerobic digestion is the process of partial oxidation of sludges, utilizing aerobic micro-organisms supported by aeration. The purpose of aerobic digestion is to facilitate the disposal of sludge by improving filtrability, reducing solids content, and eliminating odour nuisance. At present the process has limited application in British practice[22].

3.2 Development of Process

Laboratory-scale experiments[23] have shown that with surplus activated sludge there is an initial period of 3 or 4 days during aerobic digestion when there is a fairly rapid reduction in the concentration of SS accompanied by an improvement in the filtration properties of the sludge. Prolonged aeration may further reduce the content of SS but the filtrability of the sludge may significantly deteriorate. Typically the concentration of SS in surplus activated sludge is reduced by about 30 per cent in approximately 20 days.

Experiments using full-scale digesters have been carried out to investigate aerobic digestion of a mixture of primary and humus sludges. These studies[24] showed that the process could be operated without causing smell nuisance and involved low capital costs in modifying existing tanks to operate as aerobic digesters. However, long periods of aeration (about 90 days) were required to achieve 60–65 per cent reduction of the SS content. The digested sludge was difficult to dewater on drying beds and gave off rank odours after a few days' storage unless the oxidation of about 70 per cent of the organic solids had been achieved during digestion. On the other hand, the results of other experiments using a 14 m^3 tank[25] demonstrated that surplus activated sludge, when mechanically aerated for about 11 days and subsequently allowed to quiesce, did not putrefy. To achieve this result with a mixture of primary and surplus activated sludge, it was necessary to aerate for not less than 20 days. In each case the concentration of dry solids was about 2·0 per cent.

The process has a high consumption of electrical energy (about 2000 kWh per tonne of dry solids fed to the digester) and needs to operate with low concentrations of SS (about 1·5 per cent) to avoid problems from poor mixing and inadequate aeration. There are difficulties in thickening the digested sludge because of its poor settleability.

Operation of aerobic digestion at temperatures above ambient increases the rate of oxidation of SS but might not be economical. Thermophilic aerobic digestion of sludge using oxygen has been advocated in some circumstances[26] particularly when it is necessary to reduce significantly the numbers of any pathogenic micro-organisms, but few data are available to indicate the costs of such a process.

4. Anaerobic Digestion of Sewage Sludge

4.1 Introduction

Interest in the anaerobic digestion of sewage sludge originated in the finding that when sludge was stored for long periods changes occurred, organic matter was converted into soluble and gaseous products, and the amount of solid matter to be disposed of was reduced. The first step was for the fresh sludge to pass into separate compartments of the sedimentation tank; this was followed at a later date by the introduction of a two-storey tank (Imhoff tank) in which sedimentation occurred in an upper compartment and the sludge gravitated into a lower compartment in which anaerobic digestion took place. Separate digestion was initiated by Watson[27] and O'Shaughnessy[28] at Birmingham and the process has subsequently developed from an ambient temperature process to the modern mesophilic system utilizing the gas which is produced either for heating or for power generation. Normal British practice is single-stage heated digestion in primary digesters often followed by secondary holding tanks which serve as balancing units and may enable some dewatering to be carried out prior to ultimate disposal. It is estimated[29] that about half the population of England is served by sewage works employing anaerobic digestion.

Digestion of a primary sludge reduces its organic content by 30–50 per cent, the reduction of organic matter being due to its conversion into gaseous products. The process changes a malodorous sludge into one which is relatively inoffensive, destroying grease and reducing the number of certain pathogenic organisms which are present in primary sludges. Chemically there is a marked change, and a typical comparison with raw sludge is shown in Table 1 (p. 17).

The liquor which is associated with digested sludge contains increased concentrations of soluble nitrogenous compounds (especially ammonia) as a result of the breakdown of organically-bound nitrogen, and the ready availability of these sources of nitrogen to grass and plants makes digested sludge particularly suitable for utilization on land.

The gases which are evolved during digestion are mainly methane and carbon dioxide, and on many works the gas is burnt to heat the sludge. On many larger works the gas is used for power generation, thereby enabling the plant to be independent of external power supplies.

Anaerobic digestion is associated with relatively high capital costs of providing the necessary plant and equipment. Where the digested sludge is to be dewatered mechanically before disposal there will be increased costs for conditioning chemicals and equipment, as digested sludge is less amenable to dewatering than raw sludge.

4.2 Microbiology of Process

In natural ecosystems organic matter, resulting from the waste products of metabolism or death of living organisms, is broken down by the activity of heterotrophic micro-organisms. In the presence of dissolved oxygen the breakdown is accomplished by aerobic micro-organisms (mainly bacteria and fungi and some protozoa) to carbon dioxide, water, and simple salts. This process, which is referred to as mineralization, may reduce the concentration of dissolved oxygen in the water. Many aerobic micro-organisms prefer low concentrations of dissolved oxygen and are said to be micro-aerophilic and in the presence of high concentrations of organic matter, e.g. muds and sludges, total depletion of the oxygen occurs. Under such conditions aerobic breakdown ceases and is replaced by anaerobic degradation, which finally results in the production of methane, carbon dioxide, and ammoniacal compounds. Some of the bacteria which bring about aerobic breakdown are also capable of anaerobic degradation and are referred to as facultative anaerobes, whereas other bacteria are active only under anaerobic conditions and are known as obligate anaerobes. These facultative and obligate anaerobic bacteria are both active in the sludge digestion process.

In order for the bacteria to degrade the organic matter completely, the organic molecules must first enter the bacterial cell. The macromolecules which are present in raw sludge are too large to pass through the cell membranes, hence they must first be broken down by extracellular enzymes which hydrolyze:

(i) Polysaccharides via saccharides to simple sugars;

(ii) Proteins via peptides to amino-acids;

(iii) Fats to glycerol and long-chain fatty acids.

These simpler compounds are then absorbed by specific bacteria for further breakdown. This degradation within the material takes place in two phases: (a) non-methanogenic (mostly acid formation), and (b) methanogenic (methane formation).

Non-methanogenic phase. In this phase the absorbed organic molecules are degraded by the metabolic activity within the cell mostly to saturated fatty acids, carbon dioxide, hydrogen, and ammonia, together with smaller quantities of alcohols, aldehydes, and ketones. In addition there is an increase by biosynthesis of bacterial cellular biomass. Because of the problems in anaerobic culture work, determining the relative significance of different bacteria isolated from digesting sludge presents difficulties. However, a recent review of the literature suggests that although some facultative bacteria are capable of the initial hydrolytic phase and of acid formation, they are not (as was originally thought) the major group in these phases, the obligate anaerobes probably being largely responsible. Although some species are capable of both hydrolysis and acid formation, others are only acid producers, much of the flora in digesting sludge being concerned with this phase.

Methanogenic phase. In this phase the end-products of the acid formation phase are converted by another group of bacteria, i.e. the methanogenic bacteria, which are strict obligate anaerobes, to methane and carbon dioxide. At this stage also there are further increases in cellular biomass by biosynthesis.

4.3 Biochemistry of Process

The major constituents of raw sludge are (a) polysaccharides, (b) proteins, and (c) fats, and the biochemical reactions of the overall breakdown of these basic constituents may be represented as follows:

4.3.1 Decomposition of carbohydrates

Polysaccharides
e.g. starch $(C_6H_{10}O_5)n$ → Mono- or di-saccharides, e.g. hexoses and pentoses → Glucose and similar sugars, e.g. $C_6H_{12}O_6$ → Pyruvic acid $(CH_3-\underset{\underset{O}{\|}}{C}-COOH)$
↓
Acetic acid $CH_3-\underset{\underset{O}{\|}}{C}-OH$
and higher volatile fatty acids

Very simplified representations of the breakdown of volatile acids can be shown as follows: $CH_3COOH \rightarrow CH_4 + CO_2$
acetic acid

$$4\,CH_3CH_2COOH + 2H_2O \rightarrow 7CH_4 + 5CO_2$$
propionic acid

4.3.2 Decomposition of proteins

During the hydrolysis of proteins to amino-acids many acids are produced which are converted by methane-producing bacteria to methane and carbon dioxide.

e.g. (a) $CH_3-\underset{\underset{NH_2}{|}}{CH}-COOH + H_2O \rightarrow CH_3COOH \rightarrow CH_4 + CO_2$
alanine; acetic acid $+ H^+$ $+ NH_3$ $+ CO_2$

(b) $C_3H_7O_2NS + H_2O \rightarrow CH_3COOH \rightarrow CH_4 + CO_2 + H_2O$
cysteine; $+ CO_2$ $+ H_2S$ $+ NH_3$

If the process is incomplete, certain vile-smelling compounds may be produced, e.g. mercaptans from cysteine, or indole and skatole from the amino-acid, tryptophan.

4.3.3 Decomposition of fats (lipids)

Fats are first broken down by hydrolysis to glycerol and long-chain fatty acids, the latter being further degraded largely by β-oxidation to acetic acid and thence to methane and carbon dioxide.

e.g. degradation of palmitic acid by β-oxidation.

$$CH_3(CH_2)_{12}CH_2CH_2COOH$$

$$\downarrow -H_2$$

$$CH_3(CH_2)_{12}CH = CH\ COOH$$

$$\downarrow +H_2O$$

$$CH_3(CH_2)_{12}CHOH-CH_2COOH$$

$$\downarrow -H_2$$

$$CH_3(CH_2)_{12}CO-CH_2COOH$$

$$\downarrow +H_2O$$

$$CH_3(CH_2)_{10}CH_2CH_2COOH + CH_3COOH$$

$$\downarrow \text{methane fermentation}$$

$$CH_4 + CO_2$$

Further stages of β-oxidation producing CH_3COOH at each stage

The overall degradation of a long-chain fatty acid can be represented by:

$$CH_3\left(CH_2\right)_nCOOH + nH_2O \rightarrow \left(\frac{n}{2} + 1\right)CH_4 + \left(\frac{n}{2} + 1\right)CO_2 + nH_2$$

The breakdown of glycerol can be represented by:

$$4CH_2OHCHOHCH_2OH \xrightarrow{-4H_2O} 4CH_3CH_2COOH \xrightarrow{+2H_2O} 7CH_4 + 5CO_2$$

4.4 Preliminary Treatment

The preliminary treatment of raw sludges, i.e. screening, thickening or consolidation, is discussed in Section 2.

4.5 Factors Affecting Anaerobic Digestion

The anaerobic digestion of sludge is affected by the following:

(a) composition of raw sludge
(b) method of addition of raw sludge
(c) internal mixing and circulation
(d) temperature
(e) pH value of digesting sludge
(f) solids retention period.

4.5.1 Composition of raw sludge

The constituents of a sludge which may affect digestion are (a) nutrients, (b) secondary sludges and (c) inhibitory substances.

4.5.1.1 Nutrients. The bacteria which are responsible for digestion require certain nutrients for growth, the most important being nitrogen and phosphorus. The minimum requirement for nitrogen is about 2·5 per cent of the dry organic matter in the sludge and that for phosphorus is about 0·5 per cent[30]. Sewage sludges invariably have more than adequate concentrations of nitrogen and phosphorus to meet these requirements.

4.5.1.2 Secondary sludges. Although it is possible to digest surplus activated sludge or humus sludge on their own, secondary sludges are less amenable to digestion than primary sludge mainly because they contain more water and a lower proportion of fermentable matter per unit mass of total organic matter. Experiments[31] have shown that the proportion of organic and volatile matter in activated sludge which is destroyed by digestion is about 30 per cent as compared to about 50 per cent in most primary sludges. The gas yield per unit weight of organic and volatile matter destroyed is about the same as with primary, or mixed primary and secondary sludge[32].

4.5.1.3 Inhibitory substances. A large variety of chemicals are inhibitory to anaerobic digestion and if present in the sludge at certain critical concentrations may cause either difficulties in maintaining the process or complete failure of digestion.

In practice, there are three main classes of inhibitory material which are likely to cause problems: (i) heavy metals, (ii) halogenated hydrocarbons, and (iii) anionic detergents.

(i) *Heavy metals.* In the WPRL survey[29] it was found that heavy metals were the most common single cause of inhibition of digestion. The concentrations of heavy metals in digesting sludge which caused a 20 per cent reduction in gas production in laboratory experiments, together with typical concentrations, are shown in Table 6.

TABLE 6. CONCENTRATIONS OF HEAVY METALS IN DIGESTING SLUDGE WHICH CAUSE A 20 PER CENT REDUCTION IN GAS PRODUCTION IN LABORATORY EXPERIMENTS[35]

Metal	Batch digesters: concentration (mg/kg dry solids)	Typical concentration in digested sludges (mg/kg dry solids)
Nickel	2000	30–140
Cadmium	2200	7–50
Copper	2700	200–800
Zinc	3400	500–3000

The effect of the presence of a heavy metal depends upon its solubility and will therefore vary with the pH value of the digesting sludge and the concentration of sulphide present.

More recent work[33] has shown that where a number of different heavy metals are present, as is invariably the case, the inhibitory effect is additive on an equivalent weight basis. Therefore if the concentrations of zinc, nickel, lead, cadmium, and copper in a sludge (mg/l) are (Zn), (Ni), (Pb), (Cd), and (Cu), respectively, the total concentration of metals, K, may be expressed as a milligram equivalent weight (meq) per kg dry sludge solids, using the following formula:

$$\underset{(\text{meq/kg})}{K} = \frac{(\text{Zn})/32{\cdot}7 + (\text{Ni})/29{\cdot}4 + (\text{Pb})/103{\cdot}6 + (\text{Cd})/56{\cdot}2 + (\text{Cu})/47{\cdot}4}{\text{Sludge solids concentration (kg/l)}}$$

It has been shown[33] that where the sludge value of K is greater than 400 meq/kg the probability of digestion remaining unaffected is 50 per cent; where the value of K is greater than 800 meq/kg there is a 90 per cent probability of digester failure. In order to obtain a 90 per cent probability that digestion will not be affected, the value of K should be less than about 170 meq/kg.

(ii) *Halogenated hydrocarbons.* Chlorinated hydrocarbons are widely used in industry and for dry cleaning, and their accidental discharge to the sewer has resulted in complete failure of digestion at some sewage-treatment works. Their effect on digestion depends upon a number of factors[34] but mainly on the concentration of dry sludge solids (mg/kg). Chloroform is the most toxic of this class of compounds and it has been shown[34,35] that where its concentration in sludge is as low as 10 mg/kg some inhibition is detectable, with about 20 per cent inhibition occurring at 15 mg/kg. Concentrations of the most common chlorinated hydrocarbons which, if present in digesting sludge, are likely to cause 20 per cent inhibition are shown in Table 7.

TABLE 7. CONCENTRATIONS OF CHLORINATED HYDROCARBONS IN DIGESTING SLUDGE AT WHICH 20 PER CENT INHIBITION OCCURS (IN EXPERIMENTAL STUDIES[34])

Chemical	Concentration (mg/kg dry solids)
Chloroform	15
Trichlorethane	20
1, 1, 2 trichlorotrifluoroethane	200
Carbon tetrachloride	200
Trichloroethylene	1800
Tetrachloroethylene	1800

However, the micro-organisms which are responsible for digestion can become acclimatized to higher concentrations of halogenated hydrocarbons. Also with chloroform a considerable proportion of that entering a digester is lost by volatilization[36,37]. An appreciable proportion of any chloroform which is discharged to a sewer is also likely to be lost from the sewage by volatilization before reaching the sewage-treatment works. If necessary, stripping of chloroform from sewage or sludge using air can be carried out, but it is desirable to remove the chloroform by this method from an industrial effluent before discharge to the sewer.

The toxicities given in Table 7 serve as a guide but it must be pointed out that the inhibitory effect of, say, chloroform and anionic detergents is additive[36].

(iii) *Anionic detergents.* These are the detergents most commonly used in household washing powders and they are invariably present in domestic sewage and also in sludges since they adsorb strongly onto solids. Studies[38] have shown that gas production by a digester may be reduced significantly when the concentration of anionic detergent (expressed as Manoxol OT) in the feed sludge is about 1·5 per cent on dry sludge solids.

However, acclimatization to this concentration can occur and serious inhibition is likely only when the concentration reaches 2·0 per cent on dry solids. The presence of anionic detergents at concentrations above 1·5 per cent also greatly reduces the tolerance of the process to temporary overloading or other adverse conditions. With regard to toxicity to anaerobic digestion, it has been shown[35] that there is no significant difference between 'hard' and 'soft' anionic detergents, and neither type is destroyed by the process; consequently the concentration of detergent on dry sludge solids is increased by digestion.

If inhibition is caused by anionic detergents it can be reasonably quickly remedied by chemical neutralization of about half the anionic material with certain cationic materials. Stearine amine[39] is generally used and recovery may be hastened by adjusting the pH value of the digester contents to about 7·0.

The inhibitory effect of non-ionic and cationic detergents, both of which may be present in sludges, is normally very slight even at high concentrations[38].

4.5.2 Method of addition of raw sludge

Ideally, raw sludge should be fed continuously into a digester either from a primary sedimentation tank or, preferably, after consolidation or thickening. However, in practice this is not feasible, therefore sludge should be added to the digester as frequently as possible, thereby avoiding large fluctuations in gas production.

