4.1 Introduction

The most common types of anaerobic digesters for solid wastes were compared in terms of biochemical and engineering aspects. A first distinction was made among batch, single-stage and two-stage systems. Batch systems are the lowest-tech of all the systems and also the cheapest. Their major drawbacks are a large footprint and a lower biogas yield due to the impairment of the percolation process via channelling and clogging. Batch systems have a high potential for applications in the treatment of small volume of wastes especially when the nature of discharge is intermittent. Two-stage systems is the most complex, and most expensive, of all the systems. Its greatest advantage lies in the buffering of the organic loading rate taking place in the first stage, allowing a more constant feeding rate of the methanogenic second stage. This is a substantial advantage in the case of substrates whose degradation is limited by the methanogenesis rather than by the hydrolysis, e.g. cellulose-poor kitchen wastes. These wastes, being very rapidly acidified, tend to inhibit the methanogenesis in one-stage reactors when the feedstock is not adequately mixed, buffered and dosed. A special type of two-stage system, designed with biomass accumulation devices in the second stage, displays a larger resistance toward toxicants and inhibiting substances such as ammonia. The drawback of this type of two-stage system is that solid particles need be removed from the feedstock to the second stage, which decreases the biogas yield. The large majority of industrial applications use one-stage systems and these are evenly split between systems where the wastes are digested as received ('dry' systems) and systems where the wastes are slurried with water to ca. 12% TS. From a financial viewpoint, the 'wet' and 'dry' designs are comparable in as much as 'dry' designs require much smaller reactor volumes but more expensive equipment. In terms of biological performance, 'dry' designs have proven reliable due to their higher biomass concentration, controlled feeding and spatial niches. 'Wet' design may achieve similar reliability via dilution of potential inhibitors with fresh water. From a technical viewpoint, however, the 'dry'
systems appear more robust as frequent technical failures are reported with 'wet' systems due to sand, stones, plastics and wood.

4.2 Review of Design of Anaerobic Reactors

If the literature on anaerobic digestion of solid wastes may at times appear confusing or difficult to summarize, one likely reason is that it is hard to find papers with similar experimental set-ups. In fact, it is precisely the appropriateness of a given reactor design for the treatment of particular organic wastes which forms the focus of most research papers. The comparison of research data and drawing of conclusions is difficult because the great diversity of reactor designs is matched by an as large variability of waste composition and choice of operational parameters (retention time, solids content, mixing, recirculation, inoculation, number of stages, temperature). Empirical know-how is the rule and there certainly does not exist a consensus over the optimal reactor design to treat tannery solid and liquid waste. The reason most likely lies in the complexity of the biochemical pathways involved and the novelty of the technology.

The discussion and evaluation of reactor designs will greatly vary depending on whether one takes a biological, technical, economical, or environmental viewpoint. While the biologist is concerned with the rate, stability and completion of biochemical reactions, the engineer will rather focus on wear & tear and maintenance of electromechanical devices. On the other hand, a seller will rate reactor designs based on fixed and operational costs while the environmentalist will consider emissions of pollutants and recovery of energy or materials. This chapter strives to address the technical and biological viewpoints in depth and highlight a few environmental and financial issues.

4.3 Types of High Rate Anaerobic Reactors

Despite the well recognized advantages of anaerobic biological process, its application was restricted to the treatment of concentrated wastes such as animal refuse and the sludge derived from aerobic treatment processes. This was mainly due to the reactor design which employed suspended microbial system, where microorganisms were removed from the reactor along with the treated effluent. This
necessitated a long residence time of even up to 20-30 days so as to keep high concentrations of the slow growing acetogenic and methane bacteria in the reactor, thus demanding a large volume reactors. This restricted the process application to industrial and domestic wastewater treatment.

During last two to three decades, high rate reactor types which separate hydraulic retention time (HRT) from biological sludge retention time (BSRT) and allow the slow growing anaerobic bacteria to be retained within the reactor independent of wastewater flow, have been developed. Most of these high rate systems are essentially retained biomass system, where microorganisms are present in the reactor as an attached biofilm grown on a support medium or as flows/granules which are easily separable from aqueous phase. Using these reactor designs, it has been possible to operate the reactors at higher organic loading rates and at low HRTs. Increased efficiency of these reactor configurations can be attributed to higher biomass concentration as well as positioning of different trophic microbial groups in a biofilm or granule resulting in better specific waste stabilization capacity. The introduction of these reactor designs has now made the application of anaerobic biotechnology to high strength organic wastewaters.

4.3.1 Continuously Stirred Tank Reactor

In common with many of the anaerobic bioreactor systems, the simple mix digester or continuously stirred tank reactor (CSTR) was developed from its aerobic counterpart. For effective treatment this reactor design (Fig-4.2) requires an extended HRT: it has no specific means of biomass retention, thus the SRT must be sufficiently high to permit biological conversion reaction to occur. If the minimum SRT required for anaerobic treatments in the range of four to ten days, and a design safety factor of 3 is applied, the design of HRT/SRT for a conventional digester would be in the range of twelve to thirty days. For the protracted SRT/HRT high rate anaerobic treatment using the CSTR are not possible. With such a long retention time, the introduction of raw influent can be made either on continuous or intermittent basis without causing a negative impact on the reactor performance. Mixing of the vessel contents in CSTR processes is generally achieved by mechanical agitation with paddle, impeller or screw systems or by gas diffusers (draught tubes) situated near the base of the
assembly, agitation tends to be intermittent in these reactors and can be maintained by periodic recalculation of the biogas produced.

