

Anaerobic Processes

15.1 INTRODUCTION

Anaerobic digestion is a biological process in which organic matter is converted to methane (CH_4) and carbon dioxide (CO_2) by the co-ordinated activity of anaerobic microbes, mainly bacteria. The term anaerobic implies the absence of oxygen and nitrate. The process occurs widely in natural anaerobic environments such as peat bogs, marshes, lake sediments and in the rumen of cud-chewing animals. It is used as a treatment process for the stabilisation of sewage sludge and for the treatment of high-strength organic biodegradable liquid wastes.

Methane, the major gaseous endproduct of anaerobic digestion, is biochemically inert and hence its accumulation is not inhibitory to the continuation of the process. Although it was not until the third quarter of the nineteenth century that anaerobic bacteria (clostridia) were discovered by Pasteur, anaerobic fermentations have been exploited by man for thousands of years, e.g. in wine and beer making, in animal skin preparation for tanning and retting, etc. The first direct application of anaerobic digestion to sewage solids is attributed (Metcalf and Eddy, Inc., 1991) to Louis H. Mouras of Vesoul, France, who developed a sealed cesspool (ca. 1860) in which it was claimed that sewage solids were liquefied. The first exploitation of digester gas (biogas) is attributed to Donald Cameron, who built a septic tank for the city of Exeter, England, 1895. He collected and used the gas for lighting in the vicinity of the works. Anaerobic digestion processes were subsequently incorporated into sewage treatment systems using dual-purpose tanks combining sedimentation and digestion. The Travis hydrolytic tank (Hampton, England, 1904) and the Imhoff tank (Germany, 1904) are notable examples of such systems. In the 1920s and 1930s there was considerable development of anaerobic digestion for sewage sludge stabilisation with the construction of many heated digesters in the United States and Europe, particularly for large cities. Since the 1970s there has been an increasing application of anaerobic process technology for the treatment of high-strength liquid wastes of industrial origin, including the food, fermentation, pharmaceutical, pulp and paper industries.

15.2 PROCESS MICROBIOLOGY

A diverse community of interdependent microbial populations accomplishes the conversion of complex organic molecules to methane and carbon dioxide in an anaerobic digester. Scientific progress towards a complete understanding of anaerobic ecology has been retarded by, amongst other things, the potential difficulties of anaerobic culture, which demands an absolutely oxygen-free environment. Although there is an extensive literature on the subject, it would appear that knowledge of bacterial population dynamics in anaerobic digesters is rather limited. Bacteria are the main agents of biochemical conversions, but some anaerobic fungi and protozoa may also be involved. Anaerobic digestion may be described as a three-stage process, as depicted in Fig 15.1.

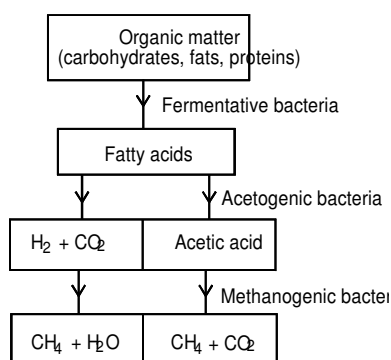


Fig 15.1

Anaerobic conversion of organic matter

The first stage involves the degradation of biopolymers to fatty acids by fermentative bacteria. In the second stage the higher fatty acids are converted in part to acetic acid and in part to the H₂/CO₂ combination by the acetogenic group of bacteria. Acetic acid and H₂/CO₂ are the key substrates of the methanogenic bacteria. It is estimated that about 70% of the methane produced is derived from acetic acid. Although hydrogen is an important precursor of methane formation in digesters, measured concentrations of H₂ are usually very low, suggesting an immediate uptake by the bacteria.

The methanogens are considered to be the key process organisms and are the most environmentally sensitive group in a digester population. They are unusual in that they are composed of many species with very different cell morphologies. Digester populations can be divided into two temperature groups: the mesophilic group is active between 10 °C and 40 °C and the thermophilic between 40 °C and 65 °C.