4.5.3 Mixing and circulation

The purposes of mixing and circulation are (a) to promote intimate contact of raw and digesting sludges, (b) to maintain a uniform temperature and solids mixture throughout the digester, (c) to discourage scum layer formation and grit settlement, and (d) to facilitate the release of gas from sludge in the lower regions of the digester. Inadequate mixing and circulation of the contents of a digester can lead to the withdrawal of incompletely digested sludge and stratification within the digester.

4.5.4 Temperature

A uniform and sufficiently high temperature is essential for satisfactory operation. Three forms of digestion are distinguished according to the range of temperatures which is employed: (i) cold digestion at temperatures less than 20°C, (ii) mesophilic digestion within the range 20–40°C, and (iii) thermophilic digestion within the range 40–50°C.

Digestion at ambient temperatures (cold digestion) is practised at many small works. However, since the process is slow at temperatures below 20°C the mesophilic range is normally employed and the preferred operating range is 30–35°C. Thermophilic digestion is not practised in the UK.

When a heated digester is operating near its maximum loading a prolonged decrease in temperature will affect its performance. Normal weekly variations of a few degrees do not cause any adverse effects but on some plants it is normal to ensure that the temperature is near the top of the preferred range before the onset of winter.

4.5.5 pH value

A pH value of 7·0–7·5 is usually required to encourage the methanogenic phase.

The activity of the non-methanogenic bacteria, by producing acids, tends to reduce the pH value. However, in a well-functioning digester an equilibrium is maintained by the buffering action of the bicarbonate alkalinity resulting from the degradation of protein.

If the digesting sludge becomes acidic, it may be necessary to adjust the pH value to within the above range by addition of alkali (see para. 4.8.2.4). This, however, is a palliative measure and unless the cause, e.g. overloading or toxicity, is remedied, acid conditions are likely to be re-established.

4.5.6 Solids retention period

The average period during which solids are retained in a digester is a crucial factor with regard to performance. If the average retention period is less than about 12 days there is a substantial danger that the slow-growing methanogenic bacteria will be washed out and the process will fail completely. In practice, much longer retention periods (i.e. 25–30 days) are usually provided for in design; this retention period allows for some build-up of grit on the base of the digester to occur without approaching the minimum retention period too closely. Even when a full retention period is provided for a sludge of normal solids content, any significant increase in the water content of the sludge could reduce the retention period to such an extent that the process would be in danger of failing.

4.6 Primary Digesters

4.6.1 Types

Primary digesters are usually covered for the collection of gas. Heating and mixing of the digester contents are normally achieved using one of the following techniques: (i) central screw mixing pump and external heat exchanger; (ii) circulating pumps and exchangers housed in projecting chambers; (iii) external circulating pump and heat exchanger, e.g. in adjacent heater house, (iv) internal gas-lift pumps and external heating units, and (v) internal gas recirculation and heating units.

4.6.2. Design criteria

4.6.2.1 Digester capacity. The basic requirement is to provide sufficient digester capacity to ensure an adequate retention period for the sludge. It is normal practice, based on long experience, to design for about 25 days average retention period although some designers prefer to allow closer to 30 days to provide a greater safety margin in the event of inadequate mixing in the digester or a considerable variation in daily sludge loadings. In theory at least, retention periods as low as 7–10 days are adequate for satisfactory primary digestion but such short retention periods in full-scale digesters would leave very low safety margins in the event of operational difficulties. However, with improvements in mixing and heating systems, it might be expected that designers will reduce retention periods nearer to 20 days.

Where digesters are being designed before a works is actually built, or where there is no information available about the volume of raw sludge produced at an existing works, the required capacity of digester can be calculated on the basis of the population served. Where industrial effluents are discharged, of course, the population equivalent (based on sludge) must be used. The normal assumption is that 1·8 l of raw sludge containing 4·5 per cent dry solids will be produced daily per head of population. Therefore to allow for a retention period of 25 days, the total capacity of a digester would be:

$$\frac{1{\cdot}8 \times 25 \times \mathrm{N}}{1000}\ \mathrm{m}^3$$

where N is the equivalent population to be served by the digester.

4.6.2.2 Organic loading. The organic loading on the digester which is usually expressed as kg organic and volatile matter/m^3, is not an appropriate design parameter for sewage sludge digesters although it is not uncommon to see it quoted in the literature as the main basis for design. With a retention period of 25 days and a typical sludge feed of 4·5 per cent total solids containing 82 per cent organic and volatile matter, the organic loading on the digester would be 1·5 kg/m^3 day. This is the "design" organic loading which is often quoted in the literature. However, the danger with the use of organic loading as a design parameter comes in the case of very thin sludges where, in order to achieve the above organic loading, a retention period much lower than the required retention period would have to be employed.

The WPRL survey[29] showed that the organic loading range was from 0·27 to 2·76 kg volatile matter/m^3 day (Table 8). This demonstrates that organic loading is a singularly inappropriate design parameter for sewage sludge digesters.

TABLE 8. LOADINGS OF HEATED SLUDGE DIGESTION INSTALLATIONS

Number of installations	Loading (kg volatile matter/m^3 d)
23	0·27–0·77
46	0·77–1·27
22	1·27–1·76
8	1·76–2·26
5	2·26–2·76

The overall weighted mean loading was 1·55 kg/m^3 d.

4.6.2.3 Shape of digester. Most digesters are circular in plan with a maximum diameter of 25 m. Designers now recognize that there is a minimum depth, the ratio of the depth of the side wall to diameter being generally within the range 1:3 to 1:2; on small installations the ratio tends towards 1:1. Normally, the base of the tank is conical having a floor angle between 12° and 30°, and a draw-off pipe should be provided to allow heavier settled particles to be withdrawn. Withdrawal of the heavier material can be expedited if the draw-off is connected to a positive-displacement pump with facilities for back-flushing into the tank. It is good practice to build an inspection access into the base of the side wall to simplify entry when the digester is emptied for maintenance.

4.6.2.4 Sludge mixing and circulation. There are three basic methods of mixing and circulation:

(i) *Central screw mixing pump* (*Fig. 7*). The Simplex system, which can be used with a fixed or floating cover (Plate 1), consists of a screw pump located in the top of a vertical uptake tube. The contents of the tank are circulated by drawing up sludge from a low level and spraying it over the surface, thereby ensuring that scum build-up is controlled; at predetermined intervals the pump is reversed for a short period to improve

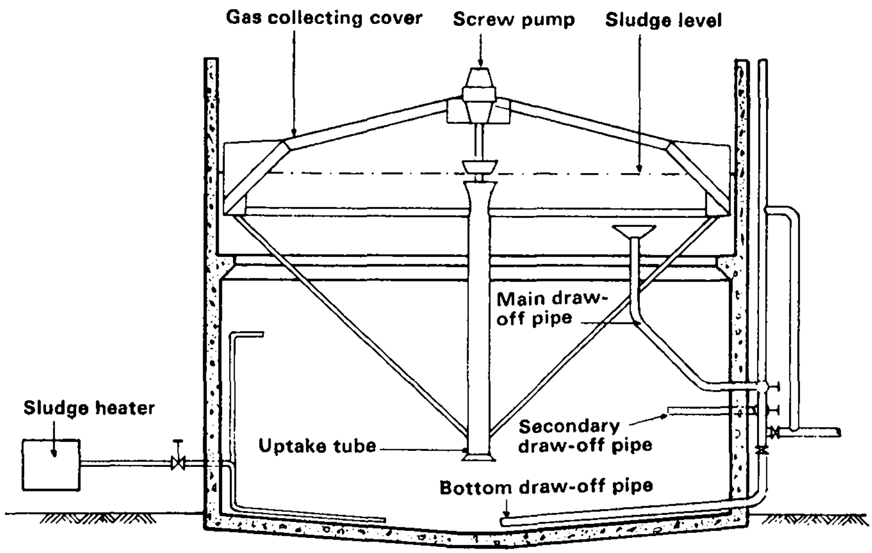


Fig. 7. Primary digestion tank with screw mixing pump and external heater.

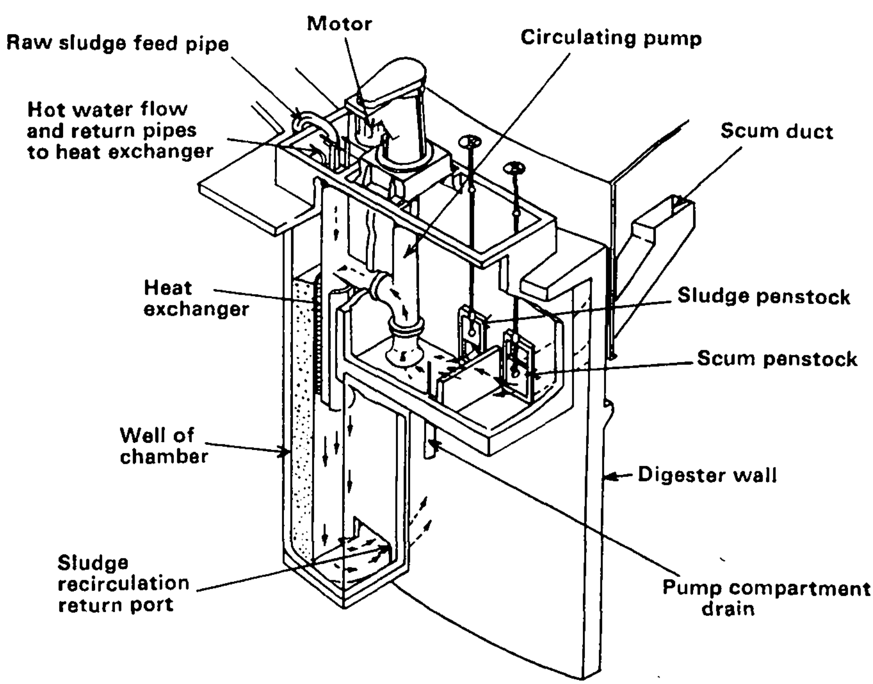


Fig. 8. 'Limpet' type external heat exchanger and sludge circulation unit.

mixing and to prevent blockages. In addition to the mixing system, sludge is drawn off above the base of the digester and is returned to the surface after passing through a heat-exchanger unit; this action improves the circulation of the sludge within the digester.

(ii) *Circulating pumps housed in projecting chambers (Fig. 8, also Plates 2 and 3)*. In this system the sludge is normally withdrawn from the digester by an axial-flow pump in the external 'limpet' and is re-introduced to the digester at a lower point through a tangential inlet. A heat-exchanger unit surrounds the down-take pipe. Any scum-forming material can either be withdrawn and recirculated or removed from the system through a drain in the circulating compartment.

(iii) *Internal gas-lift pumps*. There are two proprietary systems employing this method: in one, i.e. the Burper-mixer' (Plate 4), large pulses of gas are discharged at the base of the uptake tube and the upsurge which is created by the gas 'bubble' ascending the uptake tube (Fig. 9) distributes large volumes of digesting sludge over the surface.

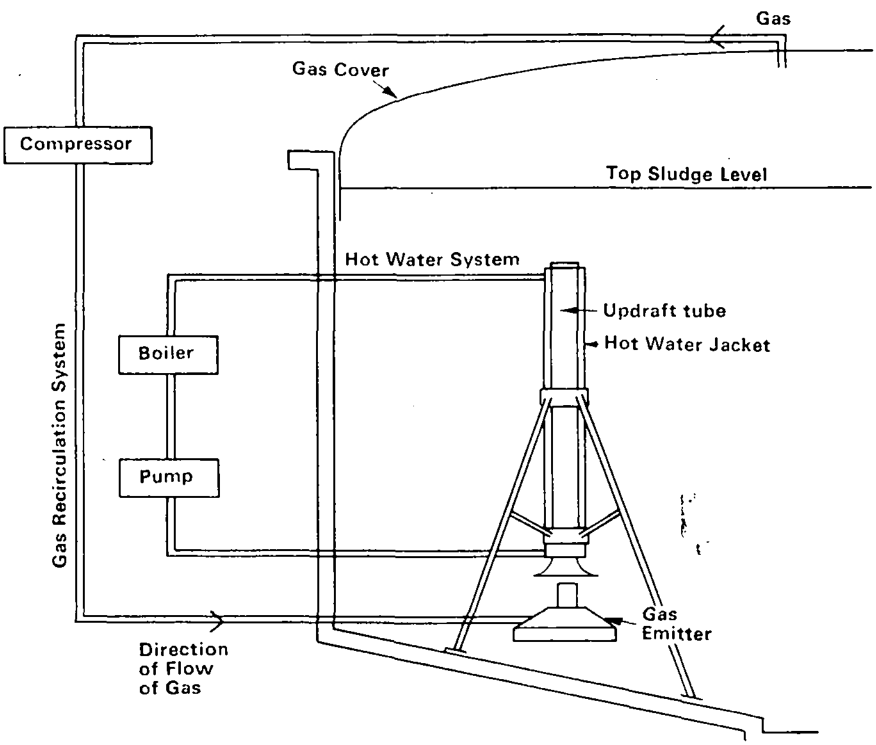


Fig. 9. Arrangement of 'Burper-mixer' sludge circulation plant.

Gas recirculation is also encountered in the 'Heatamix' unit (Fig. 10 and Plate 5) which both heats and circulates the contents of the digestion tank. It consists of a hot water jacketed uptake tube through which digesting sludge is continuously lifted and discharged over the surface. For small tanks a single, centrally-mounted unit is sufficient. Larger tank units are either mounted individually at the centre or commonly employ four symmetrically-arranged externally-mounted units.

4.6.2.5 Scum removal. Whatever type of mixing system is installed, it is inevitable that some scum will form on the surface of the digesting sludge. Scum build-up is undesirable as it reduces capacity and also inhibits the

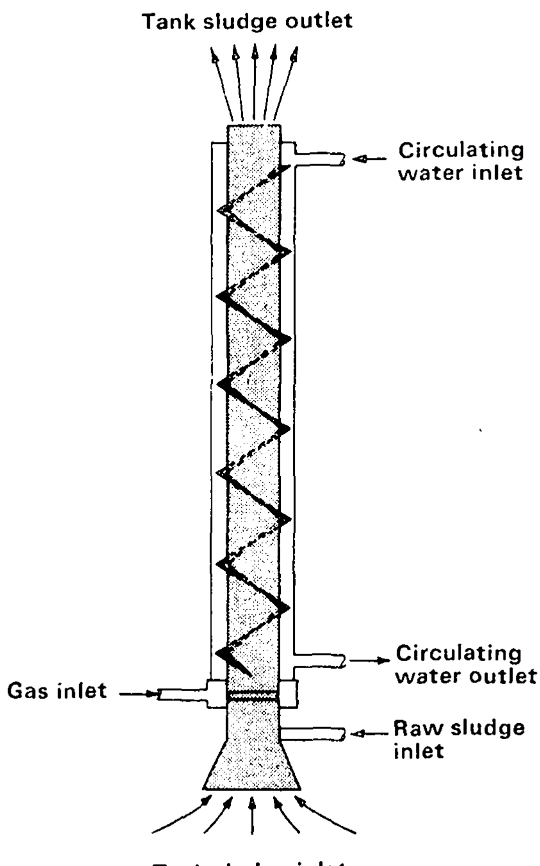


Fig. 10. Principle of 'Heatamix' unit.

release of gas. By the provision of a high-level outlet in the tank, fitted with a scum duct (or trumpet), scum can be removed when the level of the sludge is raised.

4.6.2.6 Grit removal. Some grit will settle out at the base of the digester and this has to be removed before the build-up becomes so excessive that it decreases the digester capacity and makes removal extremely difficult. Grit draw-off pipes should be connected to the base of the digester, and grit removal can be carried out if these can be connected to a ram pump having the facility for 'back-flushing'.

4.6.3 Heating equipment

Heat-exchange units can be incorporated either within the sludge circulating system or as a separate circuit. Whatever method is employed, heating is provided from a boiler which burns either the methane gas or an alternative fuel. Flame traps are essential on the pipework in order to prevent boiler blow-back, and it should be borne in mind that flame traps should preferably be made of stainless steel since copper tends to corrode.

In order to reduce heat losses, the digester and pipework should be insulated; if losses are too high, additional sources of heat may be required to ensure that the temperature of digestion is maintained. A common method of insulating a digester is to build it partially below ground level and use the excavated material to form banks around the tank, or alternatively, use insulated cladding. However, insulating with damp earth, or where there is hydraulic continuity with groundwater, could cause greater losses than without such 'insulation'.

A heat exchanger used in conjunction with a sludge digestion plant may be: (a) a concentric tube sludge/hot water heater, (b) a spiral tube sludge/hot water heater, or (c) a gas-fired multi-tube heater.

4.6.3.1 Concentric-tube sludge/hot water heat exchanger. This, the simplest form of heater, consists of two co-axial tubes with the sludge flowing through the inner tube and hot water through the outer tube in opposite directions. Experience has shown that the inner tube must be at least 100 mm diameter, which reduces the likelihood of blockages but gives less efficient heat exchange.