The conventional single stage CSTR comprises a vessel of steel, concrete or brick. The heating of anaerobic CSTR unit can be affected by the utilization of an external water heat exchanger; the vessel contents are pumped through the exchanger as necessary upon a signal from a digester thermostat. This system is used on some sewage digesters. Internal water circulation heat exchangers are now used most frequently in commercial installations as these are more economical and compact and require only a small pump for hot water circulation.
Completely mixed digesters are particularly suitable for wastewaters containing high concentrations of particulates or extremely high concentrations of soluble biodegradable organic materials. In both cases, the reactor contents will contain high concentration of suspended solids that originate from either the raw wastewater or from anaerobic biological growth during pretreatment. The organic loading rates to conventional digester systems are usually expressed in terms of volatile solids (VS) since the predominant application of the process is for high particulate wastes. Loading rates of 0.5 to 0.0 kg VS m⁻³ d⁻¹ are typical.

CSTR systems are susceptible to malfunction upon shock loading or subsequent to the introduction of a variety of toxic substances. Malfunction manifests itself in terms of reduced gas production, reduced degradation of organic materials and simultaneous increase in acidity.

The contact or recycled floc process comprises a continuously fed, completely mixed reactor state followed by solids/liquid separation (Fig. 4.3). A degasification step is frequently included in system design. The effluent is discharged from the settling device and the settled biomass returned to the digester vessel where it is mixed with the incoming feed. Reclustering of a well-acclimatized sludge can maintain optimum stabilization of industrial wastewaters, which unlike sewage sludge can maintain optimum stabilization of industrial wastewaters, which unlike sewage sludges do not contain a high proportion of micro flora. The bacteria in a contact process occur as suspended flocs and the system is maintained in suspension by mechanical stirring, gas sparging or recycle. VSS concentration of 4000 - 6000 mg/l is generally maintained in the reactor. Inert particles in the feed stack may act as media to convert the reactor to the carrier assisted contact process, but in general the bacteria must form flocs to remain in the system. The separation of solids and liquids is a crucial operation in the contact digester and the removal of gas producing particles is difficult. A number of approaches have been developed to enhance sludge stability including gas striping, stirred or vacuum degasification, inclined plate or lamella settlers, and the formation. Cooling of the effluent en-route to the separator may counteract the problem. Sludge settling characteristics tend to deteriorate at sludge loading in excess of 0.25 kg COD/kg VSS.d, and biomass separation from medium becomes more difficult above a mixed liquor VSS concentration of 18,000 mg/l. Efficient settling of sludges can also not be achieved under conditions of high influent SS in anaerobic contact reactors. High rate treatment in general is unlikely to
be efficient in this type of reactor, as influent SRT, if prolonged to any extent, will tend to lead to the displacement of biomass.

Anaerobic contact process can be applied over a wide range of wastewater concentrations. Although the lower economically practical limit of wastewater concentration is probably in the range of 1000 to 2000 mg COD/L, there is no well-established upper concentration limit. At very high wastewater concentrations, the completely mixed anaerobic reactor is the best alternative for efficient digestion while minimizing internal reactor hydraulic inefficiencies. Wastewaters of up to 1000,000 mg/COD/L can be treated in an anaerobic contact process as long as the anaerobic floc produced has satisfactory settling properties. The treatment efficiency of an anaerobic contact process is usually much greater than that of a completely mixed digester. Total COD reductions of 85-90% are possible for highly biodegradable wastewaters with COD concentrations of 2 to 10 g/L. Typical organic loading rates in anaerobic contact systems are between 0.5 to 10 kg COD/m^3 d with HRT(s) of 0.5 to 5 days.

4.3.2 Anaerobic Lagoon

The advanced form of anaerobic lagoon technology has gained acceptance for low-rate anaerobic treatment processes. The system can be constructed as either a rectangular, excavated and lined lagoon or as an above ground tank in locations where less land is available (Fig.4.4). Untreated wastewater is introduced at one end of the reactor through a distribution system to maximize contact between the wastewater and a settled bed of anaerobic biosludge at the inlet end of the tank. In the inlet zone, evolved biogas also contributes significant internal mixing. Along the length of the tank the depth of the sludge bed and the amount of associated biological activity both decrease. Near the outlet end of the lagoon, where biogas production is minimal, a relatively quiescent clarification zone is maintained to reduce the suspended solids content of the treated effluent. In the most modern system of this type, internal mixers and sludge recycle are often used to improve the contact between the wastewater and the anaerobic sludge. The entire reactor is usually covered with a floating insulated membrane that conserves process heat and permits the collection and utilization of evolved biogas.
The covered lagoon process is relatively economical to construct. It is also suitable for wastewaters that contain high levels of suspended solids or significant amount of oil and grease.