15.3 ENVIRONMENTAL INFLUENCES ON THE DIGESTION PROCESS

The methanogens are strict anaerobes and require a reduced environment for growth – the prevailing redox potential in anaerobic cultures has been found (Hughes, 1979) to be in the range –150 to –420 mV (relative to the hydrogen electrode), being generally closer to the latter value. A dissolved oxygen level as low as 0.01 mg l⁻¹ has been found (Wolfe, 1971) to completely inhibit methanogenic growth. Methane formation does not readily occur in the presence of electron acceptors such as nitrate and sulphate which, under anaerobic conditions, are reduced to nitrogen and sulphide, respectively, prior to the generation of methane.

Sulphide, which is an essential nutrient, is toxic at concentrations exceeding about 200 mg l⁻¹ (Mosey, 1976). Sulphides are removed through the formation of highly insoluble metallic sulphides.

Dissolved heavy metals, notably chromium, copper, nickel, cadmium and zinc, exhibit toxicity above certain critical levels. The sequestration of these metals by organic matter and their precipitation as sulphides can, however, greatly reduce the dissolved metal fraction. Table 15.1, taken from Barth et al. (1965), shows the concentration at which the indicated metals can be present in sewage without adversely affecting the anaerobic digestion of the resulting sludge. The light metal cations – sodium, calcium and magnesium – have also been found to be toxic at high concentrations (Kugelman and McCarty, 1965), with evidence of synergism (increased toxicity) and antagonism (reduced toxicity) when present in combination.

Table 15.1 Highest metal concentration in sewage that will allow satisfactory digestion of sewage sludge (Barth et al. (1965))

Metal	Concentration in influent sewage (mg l ⁻¹)	
	Primary sludge digestion	Combined sludge digestion
Chromium (hexavalent)	>50	>50*
Copper	10	10
Nickel	>40	>10*
Zinc	10	10

*higher dose not studied

The methanogens are particularly sensitive to the pH of the digester liquor. Digestion proceeds satisfactorily in the pH range 6.6-7.6 with the optimum value close to the neutral point 7.0. Although the growth of methanogens is inhibited below pH 6.6, the fermentation bacteria continue to function until the pH drops to the region 4.5-5.0, resulting in a rapid accumulation of volatile fatty acids (VFA) in the intervening pH range. This conjunction of low pH and VFA increase initially led to the conclusion that high concentrations of VFA were toxic to methanogens. However, many studies have shown that VFAs are not toxic to methane bacteria at the concentrations likely to occur in digesters. van Velsen and Lettinga (1979) found no adverse affect on digestion at a VFA concentration of 5000 mg l⁻¹ (as acetic acid), while Newell (1981) reported satisfactory operation of an anaerobic filter at VFA concentrations up to 11 800 mg l⁻¹.

Ammonia is an essential nitrogen source for anaerobic growth (C:N ratio ca. 30:1) but is toxic at high concentrations. In the range 1500-3000 mg l⁻¹ of ammonia-nitrogen, ammonia has been found to be inhibitory at pH above 7.4. At concentrations above 3000 mg l⁻¹ ammonia-nitrogen, ammonia has been found to be toxic regardless of pH.

Other potential inhibiting agents, which may sometimes be found in waste sludges particularly, include anionic detergents, chlorinated hydrocarbons, phenols and antibiotics. Anionic detergents, which are generally of domestic origin, may cause significant inhibition (Swanwick and Shurben, 1969) if their concentration exceeds about 1.5% of the dry sludge solids. The other organic inhibitors mentioned are generally of industrial origin and should not normally be discharged into public sewers in significant amounts.

Digestion temperature has a major influence on process kinetics, as already discussed. In the mesophilic range, i.e. 10-40 °C, it is generally found that maximum gas production occurs around 30-35 °C, the optimum value apparently depending on feed composition and the digester population. In the thermophilic range, i.e. 40-65 °C, the rate of gas production and quantity of gas produced increases with increase in temperature up to about 60 °C. Pfeffer (1979) found that thermal inhibition of methanogenic bacteria occurred at about 63 °C. There is also some evidence to indicate that there may be a thermally unfavourable temperature zone between the mesophilic and thermophilic temperature ranges, i.e. between 35 °C and 45 °C., where erratic gas production may be encountered.