4.6.3.2 Spiral-tube sludge/hot water heat exchanger. The Rosenblad heat exchanger has narrow spiral passages, the casing being circular with flat sides. An advantage of this type of heater is that, with the sludge flowing in a curved

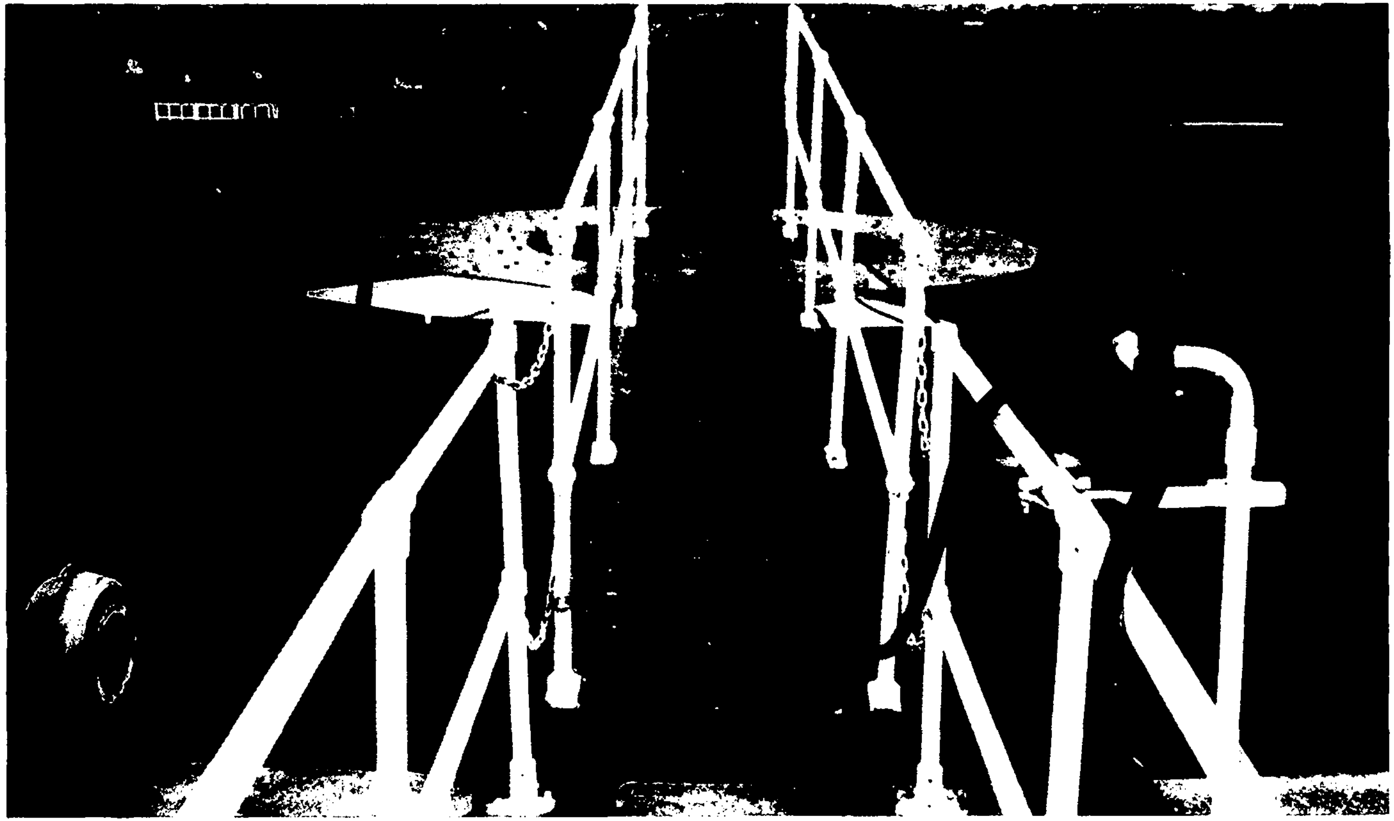


Plate 1. View of top of Simplex type digester at Aldwarke, Rotherham

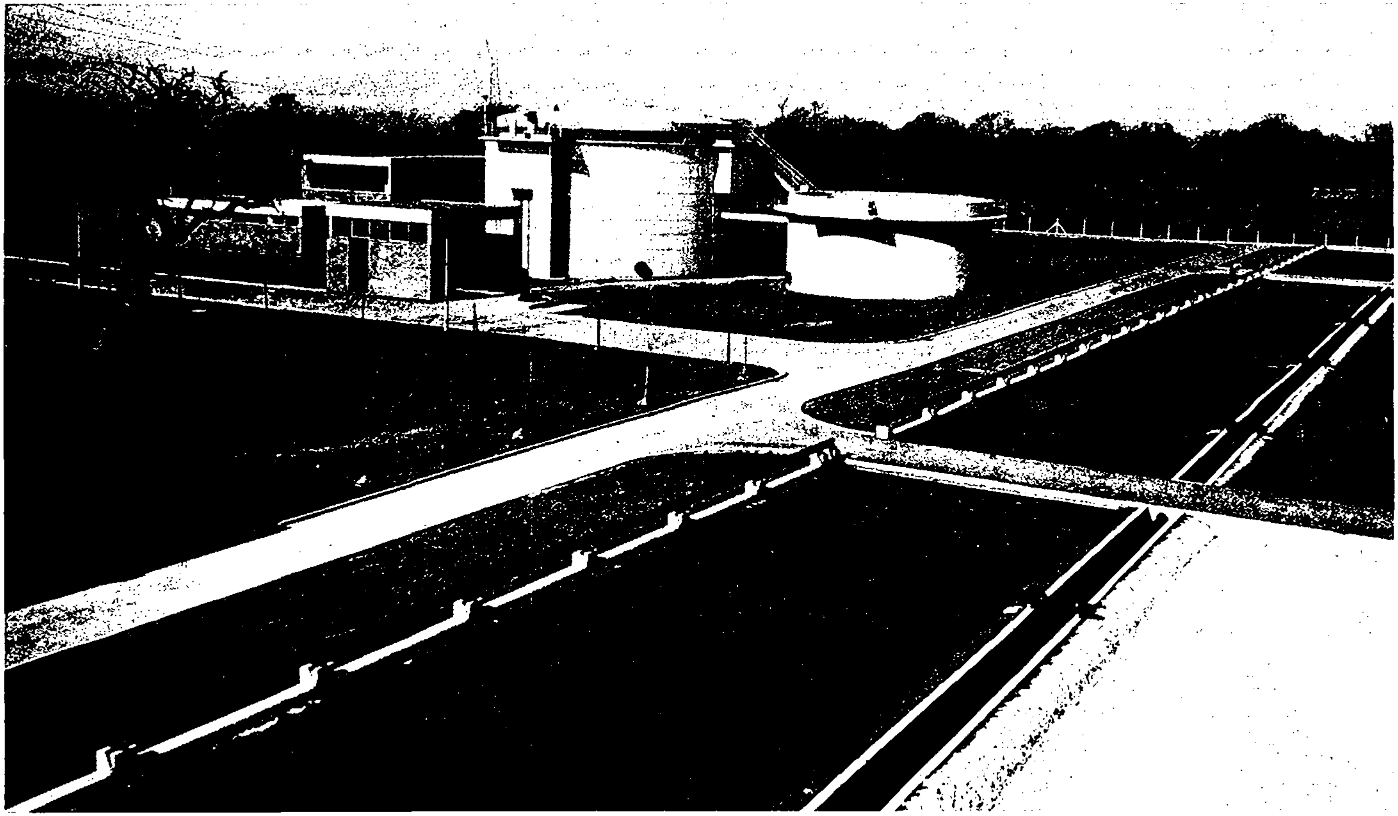


Plate 2. Primary and secondary digesters at Berry Hill, Bournemouth.

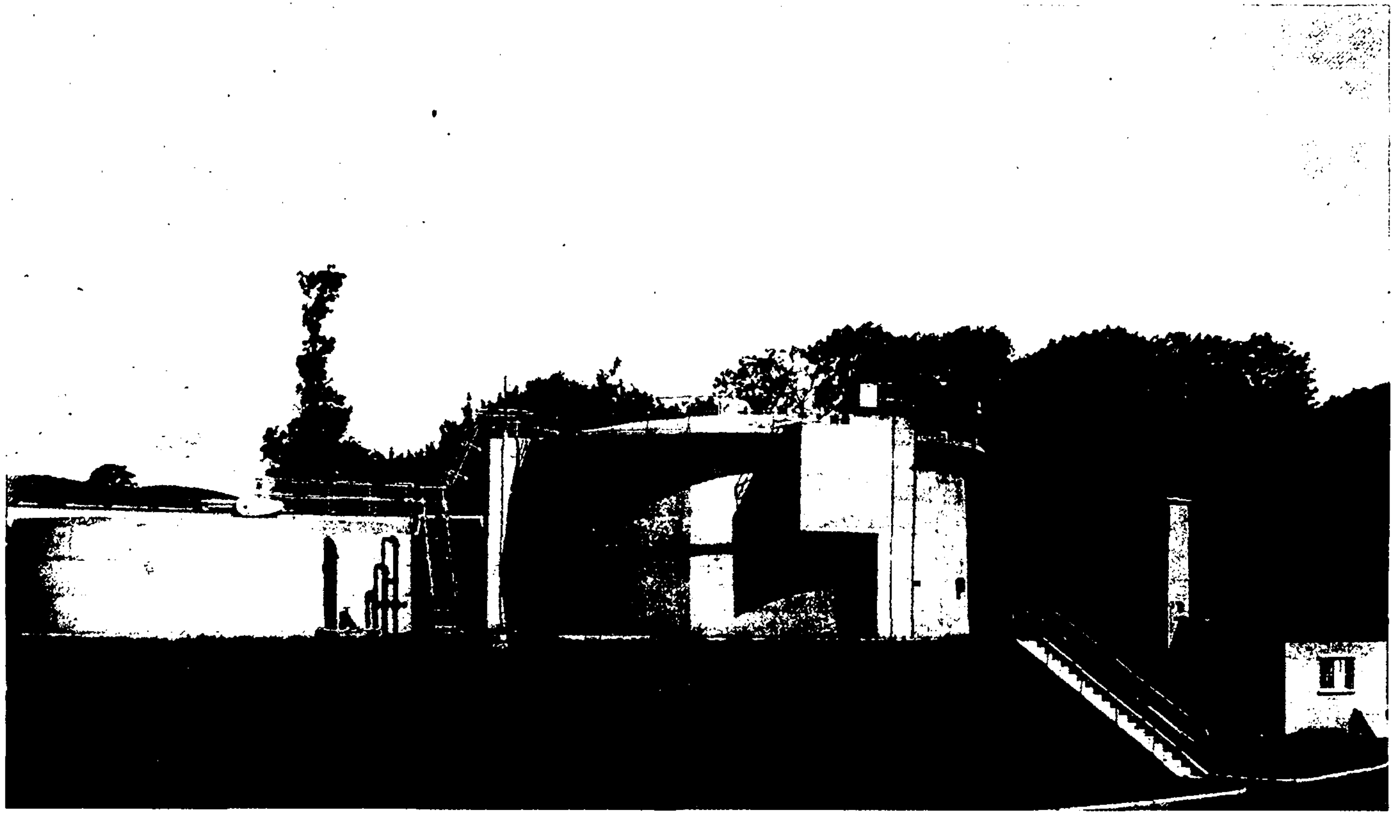


Plate 3. Sludge digestion plant incorporating 'limpet' type heat exchangers at Dunmurry.

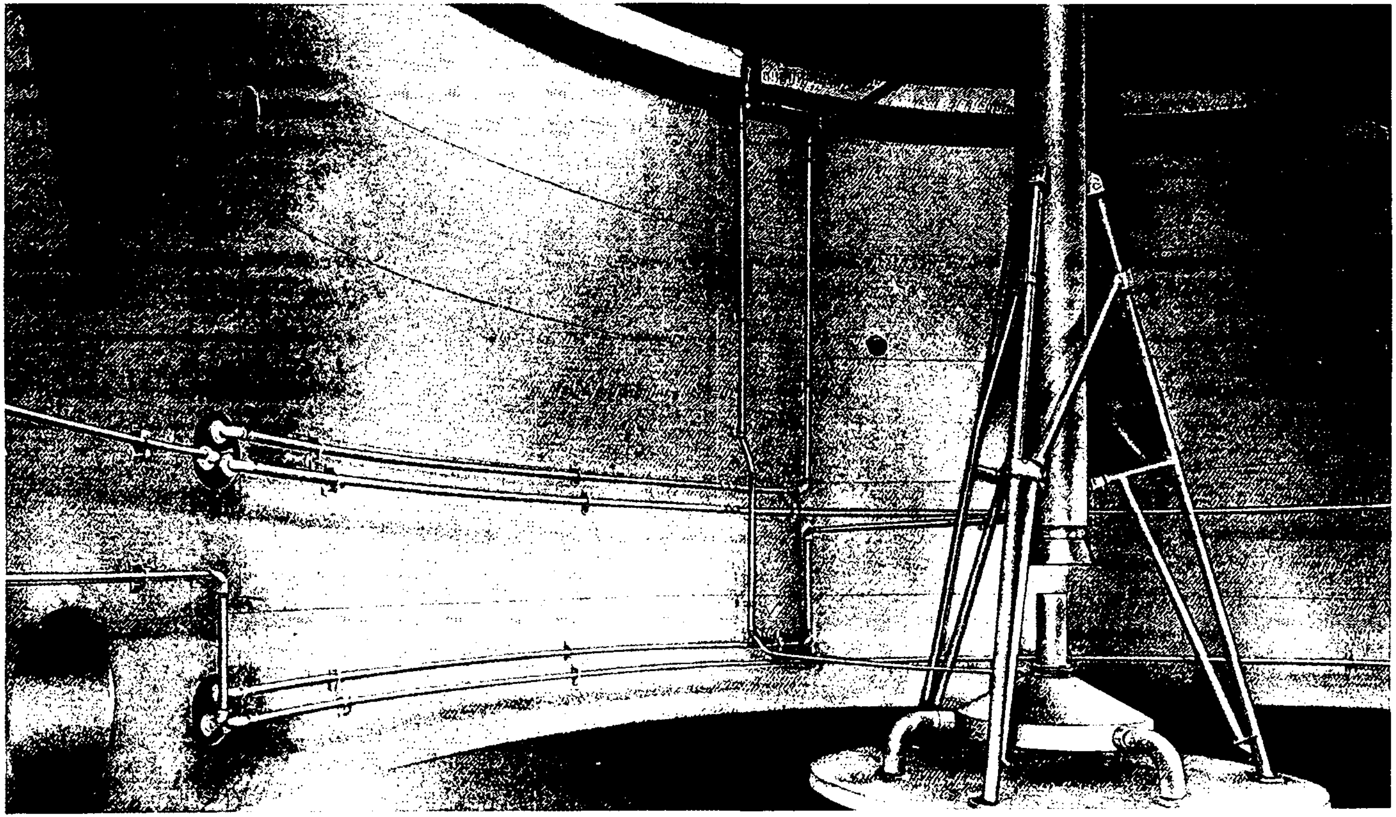


Plate 4. Arrangement of 'Burper-mixer' in sludge digester.

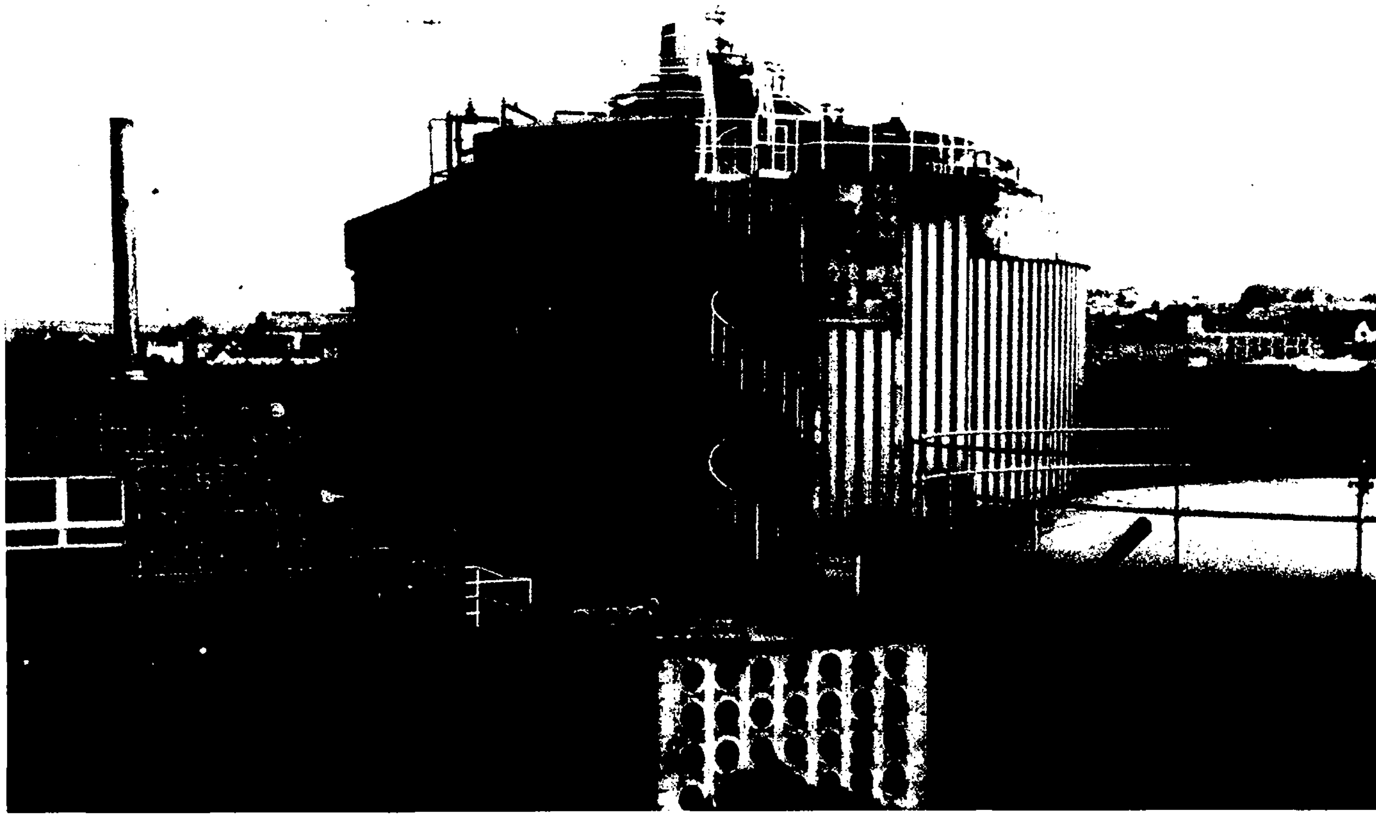


Plate 5. 'Heatamix' units on mesophilic sludge digestion plant at Swinton, Yorkshire.