The accumulation of settled biomass sludge results in very long effective SRTS and maximizes the endogenous destruction of particulates to minimize the amount of sludge requiring disposal. Nutrients released from endogenous decay of the sludge become available for reuse by the active microorganism. If the anaerobic treatment stage is followed by an aerobic treatment system, waste aerobic sludge can be returned to the covered lagoon for anaerobic digestion. Periodically, accumulated sludge may need to be removed from the process for ultimate disposal.
Typical HRTs in a covered lagoon may be between six and thirty days. Corresponding organic loading rates are usually less than 1 to 2 kg COD m\(^{-3}\) d\(^{-1}\). The low rate nature of the covered lagoon renders sludge stability less crucial than in an anaerobic contact process. The large reactor volumes provide a good degree of equalizing for toxics and organic shock loads. However, the process may suffer from mixing inefficiencies and non-ideal contact between incoming wastewater and the anaerobic biomass. Nonetheless, the effluent quality from this process is often superior to that from an anaerobic contact process.

### 4.3.3 Fixed Film Anaerobic Reactor Designs

Biofilm reactors utilize a fixed film approach for the development of the high biomass concentrations required for efficient anaerobic treatment of wastewaters. An inert medium or biomass carrier is added to the treatment vessel and the process is operated to favour the growth of microorganisms on the medium surface. This physical attachment prevents biomass washout and leads to high values of microorganism's concentration and SRT. It also permits these reactors to be operated with liquid up flow velocities which would easily washout nonattached biomass. While relatively high microorganisms concentrations can be achieved in biofilm reactors, the need to control the accumulated biomass becomes of increasing concern.

The three major up flow biofilm processes currently used in anaerobic treatment applications can be distinguished qualitatively by the degree of media expansion maintained in each. At low flow rates of the feed wastewater, there arises a pressure drop (fixed bed), but as the flow rates are increased, the pressure drop eventually becomes equal to the sum of the weight of solids per unit area of bed, plus the friction of the solids at the reactor walls (Fig. 4.5).
FIG 4.5 UPFLOW FIXED BED ANAEROBIC DIGESTER

FIG 4.6 DOWNFLOW FIXED BED ANAEROBIC DIGESTER
If the media is free flowing, an increase in up flow velocity causes the bed to expand and the pressure drop will equal the weight area of the bed (expanded bed). A further increase in up flow velocity will cause further enlargement of the bed and the voidage increases sufficiently for the solid particles to move about freely (fluidized bed). If the up flow velocity is increased beyond the terminal settling velocity of the bed particles, the media will be entrained in the liquid and carried out of the reactor (transported or moving bed).

4.3.4 Fixed Bed Process (Anaerobic Filters)

The wastewater in the anaerobic filter (fixed bed, fixed film) systems passes the reactor usually with vertical flow either up flow or down flow. Various media types have been employed in both up flow and down flow anaerobic filters of average diameter 0.2 mm – 6.0 cm and of both porous and nonporous structure. To minimize blockage filter media of relatively large diameter (~2.0 cm) is used in down flow filter reactor. The surface area of medium per m² of reactor is limited to 200 m²/m³. Due to this restricted area the sludge grows in these layers of the 1-4 mm around the packing particles. The surface roughness of the packing filter media and the degree of porosity, in addition to pore size, affect the colonization by bacteria. The synthetic packing materials, in spite, of its relatively high costs are mostly used in the commercial installations. The advantage of the synthetic packings lies in their large open structures and high void volumes (95%). The large voidage maximizes the available reaction volume and provided space for the accumulation of non-attached bioassays. There does not appear to be a best medium for use in fixed bed anaerobic reactors. Random loose-fill packings such as plastic ball rings and ordered, moulded block media formed from plastic sheet have both been used in full-scale applications.

The available data suggest that the cross flow modular media results in higher process efficiencies than random packing. The specific surfaces to volume ratio of the most commonly used bed packings are relatively low (100 m²/m³). Research evidence suggests that media surface areas of up to 220 m²/m³ do not produce a significant improvement in reactor performance. The microorganisms in the anaerobic filter reactor mostly attach to the filter media. A substantial percentage of the bioassays occurs as suspended flocks trapped in the spaces between the media
particles in the up flow reactor design (Fig.4 to) whereas in down flow systems (Fig.4.7) the bioassays is retained almost entirely as a film on the media and reactor walls. The bacterial mass in and on the inert medium rapidly degrades the substrates in the waste stream, and although the bioassays tends to disentail at intervals, its overall detention time in the digester may be of the order of 20 days thus permitting the growth of methanogenic bacteria. Once a suitable micro flora has developed to a sufficient degree, it can be maintained permanently in the reactor to ensure continuous growth. The non-attached bioassays play the major role in anaerobic conversion. Waste treatment in anaerobic packed bed reactors is frequently initiated by seeding the system with active bacteria from the anaerobic digester operating under steady state. The maturation process ranges from 3 to 10 weeks and comprises of the development of the microorganisms responsible for waste conversion and methanogenesis either attached to the media surfaces or accumulated in the interstitial void spaces by a combination of flocculation and settling. Constant effluent quality and gas production rate indicates steady state.