15.4 PROCESS KINETICS

The Monod model of microbial growth kinetics, as outlined in Chapter 11, can be applied to anaerobic methanogenic systems. To apply this model in design, information is required on the model parameters Y , $\hat{\mu}$, k_d and K_s , for which some typical values for anaerobic processes, are given in Table 11.4.

In practical design situations, however, precise values for these parameters are usually not available, especially for complex wastes such as sewage sludge. For example, substrate concentrate is not measured directly but in terms of non-specific parameters such as COD or BOD₅. Despite this limitation, the kinetic model provides a very useful basis for process evaluation. Experimental measurements indicate approximately constant values for the coefficients Y and k_d for complex substrates such as sewage sludge. The value of Y is reported to be about 0.04 mg per mg COD removed and that of k_d to be about 0.01 d⁻¹. The value of Y reflects the low production of microbial sludge in anaerobic systems.

It is well known that anaerobic processes are very sensitive to temperature. The microbial growth coefficients $\hat{\mu}$ and K_s vary with temperature according to the following empirical correlations:

$$\hat{\mu}_T = 0.08 e^{0.034T} \quad (\text{d}^{-1}) \quad (15.1)$$

$$(K_s)_T = 90.6 e^{-0.106T} \quad (\text{g COD l}^{-1}) \quad (15.2)$$

where T is the process temperature (°C). Using these $\hat{\mu}_T$ and $(K_s)_T$ values and a k_d value of 0.01 d⁻¹, the predicted residual COD for sewage sludge is plotted in Fig 15.2 as a function of residence time and temperature (based on equation (11.14)). This graphical representation of the foregoing equations underlines the key influences of temperature and residence time on process performance. It shows that the sensitivity of residual COD to residence time is high at low residence time, but becomes very low as the residence time increases. For example, inspection of Fig 15.2 shows that there is only a marginal reduction in residual COD for retention times beyond 10 days, for a digestion temperature of 35 °C. The model also implies that the residual COD is independent of the influent COD concentration. The results of laboratory experiments on sewage sludge digestion (Mosey, 1976) generally confirm the above model characteristics. It was found that regardless of whether the solids content of the sludge was 3%, 6% or 9%, the proportion of volatile solids destroyed remained constant at about 45%, when the nominal residence times were progressively reduced from 50 days to 11 days. It would appear

therefore that the design practice of using residence times of 20+ days for completely mixed mesophilic sewage sludge digesters may be unduly conservative. A nominal residence time of 12-15d should provide an adequate safety margin to cope with variable loading.

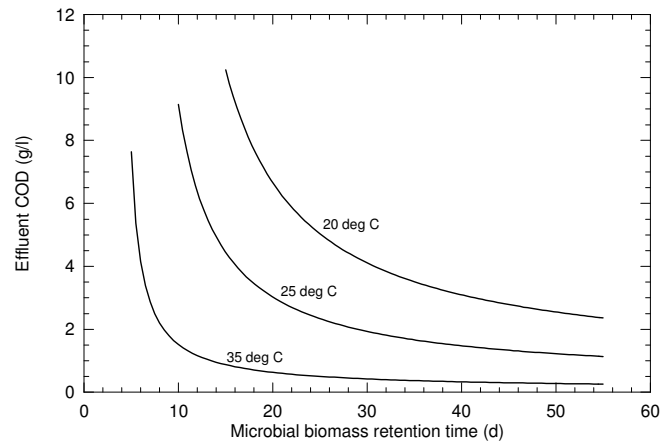


Fig 15.2 Influence of process temperature on residual COD in the Anaerobic digestion of sewage sludge

As shown in Chapter 11, the reactor volume required to achieve a given degree of substrate conversion is, according to the foregoing kinetics, less for a plug-flow reactor than for a completely mixed reactor. Upflow anaerobic sludge blanket contact reactors, which do not have an external mixing input, rely on the kinetic energy of the influent and on biogas generation to achieve an adequate level of mixing. Flow-through systems, as used in sewage sludge digestion, are invariably of the completely mixed type. However, it is also possible to use plug-flow reactors for sewage sludge provided there is adequate sludge recycling for seeding purposes, and an appropriate mixing system is used.