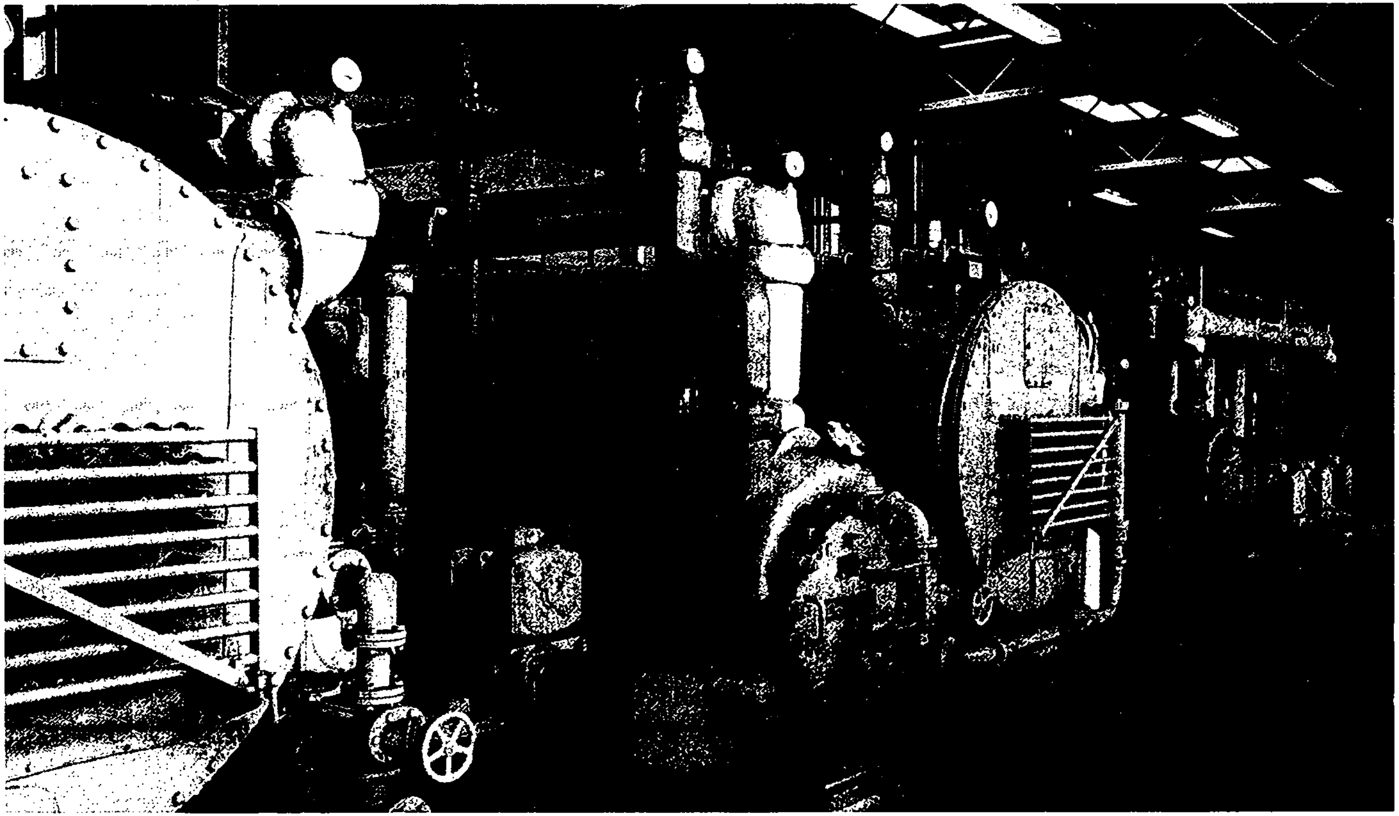


Plate 6. Installation showing gas-fired multi-tube heating units.

Plate 7. Dual-fuel engines at Hogsmill Valley sewage-treatment works.

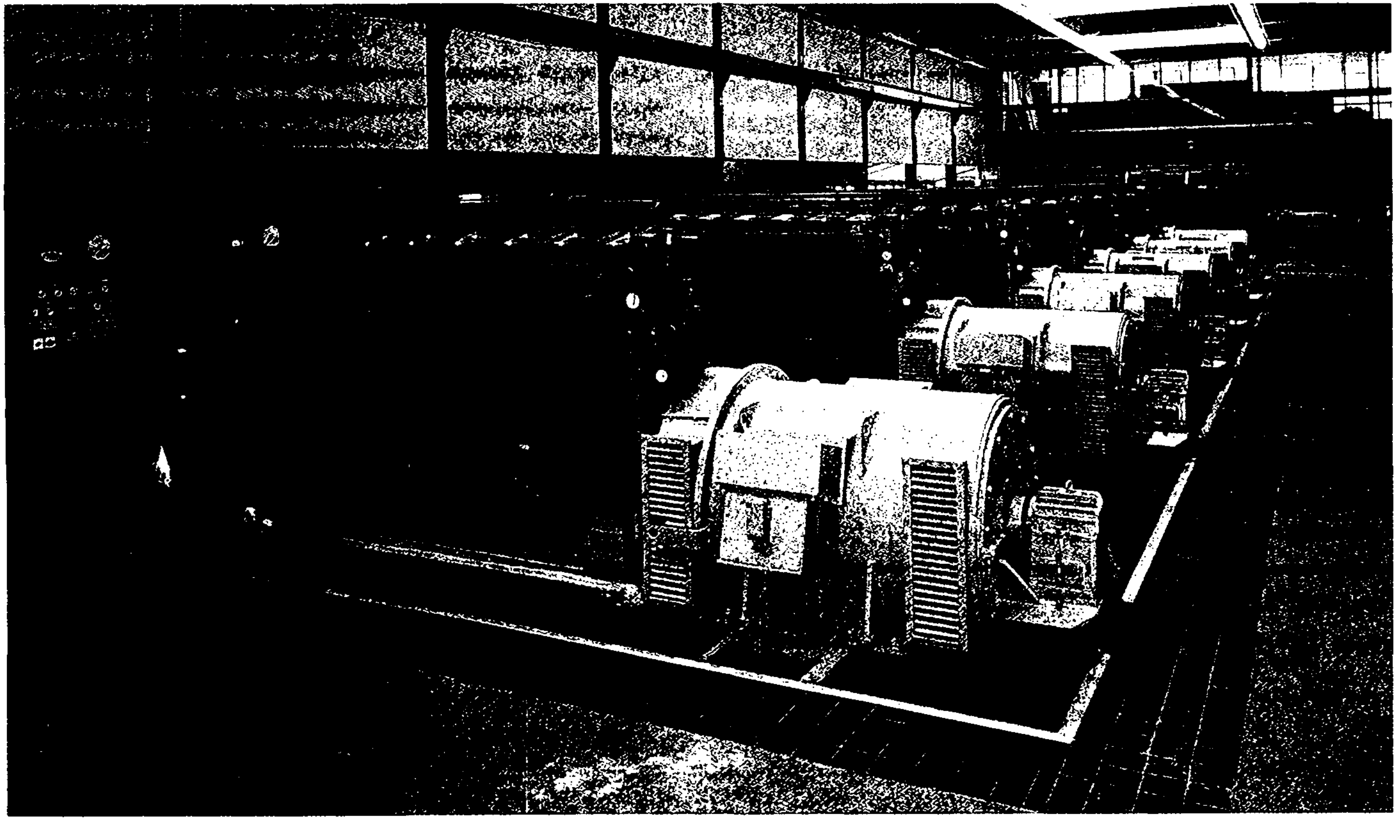


Plate 8. Power house at Croydon's Beddington sewage-treatment works.

path, turbulence is increased which facilitates mixing and results in an increased rate of heat transfer.

4.6.3.3 Gas-fired multi-tube heater. (Plate 6.) In this unit the sludge flows through a helical tubular coil mounted in a hot-water jacketed cylindrical body. Heat is supplied to the unit via a series of horizontal tubes each containing a burner, thereby indirectly heating the sludge.

4.6.4 Covers

Covers may be either fixed or floating, but whatever type is used adequate precautions must be taken to prevent the ingress of air into the gas space which would produce an explosive mixture.

4.6.4.1 Fixed covers. With a fixed cover the space between the surface of the sludge and the underside of the cover must be connected to a separate floating gas holder so that gas can move freely both ways between the cover and the holder. Unless this freedom of movement is provided a vacuum would be caused when sludge is removed from the digester.

4.6.4.2 Floating covers. Floating covers normally act as their own gas holders and rise and fall according to the volume of enclosed gas and sludge. As with other gas holders, the cover is equipped with guide rails; in circular digesters it assumes a spiral motion as it rises and falls.

The skirt of a floating cover may be up to 4 m deep, with sludge between the skirt and the tank wall forming a seal through which gas escapes only if the cover rises above the level at which an alarm is actuated. Whatever type of cover is provided, it should be fitted with: (a) several airtight manholes to provide an access and ventilation facility when emptying the digester, (b) several windows, with scrapers on the underside through which the digesting sludge may be inspected to check on gas evolution and scum build-up, (c) a vacuum and pressure-relief valve, protected by flame traps, to prevent damage being caused by a vacuum which could cause collapse of the cover or by excess pressure, (d) connexions to enable the gas to be sampled for analysis. Additionally, floating covers are fitted with limit switches to warn if the cover is at either the maximum or minimum permitted level.

4.6.5 Gas holders

A separate gas holder, which is used in conjunction with a fixed cover, is normally built to store gas and to balance supply and demand. Where dual-fuel engines are installed and the production of power is reasonably uniform throughout a period of 24 h, a storage capacity of 4–6 h is sufficient; however, with some digesters and where dual-fuel engines operate on a widely fluctuating power load a storage capacity of at least 10 h must be provided. Separate gas holders are more subject to corrosion than floating covers; this may be minimized by maintaining a layer of oil on the surface of the water-seal which will prevent the transfer of oxygen from the atmosphere into the exposed area of the water. It is also advisable to provide means for the prevention of freezing of water-sealed gas holders in cold weather[13].

4.6.6 Gas detectors

In control rooms, operating galleries or heater rooms it is recommended that the concentration of methane in the air should be monitored continuously, with an alarm operating if this reaches dangerous proportions (see para. 4.14.3.4). Gas detection devices include the following types:

4.6.6.1 Ringrose. The Ringrose detector is designed to carry out atmospheric tests for combustible and explosive gases such as methane, and asphyxiating gases such as carbon dioxide. In addition to these duties the lamp gives a separate indication of which group of gases is present. The presence of H_2S is indicated by the blackening of lead acetate paper, and the instrument incorporates two detector heads: one for combustible and explosive gases (containing a heated filament in a porous wall chamber) and one for asphyxiating gases (containing soda lime crystals). Any resulting reduction of pressure acts on a diaphragm which closes the contacts of an electrical circuit and shows a red warning light. The power is supplied by a 2–volt accumulator, and the concentrations of various gases at which a signal is given are shown in Table 9.

TABLE 9. RINGROSE DETECTOR LAMP: DANGER SIGNALS

Gas or vapour	Explosive limits		Per cent at which signal is given
	Lower limit (per cent)	Upper limit (per cent)	
Methane	5·0	15·0	1·0
Hydrogen	4·1	75·0	0·75
Domestic gas	5·3	31·0	0·75
Benzol	1·5	8·0	1·0
Petrol vapour	1·7	6·0	1·0

N.B. The presence of more than 2·5 per cent CO_2 causes the atmosphere to become asphyxiating, and the Ringrose detector signals danger at 1·5 per cent CO_2.

4.6.6.2 Spiralarm. This detector, which is a development of the original Davy lamp used in coal mines, automatically indicates the presence of combustible or explosive gases. When these gases are present the continuously burning flame increases in height causing a bi-metallic strip assembly to unwind and carry a striker pin to an electrical contact. A red warning lamp receives energy from a 2·5-volt battery, and when the concentration of O_2 in the atmosphere (20·8 per cent) falls to 17 per cent or less the flame is extinguished.

4.6.6.3 Combustible gas detectors. These are battery-powered instruments based upon the Wheatstone Bridge principle which, when the atmosphere to be sampled is drawn through a filament chamber, registers the concentration of explosive gas.

4.6.6.4 Automatic gas monitors (AGMs)[40]. These monitors automatically sample the atmosphere every few minutes and give an early warning of any potentially dangerous build-up of gases well below the lowest possible dangerous level. The principle of operation of these monitors can be illustrated by the Neotronics monitor as an example:

(a) *OTOX 80 hydrogen sulphide detection.* Brown coloured lead sulphide is formed on white lead acetate impregnated paper at a rate which is related to the concentration of hydrogen sulphide present. This simple reaction is used within the OTOX 80 to initiate an alarm at a pre-set colour density of stain.

(b) *Oxygen deficiency function of OTOX 80 monitor.* An electro-chemical sensor is used within the OTOX 80. This takes the form of a battery-like cell with its cathode exposed to the atmosphere through a fine capillary. Oxygen molecules are converted to hydroxyl ions on the surface of the cathode and cause a change of voltage between the anode and cathode, which is proportional to the per cent by volume of oxygen in the atmosphere.

An alarm level, which is set at 17·5 per cent oxygen, is actuated within 60 sec for a step change from normal air (21 per cent) to 17·5 per cent; the lower the oxygen level the faster the rate of response of the OTOX 80 monitor.

(c) *Hot catalytic sensing used in the AGM monitor for flammable gas detection.* Nearly all gases which will burn in air are detected in automatic gas monitors. A hot bead incorporating a palladium catalyst (known as a pellistor) is exposed in a flame chamber to the atmosphere. Any flammable gas will burn on the surface of the bead and cause an increase in temperature which is proportional to the concentration of gas. The resistance of the pellistor will therefore increase with increasing gas concentrations, this resistance change being sensed using a conventional Wheatstone Bridge circuit.

Use of digital logic in gas monitors. All the signals which are generated by the opto-electronic, electro-chemical and pellistor bridge outputs can be treated digitally by the use of computer type logic. The use of such logic eliminates circuit drift functions which, in other types of electrical instrumentation, result in serious changes of performance. A further advantage imparted by digital logic is the ability to ensure that any component or transducer failure will provide an automatic alarm indication, thereby making the instrument failsafe.

4.6.7 Monitoring equipment

In some part of the installation, either in the boiler house, the pumphouse or the operating gallery, it is usual to install equipment for (a) indicating/recording temperature of digestion, preferably at different depths; (b) indicating/recording rate flow and temperature of water and sludge before and after the heat-exchange unit; (c) recording volume of gas used and vented to atmosphere; (d) recording the quality of gas. The latter can be either a methane monitor or a calorific value monitor.

4.6.8 Pipework

It is essential that all pipes and valves are labelled and colour-coded to prevent mishaps from wrong valves being opened. Some of the pipes can be colour-coded as per BS.1710:1971 but a system has to be devised for the remaining pipes.

4.6.9. Installations of primary digestion tanks

Table 10 gives particulars of some installations of primary digestion tanks in the UK.

4.7 Secondary Digestion (or Storage) Tanks

Although generally known as secondary sludge digestion tanks these are normally used for sludge storage purposes.