The treatment of soluble organic wastes is mostly done in up flow design whereas for high suspended solids wastewater, the down flow mode is preferable to operation in the up flow mode. Fixed-bed anaerobic treatment processes are applicable to wastewaters with low (1000 mg COD/l) to intermediate (20,000 mg COD/l) concentrations. For high strength wastewaters, it has been recommended that effluent recycle be used to maintain the reactor inlet COD concentration between 8,200 – 12,000 mg/l. Full scale up flow and down flow fixed bed processes have been designed for organic loading rates of up to 16 kg COD/m²d. The HRT associated with these loading are between 12 – 96 hours. Anaerobic filters can resist high shock loads. Large shock loadings of toxic materials are frequently accommodated by anaerobic filters primarily because of the biofilm nature of the micro flora.
FIG 4.7 SCHEMATIC OF EXPANDED AND FLUIDIZED BED ANAEROBIC PROCESS

FIG 4.8 SCHEMATIC OF ANAEROBIC FLUIDIZED BED SYSTEM WITH GAS LIQUID SOLID SEPARATOR
4.3.5 Expanded and Fluidized Bed Processes

With the expanded and fluidized bed processes (Fig. 4.8), attempts have been made to improve anaerobic reactor mass transfer characteristics by the use of small media particles with very high surface to volume ratios. As shown in Fig. 4.7, the difference between expanded and fluidized bed reactors is due to the up flow velocity used and the degree of media expansion maintained. In expanded bed systems, sufficient flow is applied to increase the settled bed volume by 1 to 30%. The higher up flow velocities utilized in the fluidized bed produce 25 – 300% bed expansion. In the fluidized state, the media particles are supported entirely by the flowing liquid and are, therefore, able to move freely in the bed. Spherical silica sand of 0.2 – 0.5 mm diameter and specific gravity of 2.65 is the most commonly used medium in the full-scale anaerobic fluidized bed systems. Extensive pilot scale studies have been completed on expanded and fluidized bed systems containing granular activated carbon that would provide an advantage for application to the treatment of toxic or inhibitory wastewaters. If the toxicant is absorbable on the carbon, low toxicant concentrations can be maintained in the bulk liquid and biomass exposure to the toxicant may be reduced. The lower specific gravity (1.5) of GAC will also allow expanded or fluidized operation with lower up flow velocities and reduced effluent recycle power requirements than in sand-media systems.

In both process, an anaerobic biofilm is developed on the surface of the media particles. The inert medium increases the average density of the biomass particle and prevents washout of the bed even under very high flow rate conditions. The large up flow velocities applied in expanded and fluidized systems promote turbulence and in turn promote good mass transfer into and out of the biofilm, and under some conditions exerts sufficient shear to prevent the development of thick biofilms on the media. The high up flow velocities in expanded and fluidized systems allow the reactors to be designed with relatively large height/diameter ratios and smaller land area requirements.

In fluidized bed processes, the combination of their biofilms and high turbulence prevents the capture and retention of influent suspended solids within the reactor. This makes the fluidized bed a classical fixed film process that is best suited to the treatment of wastewaters containing only soluble contaminants. As the biofilm thickness increases with growth, the average density of the biofilm/media particles decreases. In a fluidized bed, these lower density particles tend to migrate to the top
of the reactor. This produces biosolids profiles that are opposite in nature to those observed in fixed bed up flow reactors. In a fluidized bed, the highest biomass concentrations occur at the top of the bed. The lowest biomass concentrations occur at the reactor bottom, where liquid velocities and the associated turbulence are the greatest. The control of the biomass inventory in a fluidized bed can be difficult. Unexpected increases in biofilm, thickness can result in accidental washout of the biomass, particularly if a small diameter medium is used. Some fluidized bed designs have incorporated gas-solids liquid separation devices for biomass control. These separators (Fig. 4.9) are similar in nature to those used in up flow anaerobic sludge blanket processes.

Expanded and fluidized bed reactors have some design requirements that are comparable to those of the fixed bed processes. The need for influent equalization should be evaluated in both cases. Efficient influent flow distribution is also critical in expanded and fluidized beds. Because very high effluent recirculation ratios are often required for media fluidization, maximum dilution of wastewater is provided incidentally at the reactor inlet. This enables the expanded and fluidized bed processes to accommodate a wide variety of wastewater concentrations (\( <1000 \rightarrow 20,000 \) mg COD/l) without concern for generating high concentrations of volatile acids near the bottom of the reactor. Organic loading rates of up to 25 kg COD/m\(^3\)d are typical of these systems. The quality of effluent is better in the fluidized bed than fixed bed anaerobic processes at higher organic loading rates. The energy required for effluent recycles for bed expansion or fluidization is one of the most significant disadvantages of these systems.
FIG 4.9 SCHEMATIC OF UPFLOW ANAEROBIC SLUDGE BLANKET (UASB) REACTOR

FIG 4.10 SCHEMATIC OF ANAEROBIC HYBRID REACTOR (UPFLOW SLUDGE BLANKET / FIXED BED REACTOR)
4.3.6 Upflow Anaerobic Sludge Blanket Reactor (UASB)

The upflow anaerobic sludge blanket reactor (Fig. 4.10) features a bed of granular and flocculated sludge suspended by an upflow of wastewater. The reactor consists of three distinct zones: a sludge bed, a sludge blanket and settling gas separation zone. The wastewater is fed through the bottom of the tank and flows upward through a bed of dense/granular sludge and a blanket of flocculated sludge particles. As the liquid moves through the floc, increased SRT is achieved relative to HRT. Gas and suspended solids are separated from the treated liquid by means of an internal gas-solid separator device. Baffles are used to release trapped gas, thus promoting the settling of sludge particles back toward the digesting zone, promoting long SRT and high concentration of sludge in digester.