15.5 PROCESS TECHNOLOGY

The process technology employed in the exploitation of methanogenic processes can be broadly divided into two categories: (a) the long-established high-suspended solids digester systems used for the stabilisation of sewage sludge and animal manures, as illustrated in Fig 15.3, in which the residence time of the feed and the microbial biomass in the process unit is the same, and (b) the more recently developed ‘contact’ systems, as illustrated in Fig 15.4, in which the feed stream is brought into contact with the active microbial biomass retained in the system.

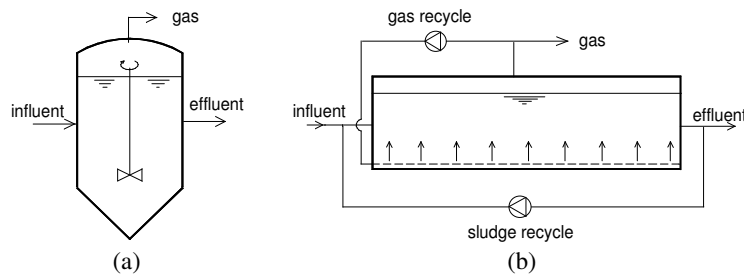


Fig 15.3 Conventional sludge digester configurations
(a) Completely mixed reactor (b) Plug-flow reactor

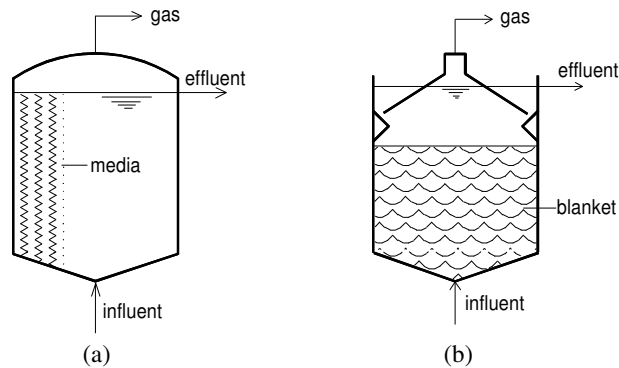


Fig 15.4
Anaerobic contact reactor configurations
(a) Upflow anaerobic biofilter (b) Upflow anaerobic sludge bed (UASB)

High-suspended solids reactors, which are used for the digestion of concentrated organic suspensions such as animal manures and sewage sludges, can operate at suspended solids concentrations in the range 2-10% on a dry weight basis. Sewage sludge digesters are invariably of the completely mixed type, with sludge recycling as a common design feature. Flow-through digesters of the plug-flow type have been used to a limited extent for the digestion of animal manures (Hayes et al., 1979). In addition to the potential kinetic advantages already discussed (refer Chapter 11), plug flow allows the use of a simple tank configuration, thus reducing capital costs.

Contact systems may be of the attached film or suspended granule type.

Attached film processes operate in a flooded upflow mode, as shown in Fig 15.4 (a), and may be of the static or fluidised media type. The medium used in static beds may be natural stone or plastic packing, while fluidised beds incorporate a fine-grained inert medium such as silica sand. Fluidised bed reactors require a high level of recirculation to achieve a fluidization upflow velocity.

Suspended granule systems incorporate a solids-separation stage, which may be external to the system and require solids recycling, as in the aerobic activated sludge process, or is more usually incorporated within the system, as in the upflow anaerobic sludge-bed reactor, shown in Fig 15.4 (b). This latter system uses a process technology similar to that used in sludge-blanket clarification in potable water treatment.

15.6 PROCESS DESIGN

The overall technical objective of process design may be said to be the provision of an optimal growth environment for the microbial population of the digester. The parameters over which the designer can exercise control include tank volume and shape, operating temperature, mixing input and, in some instances, the influent solids concentration.

From the foregoing discussion of process kinetics (see also Chapter 11), it will be clear that the reactor design volume is a function of the influent composition, the operating temperature, the microbial concentration in the digester and the required effluent quality. The effluent quality is a function of active solids residence time (SRT) and the process temperature, as illustrated in Fig 15.2.