4.7.1 Purpose

The purpose of secondary digesters is: (a) to act in a balancing and storage capacity, regularly receiving sludge from the primary digesters and supplying

TABLE 10. INSTALLATIONS OF PRIMARY DIGESTION TANKS

Works	Commissioned	Population served (× 10³)	Sewage flow (tcmd)	Sludge	Number	Diameter (m)	Depth of side wall (m)	Depth at centre (m) or floor slope	Mixing	Heating	Sludge scraper	Cover	Combined capacity (tcm)	Equivalent to (m³/person)	Reference
Aylesbury	1963–74	60	15·0	PH	3	11·3/17·0	6·4/8·5	20°/30°	CD	External	No	Fixed	3·4	0·06	41
Barnsley	1961	75	18·2	PH	2	16·7	8·1	3·5	AB	External	No	Floating	4·1	0·05	42
Bracknell	—	60	16·7	PH	3	12·2	6·5	9·8	AD	External	No	Floating	2·5	0·04	42
Coventry	1953 1964	385 —	100 —	PAH PAH	4 4	18·3 18·3	11·0 11·0	30° 11·2	B B	External External	No No	Floating Floating	8·1 6·8	— —	43 44
Hatfield	1967	15	4·5	PH	2	9·1	8·4	30°	B	External	No	Floating	1·0	0·06	45
Leicester (Wanlip)	1965	300	102	PA	4	22·9	8·4	27°	D	Heatamix	No	Fixed	19·1	0·05	46
London (Beckton)	1959 1966	— 2279	— 1009·5	PA PA	16 16	24·4 24·4	9·8 10·0	9° 30°	B B	External External	No No	Floating Floating	146·0	0·06	47
London (Crossness)	1964	1533	594·5	PA	16	24·4	7·2	13·5	AB	External	No	Floating	61·8	0·04	47
London (Deephams)	1964	683	206·5	PA	12	21·3	10·9	30°	AD	External	No	Floating	54·5	0·08	47
London (Hogsmill Valley)	1957	201	59·2	PAH	4	18·2	9·7	22·9	AB	External	No	Floating	11·5	0·06	47
London (Mogden)	1935–66	1319	519·3	PA	20	21·3	10·0	30°	E B	Internal External	No No	Fixed Floating	79·7	0·06	47
London (Riverside)	1968	339	99·3	PA	4	19·8	17·6	17°	C	External	No	Floating	20·4	0·06	47
Maple Lodge	1951	—	—	PA	3	23·1	9·1	9·4	E	Internal	Yes	Floating	12·4	0·03	48
Nottingham (Stoke Bardolph)	1954 1972	460	165·0	PA	6	19·8	15·2	33⅓°	BC	External	No	Floating	32·3	0·07	49
Ringley Fold	1965	252	68·2	PA	3	19·8	13·7	30°	C	External	No	Fixed	15·1	0·06	50
Rotherham (Aldwarke)	1961	97	24·2	PA	2	16·8	11·9	16·6	C	External	No	Floating	5·9	0·06	51
Rye Meads	1957	160	—	PA	2	20·7	—	—	—	—	Yes	Floating	6·8	0·04	52
Strongford	1938 1951	— 285	— 77·0	PAH PAH	1 1	25·9 25·9	7·9 7·9	8·2 8·2	E E	Internal Internal	Yes Yes	Floating Floating	4·3 4·3	0·05	53

Sludge: P, primary; A, activated; H, humus.
Mixing: A, tangential inlet; B, external circulation through heat exchangers; C, screw pump; D, gas recirculation; E, internal mechanism.

sludge to the dewatering units or disposal sites, (b) to enable the sludge to cool, and (c) to enable liquor to separate from the solids so that this can be withdrawn and disposed of separately. Function (a) is particularly valuable where dewatering either varies seasonally or is affected by the weather.

4.7.2 Design criteria

4.7.2.1 Capacity. In the past the usual practice was to provide secondary tanks with a capacity equal to 50–65 per cent of that of the primary digesters, i.e. a retention period of 15–20 days. Current practice is to make the secondary digesters equal in capacity to that of the primary units, and where earth-banked lagoons are provided the retention period is often more than 30 days.

When the capacity is based upon the population served, with domestic sewage the volume per person is usually within the range 0·03–0·04 m^3/hd.

4.7.2.2 Dimensions. When warm sludge is discharged into a secondary digester containing sludge at a lower temperature it tends to rise to the surface, where the cooling effect is at a maximum. As the sludge cools or is displaced by another discharge of warm sludge convection currents are set up in a deep tank and these, together with the continued evolution of gas, hinder settlement of the sludge particles and prevent separation of a solids-free liquor.

Since the cooling of the sludge mostly takes place at the surface and with separation of liquor being more readily accomplished in relatively shallow tanks, secondary digesters should have a maximum depth of 3·5 m.

Secondary digesters are either circular with vertical sides and a conical lower portion, or rectangular. With circular tanks the diameter is restricted because of the need to be able to withdraw separated liquor, usually at one point on the periphery, and the maximum should be limited to 30 m.

4.7.2.3 Inlets and outlets. Sludge from the primary tanks is usually discharged into the secondary tanks near the surface at either a point or points on the periphery opposite the separated liquor draw-offs or at the centre of the tank, sludge being withdrawn through an outlet at the centre of the conical floor.

4.7.2.4 Scrapers. In some cases each tank has a relatively flat floor and is equipped with a two- or three-armed echelon-bladed scraping mechanism which is used for sweeping the sludge to the central outlet. For example, at Manchester[54] tanks 30 m dia. with a side wall depth of 4 m and a total depth of 5·5 m are equipped with picket-fence thickeners/scrapers.

TABLE 11. INSTALLATIONS OF SECONDARY DIGESTION TANKS, GAS HOLDERS AND DUAL-FUEL ENGINES

Works	Commissioned	SECONDARY TANKS						GAS HOLDERS		DUAL-FUEL ENGINES			
		Number	Diameter or dimensions (m)	Depth of side wall (m)	Depth at centre (m) or floor slope	Combined capacity (tcm)	Equivalent to (m³/person)	Number	Combined capacity (tcm)	Number	Combined kW	Driving	Reference
Barnsley	1961	2	12·2	6·7	6·7	1·6	0·02	—	—	3	492	Alternators	42
Bracknell	—	2	12·2	5·5	8·0	2·1	0·04	—	—	—	—	—	43
Coventry	1953–64	—	To lagoons							5	2 235	Alternators	44
Hatfield	1967	2	21·3 × 9·7	3·0	2°	1·2	0·08	—	—	—	—	—	45
Leicester (Wanlip)	1965	4b	85·3 × 39·6	—	3·7	61·4	0·17	2	2·8	5	3 000	Alternators	46
London (Beckton) *	1959	4	24·4	10·9	—	19·3	0·01	—	—	5 5	3 280 7 643	Blowers } gas Alternators } turbines	47
London (Crossness) †	1964	12d	36·8	10·7	—	86·5	0·06	—	—	12	10 164	Alternators	47
London (Deephams) *	1963–64	6b	91 × 60	4·0	4·5	136·3	0·20	—	—	4 8 4	1 938 3 624 1 938	Blowers Generators Pumps	47
London (Hogsmill Valley) *	1957	3	22·8	6·9	26°	10·5	0·05	—	—	4	1 332	Alternators	47
London (Mogden) *	1935–36	10	30·5	9·3	5°	70·9	0·05	—	—	5 10	2 610 6 035	Generators Blowers	47
London (Riverside) †	1968	8a	22·8	3·6c	—	12·3	0·03	1	0·5	6	3 600	Alternators	47
Maple Lodge	1951	—	—	—	—	—	—	—	—	6	2 820	Alternators	48
Nottingham (Stoke Bardolph)	1954	2	19·8	15·2	33⅓°	9·2	0·02	1	4·5	—	—	—	49
Ringley Fold	1965		Pumped to Rhodes Farm					1	1·4	3	1 577	Alternators	50
Rye Meads	1957	4	30·4	9·1	—	26·6	0·07	—	—	3	984	Compressor-Alternators	52
Strongford	1936	8	18·0 × 11·9	4·2	4·2	7·3	—	—	—				53
	1942	2	Earth embanked			9·0	Converted to sludge storage tanks						

a, cooling tanks between primary tanks and dewatering tanks. b, earth banks—sides covered with concrete slabs. c, average depth, d, based on population of 200 000. *thickening tanks only. †holding tanks only.

4.7.2.5 Withdrawal of separated liquor. Liquor may separate to form either a layer on the surface of the sludge or layers within the sludge mass. Facilities for withdrawing separated liquor usually include: (a) an overflow weir for removing liquor separating at the surface by displacement, (b) pivoted surface withdrawal ("floating") arms, and (c) a series of pipes set at regular vertical intervals in the wall of the tank and normally offset so that the valve spindles are side by side, the pipes discharging into a chamber with a connexion to a pump well from which the liquor is returned to the sewage flow for treatment. The valves are operated until a layer of liquor is found, when this can be withdrawn. In some instances these pipes project into the tanks to avoid withdrawing sludge from the contour of the tank.

4.7.3 Installations of secondary digestion tanks

Table 11 gives particulars of installations of secondary digestion tanks in the UK.

4.8 Operation

4.8.1 Commissioning procedure

4.8.1.1 Preliminary arrangements. Before starting up a heated digestion plant the following requirements should preferably be available:

(i) *Supply of seed sludge.* Normally it is preferable to obtain a supply of seed sludge from another digester on the same works or from another works, and the ratio of seed sludge to raw sludge is 1:10 to 1:5. However, if this is not possible a supply of seed sludge can be prepared by storing raw sludge for several months.

(ii) *Treatment of excess of raw sludge.* During the commissioning period the plant will need to operate on a reduced loading, therefore some other method must be available for dealing with any excess sludge.

(iii) *Source of heating.* Digestion will be established much more quickly if it is possible to heat the sludge during the commissioning period. A source of heat other than sludge gas, e.g. propane gas or an industrial space heater, will be necessary or waste heat from engines may be available if these are running temporarily on fuel oil.

4.8.1.2 Methods of commissioning digesters. Two basic methods are used for starting up digesters: (a) gradually filling the digesters with raw sludge together with a supply of seed sludge, and (b) filling the digester with sewage or test water and gradually replacing it with seed sludge and raw sludge.

Method (a) is normally used in the UK but has the disadvantage that in many cases it is not possible to commence circulation of the sludge or heating of it until the tank has filled, depending upon the tank design; using this method it takes at least two months before digestion becomes fully established. Method (b) has the advantage that it is possible to start circulating and heating the contents immediately but it also has the serious disadvantage that the seed sludge is greatly diluted and may therefore not be effective in inoculating the raw sludge with the appropriate organisms, with a consequent greater possibility of odour nuisance occurring. Raw sludge, with its relatively high solids content, tends to settle on entering the tank, and to remedy this it is necessary to circulate the contents from the lower to the upper portion of the tank.

Useful sources of information on the commissioning of digestion plants are to be found in the literature[55,56].

4.8.1.3 Procedure when gasification occurs. With either method of starting digestion, once gasification has become vigourous, manholes on the cover are sealed and all the gas cocks are closed. Under skilled supervision gas under the cover is then purged, i.e. vented to atmosphere several times, its composition being tested with an Orsat or other apparatus each time to ensure the absence of oxygen. Three or four such purgings are usually sufficient. As soon as testing shows that the gas contains no oxygen the main to the gas-fired heaters is purged and the heater is put into service.

4.8.2 Routine operation

4.8.2.1 Frequency of feeding. In order to ensure uniform gas production and temperature control, it is preferable to feed the digester at frequent intervals. In the WPRL survey[29] it was found with 139 works using primary digesters that the frequency of feeding varied as follows:

Number of works	*Frequency of feeding*
16	Less than one per day
68	Once per day
27	Twice daily
14	Three times per day
14	More than three times per day

4.8.2.2 Mixing and circulation. When digesting sludge is circulated externally through a heat exchanger, operation is usually continuous, mixing being supplemented by the evolution of gas which is usually at a maximum two or three hours after the addition of raw sludge.

When a screw pump, 'Burper-mixer', or 'Heatamix' unit is used, operation may be continuous or controlled automatically by a time switch. At some works, for example, the screw pump is operated in the normal way for 10–15 min every hour and in reverse for about 5 min in every hour.

4.8.2.3 Temperature control. The WPRL survey[29] revealed the following operating temperatures at 130 installations:

Number of works	*Operating temperatures* (°C)
10	26 – 28
26	28 – 30
61	30 – 32
17	32 – 34
16	34 – 36

A decrease in temperature of the digesting sludge, especially during the winter months, may be the consequence of inadequate heating capacity. Less obvious causes of persistent low temperatures are scaling of heat-exchanger surfaces and an increased requirement by a sludge having a low solids content. Regular observation and recording of the temperature of the digesting sludge to provide a warning of incipient troubles is essential.

The temperature of the digester contents may be raised by (a) increasing the heat input, (b) reducing the water content of the feed sludge so that the volume to be heated is reduced, (c) descaling the heat-exchanger surfaces, or (d) reducing heat losses from the whole digestion unit.

4.8.2.4 pH control. If digestion is proceeding satisfactorily, pH control is unnecessary since the natural buffering capacity of digested sludge (based on bicarbonate and ammonium ions) usually maintains the pH close to the optimum of 7·0. However, if inhibition of the methanogenic bacteria, or overloading, causes an excessive accumulation of volatile acids, the buffering capacity may be exceeded and the pH can rapidly decrease to 6·0, bringing about a consequent failure of the process. Any continuous downward trend in pH is a warning sign and calls for attention.

Another situation in which a controlled increase of pH by addition of alkali may be appropriate is when the sludge contains an inhibitory concentration of heavy metals in solution. By increasing the pH to about 8·0 the metal ions are precipitated and thereby rendered non-inhibitory. In most cases, however, the addition of sulphide to precipitate the heavy metal ions as sulphides is the favoured remedy[57].

Lime may be used to increase the pH of digester contents to about 6·5 but it is not suitable for attaining higher pH values since at a pH in excess of 7·0 lime reacts with CO_2 to form calcium carbonate which in turn may result in serious scale formation[58]. Furthermore, removal of CO_2 from the gas phase above the sludge, and the consequent reduction in gas pressure, could cause the collapse of the roof.

In order to increase the pH of digesting sludge above 6·5–7·0, the controlled addition of sodium (or potassium) bicarbonate or sodium (or potassium) carbonate is most convenient. Sodium hydroxide is another possibility but must only be used with great care because the hydroxide will also react with the CO_2 and effectively remove it from solution. In some cases, ammonia (or its salts) has been added to increase the pH value of digesting sludge but its use also requires special expertise and it is not widely favoured. The toxicity of ammonia, or ammonium ions, also represents a potential risk to the process through inhibition.

The toxicity of potassium and sodium ions must also be considered if large amounts of their alkaline salts are added to neutralize sludge[58]. Sodium ions may cause partial inhibition at concentrations in the range 3500–5500 mg/l and severe inhibition at concentrations above 8000 mg/l. The respective concentrations for potassium ions are 2500–4500 mg/l and 12 000 mg/l. Calcium ions are also inhibitory but, as indicated previously, are not likely to be present in solution in significant concentrations at pH values above 7·0.

4.8.2.5 Withdrawal of sludge. If sludge is withdrawn from the base of the tank, the dry solids content of the sludge is higher and there is less likelihood of grit accumulating than when withdrawn from near the surface, but if too great a proportion is withdrawn from the base the solids content of the sludge in the body of the tank is gradually reduced. It has been found[59] that digestion failures attributed to depletion of solids occur when the concentration of solids in the upper portion of a tank decreases to 1·5 per cent.

The frequency with which the sludge is withdrawn from the base of the tank varies at different works: at some plants withdrawal takes place once per week whilst at others a portion is withdrawn each day, reverting to displacement when the space made by bottom withdrawal has filled.

4.8.3 Operating difficulties

4.8.3.1 Inhibition of digestion and remedial measures. In the survey conducted by the WPRL[29] returns were received from 142 works with heated digesters, serving populations ranging from 2200 to 3·0 million. An analysis of the causes of 91 cases of difficulty at 63 sewage-treatment works is as follows:

		Number of cases
Anionic detergents		5
Industrial waste waters:		
Toxic metals	11	
Chemical wastes	17	
Pharmaceutical	2	
		30
Inadequate design or operation:		
Stratification and loss of solids	12	
Overloading	12	
Temperature control	15	
Operational problems	15	
Mechanical breakdown	2	
		56
Total		91

(i) *Heavy metals.* Where inhibition by heavy metal ions is occurring, the basic remedy is to precipitate the metals as their insoluble compounds. This may be achieved either by increasing the pH to above 7·5 to precipitate the metals as carbonates or by the addition of a sulphide compound (or a compound which will be reduced to the sulphide in the digester) to precipitate the metals as insoluble sulphides. Both procedures may be applied together. It has been shown[60] that the susceptibility of the sludge to inhibition by heavy metals is inversely related to the concentration of sulphide ions present (usually expressed as the pS value). The pS may be determined by the use of a sulphide ion electrode and is a useful method of assessing whether or not remedial action against heavy metal ion toxicity is necessary.

The practical procedure is to add a suitable alkali, such as sodium carbonate or bicarbonate, to the sludge to increase the pH to about 7·5. Sodium sulphide may then be added to the sludge (ensuring that the pH is above 7·5) accompanied by adequate mixing to ensure uniform dispersion. The final concentration of sulphide in the digesting sludge should not exceed 100 mg/l otherwise the sulphide itself may have a toxic effect. As an alternative to a soluble sulphide a sulphate, such as sodium sulphate, can be used since the sulphate will be reduced to sulphide in the reducing conditions of the digester. If sodium sulphide is used, it must be handled with great care and with strict control since under acid conditions it liberates hydrogen sulphide.