Although gas bubbles from the produced gas provide mixing, some of the influent may bypass the sludge bed zone via cracks and channels. The sludge bed zone has been reported to be responsible for 80 - 90% of the waste degradation in the reactor and to occupy approximately 30% of the reactor volume. After passing through the sludge bed zone, the influent enters that sludge blanket section, which occupies the remaining 70% of the reactor volume. With the solids concentration in this zone lower than that of the sludge bed, rising gas bubbles mix the flocculated sludge blanket. This process is often considered to be an advanced form of wastewater treatment for high strength organic influent. Organic loading rates of up to 12.5 kg COD/m³.d are typical of these reactors.

4.3.7 Upflow Blanket Filter Reactor

The recent trend in up flow fixed bed reactor design is toward the use of a "hybrid" process. 50 - 75% of the media volume from the lower section is removed in the hybrid reactor. The resulting hybrid design has the potential of substantially reducing the media plugging and the associated hydraulic and mass transfer problems found in fixed bed reactors, while realizing the advantages of both fixed film and up flow sludge blanket treatment.

In the hybrid process, non-attached biosolids are free to accumulate in the unpacked zone below the media. In the absence of media, the concentration and the level of the sludge blanket is easily monitored. Further, the mixing characteristics in
the critical bottom portion of the reactor can be more easily maintained without interference from the packing. Biosolids wasting from the sludge blanket zone is also relatively straightforward. The packed zone at the top of the reactor serves as a gas-solid-liquid separator that assists in the retention of the non-attached sludge bed. It further provides a polishing zone of attached biomass that improves process stability under transient operating conditions. The most significant benefit of the hybrid reactor concept is the reduced cost of the support media required in the anaerobic filter reactor.

4.4 PLANNING AN ANAEROBIC DIGESTER

4.4.1 Objectives

In planning a digester the objectives must be very clear to choose the right type of digester and the criteria on which it must be designed. In the first instance, the decision must be made as to whether anaerobic digestion is being considered primarily as a pollution control method, with the production of a usable gas and sludge with valuable fertiliser content as by-products or whether there is greater emphasis on the methane production. Although optimisation of both are not incompatible goals, if methane production alone is important the design criteria are likely to be less exacting and the digester system cheaper to install. If pollution control is the main consideration the cost of a digester can be offset against the cost of other treatment equipment, which might have been necessary. In this case the efficiency of the process may be dictated by the requirements of the pollution control authority for safe disposal of waste, in the case of methane production being the more important benefit, the potential use of the gas will provide the criteria on which to base the design.

Plug-flow, displacement digesters take a longer time to break down the organic matter (measured by the volatile solids or BOD contents) than the completely mixed, high-rate digesters. This can be seen in Figure 4.11 in which the reduction in VS content is plotted against time for both kinds of digesters. It can be seen that high-rate digesters do not, however, necessarily produce more gas per weight of volatile solids, but because of the shorter retention time the gas is produced more quickly. The total daily gas production probably very similar for most digester types treating
the same waste since high rate digesters contain a smaller amount of volatile solids, while systems with longer retention times have a larger total weight of volatile solids but a much lower rate of gas production per day.

![Graph showing average % reductions in volatile solids with retention times](image)

**Fig. 4.11 – Average % reductions in volatile solids with retention times**

### 4.4.2 Availability of waste

The first and foremost requirement while planning a digester is to estimate the availability of digestable waste each day. Volume of waste produced varies depending upon the leather processing technique that had been undertaken; the actual figures will depend upon a number of factors. The total volume of waste will depend on the number of animals being slaughtered, volume of hides and skins, how they are preserved and processed and how much water and other tanning chemicals are used during the entire process.

Thus in estimating the volume we must take into account whether the similar leather process is done all year round, or whether, as in the case of most leather industry, they vary season to season upon the market requirement. The volume of waste that generate do also vary depending upon the process.

Secondly the calculations should take into account the way in which the tanning chemicals are added during the process. And the volume taken up and washed away.
The incidental water, which finds its way into the waste, may constitute a significant proportion of the total. It comes mainly from washing down during the process.

Thus the first stage in our calculations provides us with knowledge of how much waste is produced, at what times of day and whether it is produced all the year round. We also know what diluting factors need to be considered and whether the total waste contains toxic material or not. The figures given in the table are only guidelines and since every industry situation is different, they must be verified or corrected as far as possible before a practical digester is built. Table 1 is the illustration of amount of solid waste generated during the leather processing.

The daily volumes of industrial wastes can be calculated from knowing how much water is used to make one unit of production or to process a given weight of material. Total water usage is known far more accurately than on farms, for the water authorities usually install water meters in factories so that they can make accurate charges for the water used. However, there are often discrepancies in water use in many factories, and a survey of the wastes is necessary to verify the figures and to pinpoint the sources of water wastage.