15.6.1 High-suspended solids digesters

In high-suspended solids digesters the hydraulic and solids residence times are the same. A design residence time of 12-15d has been found to be adequate for the mesophilic digestion (30-35 °C) of

complex substrates such as sewage sludge and animal manures in flow-through digesters. The required tank volume (Fig 15.3) is simply the product of inflow rate and residence time.

In the case of substrates such as sewage sludge and animal manures, the influent suspended solids concentration is an important process variable, over which the designer may have control. The volume of a digester, for a given residence time and influent solids mass, bears an inverse relation to the solids concentration of the influent. Experience has shown that complex organic mixtures such as sewage sludges and animal manures can be digested, without significant loss in process efficiency, at solids concentrations up to 9% or 10%. Pre-thickening to remove excess water is therefore likely to be an economically attractive design option for many slurry-type influents, particularly sewage sludges. Not only is the required digester volume thereby reduced, but so the heat input requirement. Checks should be made, however, to ensure that pre-thickening of the digester feed does not concentrate inhibitory agents to a toxic level.

Mixing is an aspect of high-suspended solids digester design that merits special attention. It is essential to ensure that local dead spaces are not allowed to develop in a digester, reducing the available active volume. Equally, it is desirable to have a uniform temperature throughout the digester. A gentle level of mixing is adequate to achieve these goals. An external energy input is usually required, which may be in the form of mechanical agitation, sludge recirculation or gas recirculation. The latter is considered (Konstandt, 1976) the most appropriate method for digesters, being complementary to the mixing effect of the gas generated in the sludge bulk. It offers the designer flexibility in respect of tank geometry, being readily adaptable to any shape of tank. The mixing effect of shaft-mounted paddles, turbines or propellers, on the other hand, is dependent on the flow pattern generated by these devices, which is influenced to a large extent by tank geometry and by the viscous nature of the anaerobic mixed liquor. There appears to be no established design norm in respect of power input per unit volume for digester mixing at the present time. Indeed, it may well be that at high solids concentrations there may be adequate self-mixing through gas evolution in the system. In summary, appropriate mixing to ensure full digester volume utilisation is important, but intense mixing is not advantageous.

15.6.2 Contact Processes

Anaerobic contact processes are particularly suited to the treatment of high-strength liquid wastes with relatively low concentrations of suspended solids. Their high treatment capacity is dependent on the build-up and retention of a high concentration of active biomass in the reactor. As illustrated in Fig 15.4, they can be categorised in two groups (a) biofilm reactors, that include fixed bed, fluidised bed and expanded bed reactors, and (b) so-called granular systems such as the up-flow anaerobic sludge bed (UASB) and the expanded granular sludge bed (EGSB) reactors.

Anaerobic biofilm reactors contain a fixed or mobile inert material on which the biofilm develops and is retained within the reactor. Fixed film reactors may be operated in an upflow or downflow mode. They are suitable for treating wastewaters with a COD concentration in the range 1-20 kg COD m⁻³. For higher strength wastewaters, it is advantageous (Young and Yang, 1989) to recycle effluent to maintain an influent COD concentration in the range 8-12 kg COD m⁻³. When operated in the 30-35°C temperature range, the organic space loading rate typically varies in the range 2-10 kg COD m⁻³ d⁻¹, with a HRT in the range 10-15h (Wheatly et al., 1997).

Anaerobic fluidised bed and expanded bed attached film processes technologies have also been used with limited success, mainly due to the operational control problems.

In anaerobic suspended biomass processes of the UASB type (refer Fig 15.4b) a high biomass density is generated through the natural development of a 'granular' anaerobic sludge, that enables the generation of reactor concentrations in the range 40-60 kg m⁻³, which is some 10 to 15 times the operational MLSS concentration range of flocculent activated sludges. Granules are biomass conglomerates with a dense structure and a well-defined granular appearance. They typically vary in size within the range 0.1-5mm and have a settling velocity in the range 18-100 m h⁻¹. When operated in the mesophilic temperature range of 30-35°C, the typical loading rate range for UASB reactors is 5-20 kg COD m⁻³ d⁻¹ with a maximum upflow velocity of about 1.3 m h⁻¹ and a minimum HRT of 4-5 hours (Driessen and Yspeert, 1999).