Where inhibition by metals is due to a single slug of toxic sludge it may only be necessary to dilute the sludge with a non-toxic sludge before it is fed to the digester.

Reported cases[29] of inhibition of works' digesters by zinc show that in one case failure was caused by a concentration of zinc in the digesting sludge of 1·6 per cent on dry solids, and in the other case by a concentration of 3·0 per cent on dry solids. By partial replacement of the digester contents with non-toxic raw sludge and adjustment of the pH value with caustic soda digestion was re-established and was reported to proceed normally when the zinc concentration decreased to 0·7 per cent on dry solids.

(ii) *Halogenated hydrocarbons.* When inhibition by halogenated hydrocarbons occurs, immediate action must be taken to try and prevent any further discharge of the compound to the sewer. Once in the sewer, the only practicable remedy is to remove the volatile compounds by air-stripping (using diffused air) of the sewage or of the sludge[61]. A permanently-installed air-stripping plant to remove chloroform from sludge has been successfully operated at one works in the UK[62]. In this case, it had proved impracticable to prevent small quantities of chloroform entering the sewer in an industrial effluent and air-stripping of the sludge at the works was considered to be the best remedy. Over a period of several months, the average concentration of chloroform in the sludge, before stripping, was 15·4 mg/kg. After air-stripping for a period of 6 h, the average concentration was reduced to 3·09 mg/kg, which is well below the inhibitory level, and full-scale digestion of the sludge proved possible.

(iii) *Synthetic detergents.* The normal remedy is to add stearine amine to digesting sludge in an amount which is sufficient to neutralize and precipitate about half the anionic surface-active material. If the pH of the digesting sludge is low, adjustment to pH 7·0 may effect an improvement without stearine amine but this would apply only when the concentration of anionic detergent is just above the inhibitory level.

Stearine amine is prepared from tallow and consists of a mixture of stearylamine and palmitylamine. It is insoluble in water and is normally used as the acetate which, although only slightly more soluble than the amine, may be more readily dispersed. Stearine amine, which is toxic to digestion and should therefore not be applied in excess, may be added to ethylene oxide to produce water-soluble ethoxylated forms. These are more effective, though also more costly, than the amine acetate for the neutralization of detergents.

4.8.3.2 Stratification. In a primary digestion tank there is a tendency for the sludge to separate into layers, i.e. (a) a layer of scum at the surface, (b) under this, a layer occupying possibly more than 80 per cent of the tank capacity which consists of digesting sludge, then (c) a layer of thick sludge containing heavier solids and grit.

Mixing should ensure that the digesting sludge in layer (b) is of uniform consistency since where mixing is inadequate there will be a tendency for liquor to separate and form a further layer on top of the digesting sludge. Mixing is assisted by the evolution of gas but this becomes progressively less from top to bottom. As digestion proceeds, gasification decreases and the solids settle to form layer (c), settlement by the solids losing their gelatinous character.

(i) *Scum formation.* Scum is composed of fats, oils, grease, and soaps together with hair, plastics, and sludge particles, all of which rise to the surface of the digesting sludge.

When scum is allowed to accumulate it (a) reduces the effective capacity of the digester and therefore the retention period, (b) interferes with mixing and circulation of the tank contents, (c) can affect the movement of a floating gas-holder, and (d) can restrict the evolution of gas.

The tendency for scum to accumulate may be reduced by removing as much scum-forming material as possible before the sludge enters the digestion tank; for instance, on a large works the scum can be removed completely from the primary sedimentation tanks and the sludge itself should preferably be screened. Oil and grease should be prevented from entering the public sewer by effective industrial effluent control.

In some digestion plant installations any build-up of scum can be removed by raising the level of the contents of the digester and allowing the scum layer to pass through specially-designed removal devices. In other designs it is possible to discharge digesting sludge into the surface layer in a tangential direction and at a high velocity to create a swirling motion and thereby disperse any scum. For example, at the Modgen works[63] provision was made for discharging raw sludge at four points into the surface layer of the digesting sludge, and on a few installations spray nozzles have been incorporated[64].

In tanks which are equipped with screw mixing pumps and gas recirculation units, withdrawal of sludge from the lower part of the tank and ejecting it at the surface helps to prevent a build-up of scum. Alternatively, with the screw pump the direction of rotation may be reversed, thereby carrying down any scum into the body of the tank.

(ii) *Grit accumulation.* In order to reduce the accumulation of grit in a digester, every effort should be made to remove as much heavy inorganic matter as possible from the sewage, although a large proportion of the grit which accumulates in digestion tanks is a fine silt which settles slowly but consolidates to form a dense mass.

The rate of accumulation is reduced if sludge, containing grit, is withdrawn at regular intervals from the base of the tank.

Grit will accumulate to such an extent that it must be removed at intervals and a side entrance at the base of the side wall should be provided, otherwise the grit will have to be removed through a manhole in the cover. Such work is time-consuming, difficult, and can be hazardous, and requires a complete shutdown of the unit. Submersible electrically-driven pumps have been found to be very useful when emptying some digestion tanks; however, high-pressure jetting machines are often needed for cleaning blockages due to grit.

4.8.3.3 Foaming. Foaming of digesting sludge can be a troublesome problem, since in severe cases the foam may enter gas-outlet pipes or even overflow from the digester causing a considerable mess and inconvenience. Foaming is most common during start-up, but at other times it may be caused by a sudden vigorous activity in the sludge. The basic causes are various and not well-defined but among the explanations which have been proposed are (a) inadequate mixing, (b) a fairly rapid increase in the temperature of the sludge, e.g. in the late spring after the digester has been operating at a reduced temperature for the winter period, (c) overloading with raw sludge, and (d) a higher than normal concentration of surfactant. At one works[65] in which the feed sludge contained surplus activated sludge, foaming coincided with foaming on the aeration tanks.

When foaming occurs it may be necessary temporarily to lower the level of sludge in the digester and to reduce the rate of feeding of raw sludge until the activity subsides. Removal of scum may be advantageous and, if possible, an increase in the degree of mixing may be beneficial. If the pH is low (i.e. below 6·5) it may be advantageous to add alkali to increase the pH to 6·8–7·2 since foaming seems to be most severe under slightly acidic conditions.

4.8.3.4 Emptying. There are potential hazards in the emptying of a digester, and proper procedures must be followed. The legal requirements concerning the safety of the operator at the workplace are contained mainly in s.2 of the Health and Safety at Work Act 1974, s.63 of the Factories Act 1961, and various codes and regulations made thereunder. Water authorities are now issuing written safety procedures and insisting that a 'permit to work' is obtained before any maintenance or repair work is carried out in such potentially hazardous areas of plant.

During the emptying of a digester the following minimum safety equipment is essential: gas detection equipment, intrinsically safe lighting, spark-proof tools, rescue and life lines, suitable warning and no-smoking notices and barriers, breathing apparatus, safety hats and protective clothing.

Before a digester is emptied, feeding with raw sludge must be discontinued and the unit should be allowed to stand until gas evolution has fallen to a negligible rate. Under skilled supervision, the gas holder should be purged with an inert gas, e.g. nitrogen, before any sludge is removed.

During the removal of digested sludge, residues may be disturbed and may still produce gas; tests must therefore be made at frequent intervals for explosive conditions, gas detectors and monitors being continuously used. Methane is lighter than air and natural ventilation is often sufficient to remove the small amount of gas which is given off, but at some works it is practice to dilute the residue with effluent to reduce gas production. Strict safety precautions must be taken.

4.8.3.5 Separation and withdrawal of liquor. If digestion is incomplete when the sludge leaves the primary digestion tank, it continues in the secondary digesters and gas bubbles buoy up particles of sludge, making it impossible to draw off a good quality liquor. On the other hand, if digestion is complete, liquor separates readily in the secondary tanks after the sludge has cooled, hence the value of rapid cooling and higher efficiency of secondary digesters with a low depth to surface area ratio.

Sometimes the liquor separates to form a surface layer and at other times it forms bands which may be located by withdrawing samples at different levels from special draw-offs until the best-quality liquor has been located.

Liquor may be withdrawn each day but sludge is usually discharged at longer intervals to suit the requirements of the treatment and disposal system.

On many plants, particularly where digested sludge is tankered away, further thickening of the sludge is essential; this is achieved by using conventional secondary tanks, lagoons, or modified drying beds.

4.9 Sampling Procedures

There are three basic types of sample, i.e. (a) instantaneous, (b) continuous, and (c) discrete samples for preparing a composite sample. In the process of sludge digestion it is normally only necessary to take an instantaneous sample because the contents of the digester are being circulated continuously and the sample should be representative.

In some installations, special pipes with valves have been built into the tank at various depths. Usually, however, samples have to be withdrawn either through a suitable port on the cover or from the displaced digested sludge as it leaves the digester.

A sampler which is used by the WRC[66] incorporates a 25–mm alloy pipe in 2–m sections having suitable screwed connexions which are assembled as the device is lowered into the digester for sampling purposes. A valve and flexible pipe connect the alloy pipe to a 10–l sample bottle, and sludge is withdrawn by applying a reduced pressure to the pipe using an electric or hand-operated pump.

When sampling digester gas it is essential to ensure that all the sampling equipment and pipelines have been adequately purged.

All personnel who are required to take samples of sludges should be trained in techniques and procedures which are designed to minimize or eliminate associated risks[67].

4.10 Control Tests

4.10. 1 Monitoring of volatile acids and pH value

If digestion is proceeding satisfactorily, the pH value of the digesting sludge normally ranges from 7·0 to 7·2, alkalinities (as $CaCO_3$) from 4000 to 5000 mg/l, and concentrations of volatile acids (as acetic acid) less than 200 mg/l.

Regular determinations of the concentration of volatile acids together with records of gas production and CO_2 content of the gas indicate when a digestion plant is becoming overloaded or is suffering from inhibition of digestion. The calorific value of the gas can also be used to indicate this effect, and a recording gas calorimeter in the gas line will provide a continuous record.

The value of determining the concentration of volatile acids in the digesting sludge is in the trend which they reveal, a sudden increase in the concentration of volatile acids of 200–300 mg/l being a cause for concern.

Determination of volatile acids by gas chromatography is especially beneficial by identification of the various volatile acids; a shift to higher volatile acids, e.g. acetic to butyric, is also a sign of instability.

4.10.2 Monitoring of methane content of sludge gas

Monitoring of the methane content, e.g. using gas chromatographic equipment[68], or an infra-red gas analyzer, provides an early warning that digestion is being adversely affected.

4.10.3 Monitoring of toxicity

Where digestion is liable to inhibition due to the presence at irregular intervals of toxic substances in the feed sludge, the batch digestion test may be used to warn of their presence before the concentration in the digesting sludge builds up to a dangerous level. This valuable test consists of adding 1 part of the raw sludge to 3 parts of a satisfactorily digesting sludge and measuring the amount of gas which is produced in 24 h at 35°C; 20 per cent less than that produced by a control indicates that the sludge is unsuitable for digestion. If the raw sludge is either being temporarily stored or thickened the test indicates whether that particular batch is suitable for digestion. If it is being fed directly into the plant the result of the test becomes available too late to prevent the particular batch from being discharged into the digestion tanks, but since it is diluted on entry with about 30 times its volume of digesting sludge it is unlikely that it will cause inhibition. A more sensitive test was used by the former Water Pollution Research Laboratory[69].

Incipient heavy metal inhibition may be detected by regular monitoring of the sulphide ion concentration in the raw or digesting sludge using a sulphide-selective electrode[57].

4.11 Maintenance

4.11.1 Lubrication

Mechanical equipment should be lubricated in accordance with the manufacturer's instructions.

4.11.2 Covers

4.11.2.1 Vacuum and pressure-relief assembly. Owing to the large area of the cover, a small variation in gas pressure causes a substantial variation in the upward force on it so that valve seats need to be inspected frequently and cleaned if necessary. On some plants where steel valve plates have tended to stick and the seating corrodes, the fitting of polythene plates and rings has restored the sensitivity of the valves and has made them gas-tight.

4.11.2.2 Flame traps. Flame traps, which are installed to prevent 'flash-back' from the boiler to the gasholder, tend gradually to become blocked by condensate and particulate matter and therefore need to be checked for cleanliness regularly or replaced at frequent intervals.

4.11.2.3 Level alarm. This should be lubricated and tested at intervals to ensure that the alarm will operate if the floating cover falls to a dangerously low level.

4.11.2.4 Pipelines. When sludge gas leaves the digester it is saturated with water, therefore condensation occurs in pipelines conveying the gas when the temperature is lowered. The pipe should slope to a condensate trap which needs to be drained at frequent intervals.

4.11.2.5 Guide rollers and rails. Sludge which gradually becomes packed in the grooves of the guide rails should be removed when necessary to prevent excessive load on the carriages.

4.11.3 Heat exchangers

At several installations using spiral-tube sludge/hot water heat exchangers, difficulty has been experienced with fibrous material collecting on bars which separate the sludge circuit from the water circuit and cause blockages, necessitating removal of the debris at regular intervals. Difficulty has also been encountered with the formation of scale in water circuits, especially at places where the water supply is hard. This scale is composed mainly of calcium salts and can be removed using inhibited acids.

4.12 Performance

4.12.1 Reduction of organic matter and dry solids during digestion

The reduction of organic matter can be calculated from first principles provided that the concentrations of the dry matter and organic matter are known before and after digestion.

Alternatively, the calculation can be carried out using the formula[70]:

$$\% \text{ Reduction in organic matter} =$$

$$\left(1 - \frac{\% \text{ Ash in raw sludge} \times \% \text{ Organic matter in digested sludge}}{\% \text{ Organic matter in raw sludge} \times \% \text{ Ash in digested sludge}}\right) \times 100$$

A method of calculation of the reduction of dry matter during digestion is also given in Appendix 1.

4.12.2 Performance of heated digestion plants

4.12.2.1 Primary digesters. Details of the performance of heated digestion plants in the UK are given in Table 12.

4.12.2.2 Secondary digesters. The dry solids content of digested sludge withdrawn from secondary tanks at different works varies widely (Table 12), depending on many factors, including: (a) the solids content of the feed sludge, (b) the degree of digestion achieved in the primary tanks, (c) the surface area/depth ratio of the secondary tanks, (d) the efficiency of the decanting arrangement for supernatant liquor, and (e) the storage period.

The WPRL[29] showed that on 61 sludge digestion plants serving a population of 13 million dewatering achieved in the secondary tanks was as follows:

Number of works	*Percentage supernatant liquor removed*
25	0–20
18	20–40
18	40–70

4.13 Digestion at Ambient Temperature (Cold Digestion)

4.13.1 Application

Anaerobic digestion was originally carried out in open lagoons or tanks but when it was discovered that the process would proceed more quickly at mesophilic temperatures, enclosed tanks and ancillary equipment were incorporated.

Cold digestion at ambient temperatures was common at smaller works where there was a wide variety of design and construction practice and the

TABLE 12. PERFORMANCE OF HEATED SLUDGE DIGESTION PLANTS

Works	Feed sludge		Digested sludge		Retention period (days)	Loading (kg volatile matter/ m^3 day)	Capacity (m^3/hd)	Loss		Gas production (m^3/kg volatile matter destroyed)	Ref.
	Dry solids (per cent)	Volatile matter (per cent)	Dry solids (per cent)	Volatile matter (per cent)				Dry matter (per cent)	Volatile matter (per cent)		
Aylesbury	4·4	72·1	3·0	61·1	22	1·5	0·06	—	39·2	0·85	41
Barnsley	4·9	75·8	3·4	57·0	31	1·2	—	32·5	43·5	—	42
Bathgate (Regional Lothian Council)	5·1	71·2	6·0*	52·5	37	0·5	0·06	29·3	40·8	1·05	71
Bournemouth (Berry Hill)	3·6	77·0	2·3	66·5	—	—	0·05	31·2	40·6	—	72
Bournemouth (Kinson)	5·9	77·4	2·7 5·3†	66·0 60·5†	35	—	0·04	33·5	43·3	—	72
Bracknell	5·0	76·5	2·6	62·0	30	1·3	0·04	48·0	50·0	—	43
Coventry	4·5	76·0	2·5	63·0	19	1·0	0·04	35·1	46·2	0·83	46
Derby	5·2	65·1	3·9	55·3	22	—	0·04	21·9	33·7	0·79	73
Leicester (Wanlip)	3·7	79·9	3·2	66·0	22	1·3	0·06	35·1	44·6	1·15	47
London (Crossness)	3·7	76·5	2·3	65·0	19	1·7	0·04	41·0	43·0	1·18	47
London (Kew)	3·4	75·4	2·4	63·6	15	1·6	0·04	29·4	42·9	0·78	47
London (Hogsmill Valley)	3·5	78·6	1·8	69·8	28	0·9	0·06	48·6	37·1	1·13	47
London (Mogden)	4·0	78·7	2·4	66·8	23	1·4	0·06	40·0	45·9	1·04	47
Norwich	6·1	74·7	—	—	44	1·0	0·05	—	—	0·62	74
Rotherham (Aldwarke)	5·3	75·0	3·4	65·0	28	0·9	0·06	45·7	60·9	1·13	51

*After consolidation
†From secondary digesters

capacity was often equivalent to 80–100 days' sludge production. The degree of digestion which was achieved was extremely variable and depended upon many factors.