**TABLE 4.1 - AMOUNT OF SOLID WASTES PRODUCED FROM PROCESSING 1 T OF RAW SKIN/HIDE (RAVINDRANATH AND KAUL 2000)**

<table>
<thead>
<tr>
<th>Nature of solid waste</th>
<th>Quantity (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt from handshaking</td>
<td>80</td>
</tr>
<tr>
<td>Salt from solar pans (not realized)</td>
<td>220</td>
</tr>
<tr>
<td>Hair (pasting ovine)</td>
<td>100</td>
</tr>
<tr>
<td>Raw trimmings</td>
<td>40</td>
</tr>
<tr>
<td>Lime sludge (mostly bovine)</td>
<td>60</td>
</tr>
<tr>
<td>Fleshing</td>
<td>120</td>
</tr>
<tr>
<td>Wet blue trimmings (grain splits)</td>
<td>30</td>
</tr>
<tr>
<td>Chrome splitting (bovine)</td>
<td>65</td>
</tr>
<tr>
<td>Chrome shaving (mostly bovine)</td>
<td>95</td>
</tr>
<tr>
<td>Buffing dust (including shaving bovine after crust)</td>
<td>65</td>
</tr>
<tr>
<td>Dyed trimmings</td>
<td>35</td>
</tr>
<tr>
<td>Dry sludge from ETP</td>
<td>125</td>
</tr>
</tbody>
</table>
4.4.3 Strength of the waste

The characteristics of the waste should then be estimated and verified by further analysis. The actual concentrations will vary considerably with, size and number of the animals slaughtered, as do the daily volumes of waste produced. This will have an effect upon the daily gas production.

The moisture content, total solids and volatile solids are the easiest to measure and the most important for calculating the size of digester needed. The moisture content is needed since it shows how fluid the mixture is and how much dilution is necessary for the best results in anaerobic digestion (90 – 98% moisture). Having chosen working moisture content, the quantity of dilution wastewater required can be calculated to derive the total volume of the waste to be digested. Fry (1973) states that the best moisture content is when the slurry has the consistency of cream.

The total solids plus the moisture content make up the whole waste. The volatile solids are expressed as a percentage of the total solids, and from this the total weight of volatile solids can be calculated. The total daily volume of the waste and the total daily weight of volatile solids provide the figures on which the design of the digester is based.

The BOD produced per animal and their concentrations in the waste are useful parameters, for they are also an indication of the organic load upon the digester. The amount of BOD produced per animal is sometimes used to calculate the Population Equivalent (PE) of each animal, a figure that is useful in order to obtain an overall idea of the amount of polluting material in the waste. For instance a herd of 100 cows is the equivalent of 730 people. Sewage works designers sometimes use population equivalents in sizing various parts of the works, including anaerobic digesters, but since digesters for treating tannery wastes have slightly different criteria, PE is not all that useful for this purpose.

The BOD figures also give a measure of the total biodegradable carbon in the waste. A rough estimate of the total carbon content is obtained by dividing the BOD by 1.7. This is useful in the determination of the carbon/nitrogen ratio. This should be in the region of 20 – 30 to 1 for optimum digestion. The C/N ratio should never be above 30:1, but digestion will take place satisfactorily if it is below this figure. Most animal manures have a low C/N ratio, especially if urine, which contains much of the nitrogen is collected with the faeces. However, animal wastes usually have quite a high proportion of vegetable matter, either from bedding material or foodstuffs, mixed
in with the excreta. Since these have lower nitrogen content the result is that many slurries or farmyard manures have a reasonably high C/N ratio.

**TABLE 4.2 – NITROGEN CONTENTS OF SOME TYPICAL PLANT MATERIALS**

<table>
<thead>
<tr>
<th>Plant material</th>
<th>Total N % Dry weight</th>
<th>C/N Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straws</td>
<td>0.5 – 1.1</td>
<td>50 – 150</td>
</tr>
<tr>
<td>Hay</td>
<td>2 – 4</td>
<td>12 – 20</td>
</tr>
<tr>
<td>Grass clippings</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Non-legume vegetables</td>
<td>2.5 – 4</td>
<td>11 – 19</td>
</tr>
<tr>
<td>Sawdust</td>
<td>0.1</td>
<td>200 – 500</td>
</tr>
</tbody>
</table>

Some industrial wastes, especially those from the food industry, may contain very little nitrogen and phosphate, e.g., starch wastes from potato processing and from starch-reduced food manufacture, malting wastes from breweries and distilleries, and vegetable-processing wastes. Their very high carbon content will need to be balanced by some nitrogen, and it might be possible to do this by adding some of the high nitrogenous wastes from abattoirs and meat-processing factories. Blood and meat wastes often have C/N ratios between 3 and 5 to 1.

**TABLE 4.3 – C/N OF TANNERY SOLID AND LIQUID WASTE**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Type of Waste</th>
<th>C/N Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Limed Fleshing</td>
<td>35 : 11.2</td>
</tr>
<tr>
<td>2</td>
<td>Sulphide Fleshing</td>
<td>29.5 : 8.4</td>
</tr>
<tr>
<td>3</td>
<td>Secondary Sludge</td>
<td>16.5 : 1.5</td>
</tr>
<tr>
<td>4</td>
<td>Primary Sludge</td>
<td>23.7 : 2</td>
</tr>
</tbody>
</table>
Apart from the C/N ratio the nitrogen content of wastes is also important from the point of view of ammonia toxicity. The toxic limit for ammonia is about 3000 mg/l (provided the pH is above 7.0); the nitrogen content of the waste should be kept well below this figure. The most practicable way of doing this is by dilution. Thus the waste may have to be diluted on two counts. One, the solids content may be too high and secondly, the ammonia or total nitrogen contents may be toxic. A balance should be found so that the criteria of correct moisture and low enough nitrogen content are satisfied by the dilution.