The expanded granular sludge bed reactor (EGSB) is a variant of the UASB reactor (Kato et al, 1997). It is operated at liquid upflow velocities in the range 4-10 m h⁻¹ and organic space loading rates up to 40 kg COD m⁻³ d⁻¹. Such a high upflow velocity invariably requires re-circulation and inevitably means that lighter flocculent particles are washed out of the reactor and only the denser granular biomass is retained.

15.6.3 Digester heating

In high-suspended solids digesters the digester gas is conventionally used as a fuel to maintain the digester temperature close to the mesophilic optimum of 35 °C. It is rarely economic to raise the temperature of the more dilute waste streams treated in contact anaerobic processes.

The temperature of operation is a basic design parameter, influencing process kinetics and the overall degree of gasification, as shown in Fig 15.2. It also directly affects the energy balance of the process, which is a critical factor where the digester gas is used for heating or where the net energy production is the prime objective of process design. The required heat input is made up of two components: that required to raise the influent temperature to the operating level for the digester, and the make-up heat required to offset the heat loss from the digester vessel:

$$\text{heat input } H_i = \rho Q S_h \Delta T_1 + A U_a \Delta T_2 \quad (15.3)$$

where ρ and S_h are the density and specific heat capacity, respectively, of the digester influent, ΔT_1 is the temperature difference between the digester and the influent, ΔT_2 is the temperature difference between the digester and the surrounding air, A is the total surface area of the digestion vessel and U_a is its average overall heat transfer coefficient. In mesophilic applications, ΔT_1 typically has a design range of 10-35 °C, while the corresponding range for ΔT_2 , under temperate climatic conditions, is about 5-40 °C. It will be obvious from equation (15.3) that the heat input requirements can be reduced by reductions in the influent volume, the digester surface area and the thermal conductivity of the construction. Thus, in a particular application, an increase in influent solids from 2% to 4%, which reduces the volume by a factor of about two, effectively halves the heat input requirement. The importance of thermal insulation is demonstrated by an illustrative example in Fig 15.5. The plotted graphs relate to a free-standing cylindrical tank with a flat floor and roof, having a constructional thickness of 200mm throughout. At a typical flow-through digester design of 15d, the use of 50mm thick glass wool insulation on the walls and roof reduces the heat required to about half that required for the insulated system. The optimum degree of insulation can be determined from economic evaluation, taking into account the respective costs of heat energy and insulation.

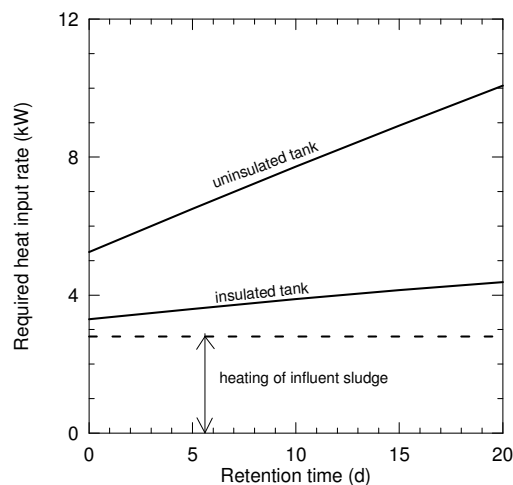


Fig 15.5 Influences of insulation and retention time on flow-through digester heating requirements $\Delta T_1 = 30$ °C; $\Delta T_2 = 30$ °C; $Q = 1.875$ m³ d⁻¹.

15.7 DIGESTER GAS

Digester gas consists mainly of methane and carbon dioxide, in proportions that vary with the composition of the substrate being degraded and in output quantities proportional to the amount of organic matter mineralised. Small amounts of other gases, notably nitrogen, hydrogen and hydrogen sulphide, may also be present. Average values for digester gas yield and composition are given in Table 15.2 and Table 15.3.