Very often, and particularly recently, the emphasis on cold digestion has shifted towards storage before spreading the sludge on land. Digestion has therefore sometimes become a secondary objective and only occurs with extended storage.

4.13.2 Factors affecting digestion at ambient temperature

The factors affecting mesophilic digestion (see section 4.5) also affect digestion at ambient temperature, and it can be demonstrated that to obtain the same results, digestion at summer ambient temperature requires 90 days compared with 30 days or less at a temperature of 30°C. The capacity of unheated digestion tanks should normally be based on a retention period of about 90 days.

4.13.3 Construction

Many open digestion tanks are constructed partly by excavation, using excavated material to form embankments, the inside face of which has a slope of, say 1 in 1·25. Emptying is facilitated if the tank is lined with concrete slabs and has a concrete floor. In the WPRL survey[29] it was found that 63 tanks were constructed of concrete and 20 were earth-banked lagoons. At a few works[51] tanks constructed in concrete have been arranged so that covers can be installed and the gas collected at a later date if desired (Fig. 11). In recent years, however, interest has been shown in converting deep open earth-

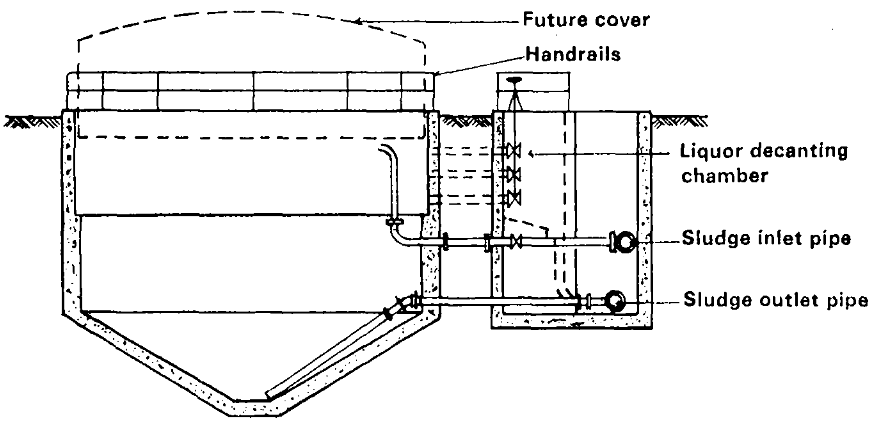


Fig. 11. Cross-section of circular 'cold' digester.

banked lagoons to heated digestion plants wherein the formation of a thick crust limits losses of heat, and the installation of an oil-fired boiler can be carried out at minimal cost. Under good management control this system works satisfactorily; however, it must be recognized that the weed growth on the thick crust formation hides the inherent dangers.

With rectangular tanks (Fig. 12) there is often an inlet at one end and an outlet at the other end but with this arrangement there are likely to be dead patches in the corners and short-circuiting is therefore experienced. One arrangement[75] which was found to be very efficient with an earth tank measuring 55 m × 42 m and 3 m deep was to have a submerged feed pipe in each of three corners, discharging 0·9 m above floor level, with the outlet in the fourth corner. An inlet discharging above sludge level can be used for breaking up the scum.

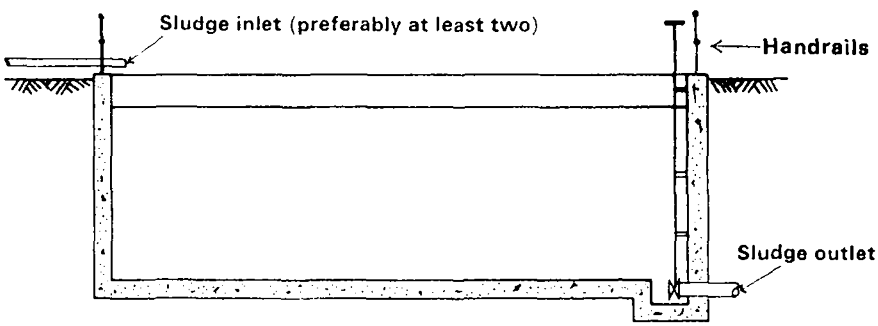


Fig. 12. Cross-section of rectangular 'cold' digester.

Over the last few years where the disposal of liquid sludge has been practised more commonly, outlet sumps have sometimes been provided for ease of removal into tankers.

4.13.4 Operation

Mixing and circulation, which are usually very inefficient in rectangular tanks, are carried out by withdrawing sludge through the outlet and returning it to the inlet. Mixing is improved by having more than one outlet and inlet, and if possible should be carried out as a daily routine. Recirculation of digesting sludge should preferably proceed whilst raw sludge is being introduced.

When digestion is carried out in a single tank of large capacity, liquor which separates is difficult to locate and reach so that, although facilities for its withdrawal may be provided, much of the liquor is removed with the sludge. Periodically it may be desirable to remove any excessive build-up of scum (or crust) using a drag line.

4.13.5 Performance

Reference to the literature[76,77,78,79] shows that there is a shortage of consistent operational data available on the performace of 'cold' digesters.

4.14 Products of Anaerobic Digestion

The products of anaerobic digestion are (a) digested sludge, (b) liquor, and (c) gas.

4.14.1 Digested sludge

Digested sludge has a faint, relatively inoffensive tarry odour, and dries to an inert friable condition; a typical analysis is given in Table 1. In liquid form it is especially suitable for application to agricultural land, and a full discussion of the subject is available elsewhere[80].

4.14.2 Liquor

4.14.2.1 Composition. The results of analysis of liquors from four heated digestion plants are given in Table 13. There was a wide variation in the concentration of SS, with the solids being very finely divided and virtually unsettleable. Comparing the results of the filtered samples with those of the

TABLE 13. RESULTS OF ANALYSIS OF LIQUORS FROM FOUR LARGE SLUDGE DIGESTION PLANTS

(Results in mg/l)

	Unfiltered		Filtered	
	Range	Average	Range	Average
Suspended solids	295–1115	785	—	—
PV	140–200	170	80–120	95
BOD	373–515	450	120–205	150
COD	1500–1760	1650	500–750	610
Organic carbon	444–590	525	197–260	225
Ammonia (as N)	734–1000	820	—	—
Total solids	1885–2265	2050	1070–1590	1270
Anionic detergent (as Manoxol OT)	22–33	28	10–24	14

unfiltered samples, it is evident that the SS are responsible for a considerable proportion of the BOD which is exerted by the liquors.

4.14.2.2 Treatment. The liquor is usually returned to the works' inlet, at a controlled rate, to be treated in admixture with the incoming sewage. Separate treatment of liquors has been shown to be difficult.

Because nitrogenous organic compounds are decomposed during digestion some of the nitrogen passes into solution and therefore into the returned liquor, thereby imposing an additional nitrogen loading on the treatment plant.

4.14.3 Sludge gas

4.14.3.1 Composition. Sludge gas, which is saturated with water vapour, contains 65–70 per cent methane and 30–35 per cent carbon dioxide by volume depending upon the organic matter which is being degraded (see Appendix 2). It also contains traces of unsaturated hydrocarbons with very small but widely varying concentrations of hydrogen sulphide. For example, at Birmingham[81] this was considered to be due to varying amounts of iron in industrial waste waters which were present in the sludge, the concentration of H_2S being inversely proportional to the iron content.

4.14.3.2 Calorific value. For gases which produce water on combustion there are two calorific values, i.e. the net calorific value for combustion in which the water formed remains in the vapour phase, and the gross calorific value for combustion in which the water formed is condensed.

With sludge gas, heat is obtained almost exclusively from the combustion of methane. Calorific values are therefore calculated from the methane content[82]:

$$\text{Net value} = (334 \times M)\ \text{kJ/m}^3\ \text{(saturated with water)}$$

$$\text{Gross value} = (370 \times M)\ \text{kJ/m}^3\ \text{(saturated with water)}$$

(Both at 15·5°C and 1 bar)

where M = percentage of methane.

The gross calorific value of sludge gas is normally 24 000–26 000 kJ/m^3, the net calorific value being about 10 per cent less than this range.

4.14.3.3 Production. The composition and quantity of gas produced by anaerobic digestion depends upon the composition of the organic matter undergoing digestion. In theory the proportions of methane and carbon dioxide which are produced can be determined using Buswell's formula (see Appendix 2).

Total gas production from the digestion of raw sewage sludge is typically about 1·0 m^3/kg organic and volatile matter destroyed. For a mixed primary and secondary sludge, derived from a sewage which is predominantly of domestic origin, this is equivalent to about 0·5 m^3/kg organic and volatile matter, or about 0·375 m^3/kg total dry solids, added to the digester. In terms of contributing population, gas production is typically about 0·03 m^3/hd d. Reports in the literature indicate that gas production may vary from 0·5–1·2 m^3/kg organic and volatile matter destroyed, or 0·3–0·7 m^3/kg organic and volatile matter added. Some of the large apparent variation can undoubtedly be attributed to inaccuracies in determining the weight of organic and volatile matter added to or removed from the digester and to inaccuracies in measuring gas production. Leaks in and around digester roofs are also not uncommon and may account for apparently low gas production in relation to organic and volatile matter destroyed.

4.14.3.4 Hazards. Hazards can arise from the methane, carbon dioxide, and hydrogen sulphide in sludge gas, the characteristics of which are given in Table 14.

(i) *Methane.* When methane leaks into the atmosphere a potentially flammable mixture occurs when the concentration ranges from 5 per cent to 15 per cent; below this concentration the flame is not self-propagating. It has been suggested[82] that any concentration of methane exceeding 1·25 per cent (25 per cent of the lower explosive limit) should be regarded as dangerous.

Methane is not a poisonous gas but in admixture with air may reduce the oxygen content of the mixture to such a level that asphyxiation occurs.

(ii) *Carbon dioxide.* The maximum safe concentration of carbon dioxide is 2–3 per cent in air; above this it is an asphyxiant.

(iii) *Hydrogen sulphide.* A concentration of 1·0 per cent (1500 mg/m^3) of hydrogen sulphide paralyses the sense of smell and causes instant unconsciousness. The physiological effects at different concentrations are shown in Table 14.

4.14.3.5 Precautions. The precautions which are necessary when working in or around sludge digestion plants should be made known to all operators,

TABLE 14. CHARACTERISTICS AND PHYSIOLOGICAL EFFECTS OF GASES ENCOUNTERED IN SLUDGE DIGESTION PLANTS

Gas	Common properties	Specific gravity or vapour density (air = 1)	Toxicology	Threshold limit value (TLV) (ppm)	Maximum safe 60 min exposure (per cent by volume in air)	Explosive range (per cent by volume in air)	
						Lower limit	Upper limit
CH_4	Colourless, odourless, flammable and forms explosive mixture with air	0·55	Non-toxic but can have narcotic effects in high concentrations in absence of oxygen	—	Probably no limit, provided concentration of O_2 is sufficient to support life	5·0	15·0
			Deprives tissues of oxygen by interfering with oxygen-carrying capacity of oxy-haemoglobin				
CO_2	Colourless, odourless, non-flammable	1·53	A simple asphyxiant. Symptoms resulting only when high concentrations are reached are headache, dizziness, drowsiness, tinnitus (ringing in ears). Removal from exposure results in rapid recovery	5000	4·0–6·0	—	—
H_2S	Colourless, smells of rotten eggs. Flammable (may travel considerable distance to a source of ignition and flash back)	1·19	An irritant and asphyxiant, concentrations of 20–150 ppm cause eye irritation. Higher concentrations affect nervous system. A 30-minute exposure to 500 ppm results in headache, dizziness, diarrhoea dysuria. A 30-minute exposure of 800–1000 ppm may be fatal. Its asphyxiant action is due to paralysis of respiratory centre	10	0·02–0·03	4·3	46·0

and appropriate "No Smoking" and "No Naked Lights" notices should be displayed prominently.

The recommended procedures[83,84] must be strictly adhered to for starting up or venting closed digesters and for preventing fires in the vicinity of digestion plants.

Formal training of all personnel with safety procedures for gas testing and use of resuscitation equipment is essential (see para. 4.8.3.4).

Operators should be provided with portable detectors for use before entering a potentially hazardous situation and detectors should be carried on their person which will give warning in sufficient time for an escape to be made.

4.14.3.6 Detection (see also section 4.6.6). Hazardous working conditions can result from (a) a flammable atmosphere, (b) poisonous gases, or (c) oxygen deficiency. Each location will have its own peculiarities and these must be known to the operators and suitable equipment provided. Buildings which are associated with digestion plants should be provided with gas detectors which sound alarms if the atmosphere becomes potentially dangerous.

The technology of detection equipment is changing appreciably and modern equipment has advantages over that which was used only 5 years ago. Several types should be examined before purchase and manufacturers are glad to supply information about explosive and threshold limits. In addition, the literature should be consulted[81,82,83,84,85,86].

5. Utilization of Sludge Gas

Sludge gas is normally used for heating the contents of a digester; however, surplus gas is quite commonly used for space heating on the treatment works and for power production. It is also interesting to note that sludge gas has been used for (a) incineration of screenings, (b) sludge drying, and (c) in an emergency for vehicle propulsion.

5.1 Power Production

At some large sewage-treatment works, including the major London plants, Birmingham (Minworth), and Manchester (Davyhulme), sludge gas is used for power production, the waste heat from the engines being used for heating the sludge. Power which is derived from the engines may be used for generating electricity or for driving air compressors or pumps.

5.1.1 Economics

When comparing the cost of power generation from sludge gas with that of purchasing mains electricity many factors have to be taken into consideration. Although sludge gas may be free, costs of utilizing it for power production include operating costs, loan charges and depreciation. Operating costs include fuel oil for ignition, lubricating oil, stores and water, wages for shift operatives, and repairs and maintenance. Usually the power station houses other machinery such as compressors, pumps and sludge heating equipment.

When assessing the cost of mains electricity, to the price quoted may have to be added a fixed standing charge, a maximum demand charge, and a charge based on the price of coal. Also there may be transformer and transmission losses after the incoming meter. Other factors to be taken into consideration include the added reliability of having a works which is self-sufficient in power, especially with the possibility of either power failure or industrial action. Normally the capital and operating costs of the digestion plant are disregarded.

There is usually a size of works at which the utilization of sludge gas for power production becomes worthy of consideration. Expert opinion on this subject is often at variance and factors such as oil prices, labour, and interest rates affect the economics.

5.1.2 Dual-fuel engines (Plates 7 and 8)

When sludge gas was first used for power production the conventional gas engine with a low compression ratio and spark ignition was used. About 1940, however, a gas engine was converted into a dual-fuel engine, with the gas being fired in a high compression machine by a small charge of fuel oil mixed with the gas, or fuel oil alone could be used if gas was unavailable. Dual-fuel engines normally produce a higher efficiency, exhaust temperatures are lower and maintenance is reduced; they are easier to start and give smoother running than spark ignition gas engines. Table 11 gives particulars of some dual-fuel engine installations in the UK.

5.1.2.1 Description. A dual-fuel engine is basically a mechanical-injection diesel engine, with gas-mixing apparatus applied to its air intake system so that, instead of inducing air only, a combustible mixture of air and gas is induced and this mixture, after undergoing full compression in the working cylinder, is fired by a small igniting charge of diesel fuel. This charge is timed and injected by the ordinary diesel fuel injection pump and sprayer valve into a gaseous mixture. The calorific value of the quantity of fuel oil injection amounts to only 5–10 per cent of the total heat supplied at full load[87]. If the gas supply fails an engine can be changed over from operating as a dual-fuel engine to diesel engine operation, and arrangements may be made for this to be done automatically if required.

An engine should give its most economical output at three-quarters load, this being the average of its full load rating[87], and when nearing the time for a general overhaul it should still be capable of coping with the load.

5.1.2.2 Operation. The operation of a dual-fuel engine will have been described in the manufacturer's handbook and will not be discussed here. Suffice it to say that tripping out of an engine may be caused by: (a) the spindle of the needle valve in a fuel-injection nozzle 'shellacing', (b) mechanical failure of the gas-control gear, governors, etc., when changing from gas to oil, (c) load variations when testing an engine after overall, or (d) when the engine is direct coupled to an alternator, a voltage regulator needing servicing.

5.1.2.3 Maintenance. Dual-fuel engines need regular maintenance, based usually on running hours. The frequency depends on the size and speed of the engine and it is important that servicing is carried out in accordance with the manufacturer's instructions.

5.1.2.4 Performance. Efficiencies of dual-fuel engines range from 30–36 per cent on full load or from 22–30 per cent under actual operating conditions.

Allowing for starting-up periods and test runs, gas consumption ranges from 0·45 to 0·55 m^3/kWh, the consumption being higher with a varying load.