Thus the second stage in planning for a digester has been to decide how much dilution of the waste will be necessary, whether to include any additives to correct the C/N ratio and finally, to fix an estimate of the total daily volatile solids content.

4.4.4 Sizing the digester

There are three ways in which digesters can be sized: by having a fixed retention time and knowing the total daily volume of influent; by having a fixed loading of volatile solids per volume of the digester; and by having a fixed volume for every population equivalent in the waste.

Usually a combination of the first two methods is used. Different types of digesters have their own optimum retention times to achieve sufficient breakdown of the volatile matter and the maximum gas production. It would seem that in general the variation in the loading rate between the different types is not that great. An analysis of the design criteria of some working digesters is given in Table 4.4, to show how they differ. The retention time varies between about 10 and 40 days depending upon the system, but the organic loading only varies between 0.05 and 0.2 lb/VS/cu.ft/day (0.8 – 3.2 kg VS/m³/day) for most purposes and is generally around 0.17 lbs VS/cu.ft/day (2.8 kg VS/m³/day). This, then, is more important a criterion than retention time, for retention time can be easily altered by adjustment of the moisture content. The third method is probably not very useful for purposes other than the design of sewage-works digesters and even then it is open to errors. As a point of interest, cold digesters have been designed on 6 – 12 cu.ft of digester volume per person and heated digesters on 2 - 5 cu.ft per person. Having evaluated the waste as it arrives for digestion, for daily volume, moisture content, total and volatile solids produced per day, if we take a figure of about 0.17 lbs VS/cu.ft/day (2.8 kg/m as
being around the correct loading for a digester, we can calculate the minimum volume necessary to digest that weight of volatile solids. In choosing a figure of 0.17 lbs VS/cu.ft/day (2.8 kg/m³) as a preliminary design loading we can be sure of sizing the digester in approximately the correct range. It is better to oversize than to undersize it, for this not only allows for an increase in the amount of waste produced but also for estimating errors, and ensures that the waste will be sufficiently digested. It may be an advantage to find a range by calculating the sizes with loadings of both 0.1 and 0.2 lbs VS/cu ft/day (1.6 – 3.2 kg VS/m³/day). The next stage is to divide this minimum size by the volume of waste produced per day to find the retention time. If this retention time falls within the range of the digester system chosen, this is all to the good and the waste does not need any further dilution or concentration. Figure 4.12 shows some of the ranges of operating moisture contents with the retention times of various digesters. It is not a hard and fast rule that the more diluted a waste the shorter the retention time, but there does appear to be a general trend towards this. It is obvious, however, that for a completely mixed high rate system the dilution should be greater than for a plug-flow digester (and also for a batch process) since wastes with a high solids contents are more difficult to mix efficiently. The process chosen should take into account that a high rate system achieves a greater reduction in organic matter with a slightly reduced gas production, while a longer retention time system (e.g., a plug-flow) may not reduce the polluting material so much, but would have a similar or slightly higher gas production. So, if the retention time is too short for the process the moisture content should be reduced and with it the volume. A waste of 95% moisture content is twice the volume of one of 90% moisture content and three times the volume of one of 85% moisture, the retention times are thus twice and three times longer for these moisture contents. On the other hand, if the retention time is too long or the waste is too thick to be pumped or mixed efficiently, then the volume should be increased by diluting it. Thus the next stage is to find the moisture content which, when put into a digester of the correct capacity to deal with the total weight of volatile solids, will give the appropriate retention time.
### TABLE 4.4 – OPERATING PARAMETERS OF VARIOUS DIGESTER SYSTEMS