Table 15.2 Biogas composition and yield (Konstandt, 1976)

Substrate	Gas yield and composition		
Carbohydrates	0.8 m ³ kg ⁻¹	50% CH ₄	50% CO ₂
Proteins	0.7 m ³ kg ⁻¹	70% CH ₄	30% CO ₂
Fats	1.2 m ³ kg ⁻¹	67% CH ₄	33% CO ₂

It will be noted that the yield of methane from fats is about twice that from carbohydrates. Methane is the valuable component of digester gas. It is therefore useful to express gas yield in methane terms as m³ CH₄ per kg organic matter converted or as m³ CH₄ per kg COD removed. Some reported methane yield values are given in Table 15.3. The methane yield from liquid wastes, treated in contact processes, has been reported (Hayes et al., 1979) to vary in the range 0.3-0.5 m³ per kg COD removed.

Table 15.3 Typical methane yields at 35 °C

Substrate	Methane yield m ³ per kg organic matter removed
Mixed sewage sludge	0.8-0.9
Dairy manure	0.5-0.6
Pig manure	0.4-0.5

It will be clear from the discussion on kinetics that the extent of conversion of organic matter to gaseous end-products depend on the operating temperature and the residence time in the digester. At 35 °C some 40-50% of the volatile fraction of sewage sludge is removed in retention times of 12-15d. The yield of methane from sewage sludge under these conditions, on a per capita basis, has been reported (Metcalf and Eddy, Inc., 1991). To be 12-16 l per capita per day for primary sludge and about 20 l per capita per d for combined primary and secondary sludges. Pfeffer (1979) found that the anaerobically biodegradable fraction of solid refuse increased from 30% of the volatile solids at 35 °C to 55% at 60 °C.

Digester gas is usually stored in low-pressure, variable-volume gas-holders at a pressure in the range 100-300mm water gauge. The required storage volume depends on the usage pattern. Utilisation for purposes other than digester heating is generally determined by economic considerations. Potential uses include heating of local buildings, use as an engine fuel to drive electrical generators or vehicles, local industrial use and discharge to municipal gas network after appropriate upgrading.

It scarcely needs stressing that detailed attention to the safety aspects of gas handling is essential both at the design stage and during operation.

15.8 POTENTIAL PROCESS USES

The extent to which anaerobic processes may displace aerobic processes for organic waste stabilisation in the future will depend to a large extent on economic factors, which are likely to be influenced to an increasing degree by energy costs. The organic waste residues in question include domestic sewage and sewage sludge, solid refuse, organic industrial wastewaters, animal manures and crop residues. Anaerobic digestion processes are likely to be applied to an increasing extent in the case of three of

these residues, namely sewage sludge, concentrated organic industrial wastewaters and animal manures.

Flow-through mesophilic digestion processes having a residence time of 15-25d have long been used for sewage sludge stabilisation, particularly in treatment plants of medium to large size (>30,000 PE). Aerobic stabilisation is generally preferred for smaller plants.

Factors such as the cost of energy and the development of more efficient and less costly digester configurations will potentially lead to the increased use of anaerobic digestion in the sludge disposal field. Modifications of current design practice, which would lead to significant reductions in process capital cost, include:

- reduction in the sludge residence time from 20-25d to 12-15d;
- use of plug-flow digesters of simple shape, mixed by recycled gas;
- reduction in sludge volume by thickening prior to digestion.

In the field of industrial wastewater treatment, anaerobic contact processes would appear to have great potential for partial treatment of warm concentrated biodegradable wastes. The particularly attractive features of the process in this field of application are:

- very little surplus sludge is produced
- no external heat input is required
- usable energy in the form of methane gas is produced.

Summing up, therefore, it seems probable that the combined influences of improved technology and energy cost inflation could lead to a growing use of anaerobic digestion processes. However, the inherent operational sensitivity of the process will remain a serious constraint on this expansion. This applies particularly to situations where there is inadequate control over influent quality, as is sometimes the case with sewage sludges, particularly at small municipal wastewater treatment works receiving significant industrial discharges. In such situations, the environmentally more robust aerobic processes will continue to be preferred.

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