5.1.3 Other engines running on sludge gas

Supercharged dual-fuel engines are in operation at the Mogden works, Croydon's Beddington works, and Southampton's Millbrook works. At London's Beckton works 10 gas turbines are in operation, 5 of which are directly coupled to blowers for the activated-sludge plant. The turbines have advantages in that they run on sludge gas without the use of fuel oil for ignition, they are lighter and therefore the foundations may be cheaper, and they occupy a smaller space than dual-fuel engines; however, they are less efficient.

Appendix 1

Calculation of Reduction of Organic Matter and Dry Solids during Digestion

	Dry matter (%)	*Organic matter (% of dry matter)*
Given:		
Before digestion . . .	4·78	73·4
After digestion . . .	2·34	57·7

Let x g be the amount destroyed during digestion (which is all organic and volatile matter since the mineral matter remains unchanged).

Suppose there are 100 g of sludge. Therefore there will be 4·78 g of dry solids and $4{\cdot}78 \times \frac{73{\cdot}4}{100} = 3{\cdot}51$ g O and V matter.

$\therefore$ After digestion, O and V matter $= 3{\cdot}51 - x$ g
dry matter $= 4{\cdot}78 - x$ g

But after digestion the O and V matter is given as 57·7 per cent

$$\therefore \frac{3{\cdot}51 - x}{4{\cdot}78 - x} = \frac{57{\cdot}7}{100}$$

$$\therefore 0{\cdot}577\,(4{\cdot}78 - x) = 3{\cdot}51 - x$$
$$2{\cdot}758 - 0{\cdot}577x = 3{\cdot}51 - x$$
$$x - 0{\cdot}577x = 3{\cdot}510 - 2{\cdot}758$$
$$0{\cdot}423x = 0{\cdot}752$$
$$x = \frac{0{\cdot}752}{0{\cdot}423} = 1{\cdot}78$$

$\therefore$ Reduction in organic matter $= \frac{1{\cdot}78}{3{\cdot}51} \times 100 = 50{\cdot}7$ per cent

and reduction in dry solids $= \frac{1{\cdot}78}{4{\cdot}78} \times 100 = 37{\cdot}2$ per cent

Appendix 2

Production of Digester Gas

The composition and quantity of digester gas which is produced by complete degradation depends upon the organic matter which is being broken down and, in theory, may be determined using Buswell's formula[88]:

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right).H_2O = \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4$$

If this formula is applied to the main classes of degradable organic matter the values[30] which are obtained are shown in Table 15.

TABLE 15. COMPOSITION AND VOLUME OF GAS FROM COMPLETE ANAEROBIC DIGESTION OF DIFFERENT CLASSES OF ORGANIC MATTER

Material	Composition* (per cent by weight)		Volume from 1 kg dry matter	
	CO_2	CH_4	Digester gas (m^3)	Methane (m^3)
Carbohydrate	73	27	0·75	0·37
Lipid	52	48	1·44	1·04
Protein	73	27	0·98	0·49

*Neglecting the very small amounts of other gases formed.

References

1. Institute of Water Pollution Control. *Glossary of Terms used in Water Pollution Control.* Manuals of British Practice in Water Pollution Control, 1975.

2. Bruce A. M., and Boon, A. G. Aspects of high-rate biological treatment of domestic and industrial waste waters. *Wat.Pollut.Control,* **70**, 1971, (5), 487.

3. Lee, H. V., and Duckworth, R. M. Aspects of power generation and sludge treatment at Coventry. *Wat.Pollut.Control,* **73**, 1974, (5), 469.

4. Kent, C. G. Extensions of the Manchester Corporation sewage works at Davyhulme. *J.Proc.Inst.Sew.Purif.,* 1935, (1), 7.

5. Morris, A. T., Copeland, C. E., and Lewin, V. H. City of Oxford: Extension to sewage-treatment works. *Wat.Pollut.Control,* **69**, 1970, (3), 249.

6. Water Research Centre. *Gravity Thickening of Biological Sludges.* Tech. Report TR39, Feb. 1977.

7. Christian, J. A. Reconstruction at Lundwood, Barnsley. *J.Proc.Inst.Sew.Purif.,* 1962, (4), 342.

8. Haigh, M. D. F. Sewage treatment at Barnsley 1961–71: A decade of set-backs and progress. *Wat.Pollut.Control,* **72**, 1973, (4), 373.

9. Suriyadasa, R. Redevelopment of Haven sewage-treatment works, Colchester. *Wat.Pollut.Control,* **72**, 1973, (6), 693.

10. Kershaw, M. A., and Wood, R. Sludge treatment and disposal at Maple Lodge. *J.Proc.Inst.Sew.Purif.,* 1966, (1), 75.

11. Cotton, P. City of Norwich sewage works. *Wat.Pollut.Control,* **67**, 1968, (4), 454.

12. Edmondson, B. R. In discussion. *Wat.Pollut.Control,* **68**, 1969, (2), 164.

13. Brown, P., and Thomas, A. Some experiences in the consolidation of surplus activated sludge. *Wat.Pollut.Control,* **68**, 1969, (2), 203.

14. Laboon, J. F. Experimental studies on the concentration of raw sludge. *Sewage ind. Wastes,* **24**, 1952, 423.

15. Rudolfs, W. Concentration of activated sludge by compaction and flotation. *Sewage Wks. J.,* **15**, 1943, 642.

16. Ames Crosta Babcock. *Komline-Sanderson Dissolved Air Flotation.* Publication 102.

17. Clark, E. I. Personal communication.

18. Water Research Centre. *Settling of Activated Sludge.* Tech. Report TR 11, May 1975.

19. Hirst, G. Personal communication.

20. Butler, B. Personal communication.

21. Gillett, P. M. Personal communication.

22. Operation Manual: Sludge Handling and Conditioning. EPA 430/9-78-002, 1978.

23. Water Pollution Research Laboratory. *The Aerobic Digestion of Sewage Sludge.* WPR Rep. No. 1271, 1972.

24. Thames Water Authority. *Kidlington Aerobic Digestion Experiment.* Final report of steering committee. July, 1976.

25. McNicholas, J. Personal communication.

26. Walker, D. G., and Murdoch, I. *Thermophilic oxidative digestion of sludge using oxygen.* Preliminary report of the Ponthir pilot plant treatment. Welsh National Water Development Authority. January 1976.

27. Watson, J. D. Sludge digestion. *Proc.Ass.Mgrs Sewage Disp.Wks,* 1923, 117.

28. O'Shaugnessy, F. R. Destructive anaerobic fermentation. *Sewage Wks. J.* 1931, **3**, 86.

29. Swanwick, J. D., Shurben, D. G., and Jackson, S. A survey of the performance of sewage sludge digesters in Great Britain. *Wat.Pollut.Control,* **68**, 1969, (6), 639.

30. Department of the Environment. Anaerobic treatment processes and methane production. *Notes on Water Pollution.* No. 64, March 1974.

31. Stanbridge, H. H. The consolidation and digestion of activated sludge. *J.Proc.Inst. Sew.Purif.,* 1966, (5), 492.

32. Chapman, W. H. Some experiences on sludge digestion. *J.Proc.Inst.Sew.Purif.,* 1965, (5), 485.

33. Mosey, F. E. Assessment of the maximum concentration of heavy metals in crude sewage which will not inhibit the anaerobic digestion of sludge. *Wat.Pollut.Control,* **75**, 1976, (1), 10.

34. Swanwick, J. D., and Foulkes, M. Inhibition of anaerobic digestion of sewage sludge by chlorinated hydrocarbons. *Wat.Pollut.Control,* **70**, 1971, (1), 58.

35. Department of the Environment. Inhibition in the anaerobic digestion process for sewage sludge. *Notes on Water Pollution.* No. 53, June 1971.

36. Barrett, K. A. An investigation into the effects of chlorinated solvents on sludge digestion. *Wat.Pollut.Control,* **71**, 1972, (3), 389.

37. Stickley, D. P. The effect of chloroform in sewage on the production of gas from laboratory digesters. *Wat.Pollut.Control,* **69**, 1970, (1), 55.

38. Bruce, A. M., Swanwick, J. D., and Ownsworth, R. A. Synthetic detergents and sludge digestion: Some recent observations. *Wat.Pollut.Control,* **65**, 1966, (5), 427.

39. Swanwick, J. D. and Shurben, D. G. Effective chemical treatment for inhibition of anaerobic sewage digestion due to anionic detergents. *Wat.Pollut.Control,* **68**, 1969, (2), 190.

40. Neotronics Ltd. *Protection by Detection.* 1975.

41. Jones, C. E. Personal communication.

42. Swanwick, K. H. Personal communication.

43. Jones, C. E. Personal communication.

44. Pearce, M. H. Personal communication.

45. Jones, C. E. Personal communication.

46. Roberts, S. D. Personal communication.

47. Thompson, L. H. Personal communication.

48. Brown, W. F. The Maple Lodge sewage purification works of the Colne Valley Sewerage Board. *J.Proc.Inst.Sew.Purif.*, 1950, (3), 316.

49. Fearn, R. J. Personal communication.

50. Ritchie, I. B. Personal communication.

51. Haigh, M. D. F. Personal communication.

52. Middle Lee Regional Drainage Scheme. *J.Proc.Inst.Sew.Purif.*, 1956, (4), 369.

53. Rock, W. C. Personal communication.

54. Clark, E. I. Personal communication.

55. The starting up of digesters: a symposium. *J.Proc.Inst.Sew.Purif.*, 1964. (4), 303.

56. Sambidge, N. E. W. Commissioning of a primary heated digester. *Wat.Pollut.Control*, **71**, 1972, (1), 105.

57. Mosey, F. E., Swanwick, J. D., and Hughes, Deborah A. Factors affecting the availability of heavy metals to inhibit anaerobic digestion. *Wat.Pollut.Control*, **70**, 1971, (6), 668.

58. Mosey, F. E. Anaerobic biological treatment. In *Symposium on Treatment of Wastes from the Food and Drink Industry*. Institute of Water Pollution Control, University of Newcastle-upon-Tyne, 1974.

59. Oliver, W. E. Sewage works of the Borough of Sutton and Cheam: Operational experiences. *J.Proc.Inst.Sew.Purif.*, 1963, (5), 434.

60. Mosey, F. E., and Hughes, Deborah A. The toxicity of heavy metal ions to anaerobic digestion. *Wat.Pollut.Control*, **74**, 1975, (1), 18.

61. Swanwick, J. D., and Foulkes, M. Inhibition of anaerobic digestion of sewage sludge by chlorinated hydrocarbons. *Wat.Pollut.Control*, **70**, 1971, (1), 58.

62. Lumb, C., Brown, D., and Bottomley, M. K. V. A chloroform problem at Great Warford and its solution. *Wat.Pollut.Control*, **76**, 1977, (4), 459.

63. Townend, C. B. Reflections on twenty-five years in Middlesex. *J.Proc.Inst.Sew.Purif.*, 1962, (1), 19.

64. Jackson, H. The sludge digestion plant of the Gravesend sewage disposal works. *J.Proc.Inst.Sew.Purif.*, 1934, (2), 76.

65. Stanbridge, H. H. Operation and performance of the Hogsmill Valley sewage treatment works of the Greater London Council, 1958–1966. *Wat.Pollut.Control*, **67**, 1968, (1), 21.

66. Department of the Environment/National Water Council. *The Sampling and Initial Preparation of Sewage and Waterworks' Sludges, Soils, Sediments and Plant Materials Prior to Analysis*. H.M.S.O., London, 1977.

67. NATIONAL JOINT HEALTH AND SAFETY COMMITTEE FOR THE WATER SERVICE. *Water Industry Health and Safety at Work*. Advisory Broadsheet 3-10.

68. WATER RESEARCH CENTRE. *Chromatographic Analysis of Digester Gas*. TR85, July 1978.

69. MINISTRY OF TECHNOLOGY. *Water Pollution Research* 1966. H.M.S.O., London, p. 109.

70. KLEECK, L. W. Van. Operation of sludge drying and sludge gas utilization units. *Sewage Wks. J.*, **17**, 1945, 1240.

71. PETTIGREW, F. Personal communication.

72. CASSIDY, J. E. Personal communication.

73. GREENE, G. Operation of the extended sewage works at Derby. *J.Proc.Inst.Sew.Purif.*, 1963, (3), 245.

74. COTTON, P. Personal communication.

75. STANBRIDGE, J. Maidenhead sewage works. *J.Proc.Inst.Sew.Purif.*, 1964, (2), 175.

76. WINSOR, C. E. Some problems of sludge digestion at small sewage purification works. *J.Proc.Inst.Sew.Purif.*, 1965, (1), 93.

77. HOYLE, W. H. Sewage disposal at Exeter. *J.Proc.Inst.Sew.Purif.*, 1936, (1), 8.

78. WARD, A. R. Sludge disposal at Stockport. *J.Proc.Inst.Sew.Purif.*, 1935, (1), 204.

79. THORNHILL, S. Chesterfield sewage works. *J.Proc.Inst.Sew.Purif.*, 1949, (3), 344.

80. INSTITUTE OF WATER POLLUTION CONTROL. *Unit Processes. Sewage Sludge III: Utilization and Disposal.* Manuals of British Practice in Water Pollution Control, 1977.

81. JENKINS, S. H. In discussion. *J.Proc.Inst.Sew.Purif.*, 1964, (1), 44.

82. BURGESS, S. G., and WOOD, L. B. The properties and detection of sludge gas. *J.Proc. Inst.Sew.Purif.*, 1964, (1), 24.

83. INSTITUTION OF CIVIL ENGINEERS AND MINISTRY OF HOUSING AND LOCAL GOVERNMENT. *Safety in Sewers and at Sewage Works*. 1969.

84. NATIONAL JOINT HEALTH AND SAFETY COMMITTEE FOR THE WATER SERVICE. *Water Industry Health and Safety at Work*. Advisory Broadsheet 7-6.

85. WOOD, L. B., and FOSSEY, P. The rôle of the scientist in safety measures at sewage works. *Wat.Pollut.Control*, **66**, 1967, (4), 386.

86. GOW, W. F., and NEILLY, W. M. Health and Safety at Work with special reference to Safety in Sewers. *Chart.mun.Engr*, **105**, Feb, 1978, 39.

87. POWNALL, E. R. Application of diesel and dual-fuel engines for sewage works duties. *J.Proc.Inst.Sew.Purif.*, 1953, (2), 111.

88. BUSWELL, A. M., and MUELLER, H. F. *Indust.Engng.Chem.*, **44**, 1952, 550.

INDEX

MANUALS OF BRITISH PRACTICE IN WATER POLLUTION CONTROL

Previous Manuals:

Glossary of Terms used in Water Pollution Control

Definitions of terms used in connexion with sewerage, sewage treatment, the treatment of industrial waste waters, and in pollution prevention and control. Includes definitions of engineering, financial, legal and scientific terms used in this connexion, terms associated with computerization, design, electrical equipment, instrumentation, laboratory control, management, process control techniques, safety equipment, telemetry, and work study. Short descriptions of industrial processes producing waste water are included, together with definitions of terms used in industry and in connexion with industrial waste control. Contains pronunciations of difficult terms (especially biological terms) and ends with a list of acronyms. Where processes are known by several different names, preferred terms are given which it is hoped will be used in future throughout the water industry. An authoritative reference book, recommended for use by everyone engaged in the water industry and especially by students. Price £3·50 (£2·50 to members, including subscribers); library edition £6 (£4 to members).

Preliminary Processes

Contains sections on screening and disintegration, grit removal, and proportionment and treatment of storm sewage. It includes 25 line diagrams and photographs and is complete with an index. Price £1·50 (£1 to members).

Primary sedimentation

Contains sections on sedimentation, horizontal-flow tanks, radial-flow tanks, upward-flow tanks, operation and maintenance of primary sedimentation tanks, pattern of flow in primary sedimentation tanks, special-purpose sedimentation tanks, aids to sedimentation, products of primary sedimentation, and septic tanks. Contains 41 line diagrams and photographs, together with an index. Price £2·50 (£1·75 to members).

Tertiary Treatment and Advanced Waste Water Treatment

Tertiary treatment processes described include removal of solids by prolonged settlement, irrigation over grassland, microstraining, slow sand filters, rapid downward-flow sand filters, upward-flow sand filters, and upward-flow clarifiers. Under advanced treatment, methods are described for removal of nitrogen compounds, phosphate, residual organic matter, and inorganic salts. These include chemical coagulation, activated carbon treatment, ozone treatment, ultrafiltration and reverse osmosis, electrodialysis, distillation and freezing, and ion exchange. Contains 27 line diagrams and photographs and is complete with index. Price £2·25 (£1·50 to members).

Sewage Sludge III: Utilization and Disposal

Contains sections on soil fertility, constituents of sewage sludges, heavy metals, nutrients and micro-nutrients, pathogenic organisms, application of sludge, disposal of liquid sludge to land, disposal of semi-dried sludge to land, dumping of sludge at sea and incineration. It includes 10 line diagrams, 12 plates and is complete with an index. Price £3·50 (£3 to members) including postage and packing.

Copies obtainable from the Institute's offices, Ledson House, 53 London Road, Maidstone, Kent ME16 8JH, cash with order.

PRINTED IN ENGLAND BY EDWARDS THE PRINTERS LTD., COVENTRY