<table>
<thead>
<tr>
<th>Type of digester system</th>
<th>Temp <em>°C</em></th>
<th>HRT Days</th>
<th>OLR Kg/m²/day</th>
<th>VS destruction %</th>
<th>Specific Gas Production m³/kg VS</th>
<th>Rate of Specific Gas Production m³/kg VS/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional sewage digesters</td>
<td>Ambient cold digestion</td>
<td>55-75</td>
<td>1.33</td>
<td>97-94</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(Displacement type)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Standard sewage works digester.</td>
<td>Heated</td>
<td>25-30</td>
<td>2.6-3.4</td>
<td>97-94</td>
<td>0.43-0.56</td>
<td>0.017-0.022</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>11-46</td>
<td>0.73-3.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(avg. 27)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High rate</td>
<td>35</td>
<td>15</td>
<td>5.2-11.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimum sewage</td>
<td>12-15</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Rowett Research</td>
<td>35</td>
<td>10</td>
<td>2.6-3.7</td>
<td>95-94</td>
<td>0.42</td>
<td>0.042</td>
</tr>
<tr>
<td>Piggy wastes</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td>0.38</td>
<td>0.054</td>
</tr>
<tr>
<td>(High rate)</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>0.39</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>10</td>
<td></td>
<td></td>
<td>0.39</td>
<td>0.039</td>
</tr>
<tr>
<td>4. Auchincruive</td>
<td>Heated</td>
<td>23</td>
<td>3.2</td>
<td>90</td>
<td>0.39</td>
<td>0.017</td>
</tr>
<tr>
<td>5. Imhoff mixed farm wastes</td>
<td>Heated</td>
<td>36</td>
<td>2.8</td>
<td>86-90</td>
<td>0.31</td>
<td>0.008</td>
</tr>
<tr>
<td>6. Gobar gas plant</td>
<td>25-35</td>
<td>28</td>
<td>2.9</td>
<td>91-93</td>
<td>0.24-0.54</td>
<td>0.009-0.02</td>
</tr>
<tr>
<td>7. Fry original expts. Piggy</td>
<td>35 c.60</td>
<td>2.9</td>
<td>86-88</td>
<td>0.47</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>Suggested optimum</td>
<td>35-40</td>
<td>2.8</td>
<td></td>
<td></td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>8. Biomechanics</td>
<td>Heated</td>
<td>5-10</td>
<td>84-90</td>
<td>0.5</td>
<td>0.05-0.1</td>
<td></td>
</tr>
<tr>
<td>High rate, sludge - Recycle, Piggy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Meat Packing</td>
<td>33</td>
<td>2</td>
<td>1.3</td>
<td>0.47</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Yeast manufacture</td>
<td>2</td>
<td>1.8</td>
<td>0.25</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maise starch</td>
<td>23</td>
<td>3.3</td>
<td>1.8</td>
<td>0.44</td>
<td>0.14</td>
<td></td>
</tr>
</tbody>
</table>
There are various ways of concentrating or diluting the waste, but the first thing to do at this point is to reconsider the waste itself and how it is produced. If it is too dilute a more concentrated waste will obviously be created by using less water, this is a matter for good 'housekeeping' by making sure that no taps are left on, that drinking troughs do not overfill, that rain water does not find its way into the waste, and by considering whether less water could be used to wash down the yards, animal houses, lavatories or during the process. Another way to concentrate the waste is to add more organic material; this may be useful for balancing the C/N ratio correctly, but will involve resizing the digester. The third and most practicable way, if the other two are not feasible, is to concentrate the waste by allowing the solids to settle out and discarding the supernatant. This method leaves a highly polluting supernatant to be disposed of, which could present problems of water pollution, and public and animal health.

Dilution is perhaps easier than concentration, the main problems being where the water is to come from and possible increased disposal costs after digestion. Water may obviously be obtained from the normal sources (mains or wells), but this could be expensive, there is no real objection to using water from the supernatant of the digested waste as a dilutant or to the use of yard washings and rain water. The main rule for dilution is that it must be carefully controlled and the correct amount of water added to the waste. Once the moisture content and retention time have been fixed, we
should make sure that the nitrogen content is still below the toxic limit, especially if the waste has been concentrated.

4.4.5 Heating and Insulating Requirements

In most cases, except perhaps in a tropical climate, the digester is heated and maintained at the temperature chosen (around 86 – 95°F, 30 – 35°C). The average and minimum winter and summer temperature should be found out to estimate the energy required for heating the digester. Local meteorological offices will be able to supply this information quite easily. Secondly the temperature at which the waste, enters the digester is to be estimated or found out (if it is put in fresh it will probably be several degrees higher than if it has to be kept for a day or so). As the size for the digester, is known the surface area exposed to the air can be calculated. A larger digester has less surface area per volume than a smaller one, so that heat losses through the surface will be proportionately lower. Therefore in shaping the digester, the one with the smallest surface-area to volume ratio would be the best. Heat is needed to warm up the sludge coming into the digester and to compensate for the radiation losses from the digester surface.

There are various ways of raising the temperature, and they should be considered in the light of the existing situation. The sludge can be heated either once inside the digester or as it is put in. Since some sort of heating device will probably be needed to compensate for radiation losses, the former method would require only one sort of heating system. However, it would obviously help if the input slurry was somewhat warmer, and either the warmed supernatant can be used as dilution water or the effluent can be used to heat up the influent. If the sludge has to be settled before the supernatant can be taken off, the temperature of the supernatant would probably have fallen considerably. If the supernatant is taken directly from the digester, as in conventional and displacement digesters, the warmth will be retained. If there is a separate source of warmed water, which could also be used for dilution, this should be considered as well. The temperature of the diluted wastes can be calculated by applying the formula:
\[ T_1 \text{(diluted waste)} = \frac{(V_1 T_1 + V_2 T_2)}{T_2} \]

where \( V_1 \) and \( V_2 \) are the volumes, and \( T_1 \) and \( T_2 \) are the temperature of the waste and dilution water.

It is essential to insulate the digesters while operating in cold climate. The thickness requirement of insulation can be calculated from the standard formula, and most of the normal insulating materials are suitable. However, the insulating material must always be kept dry, for moisture reduces its efficiency in retaining the heat. This is a big disadvantage of fibreglass, for instance, compared to expanded polystyrene. The latter on the other hand may tend to trap pockets of biogas, which have escaped. Other methods such as the use of straw, covering the digester with earth, or sinking it into the ground have been used effectively, but again the moisture content should be kept low. Some people have used compost to insulate their digesters. In this way the heat generated by the compost can be used to warm the digester as well as to insulate it, but this may be unnecessarily complicated.

Besides the digester itself, the influent and effluent pipes for the heat exchangers, and the gas pipes, should be insulated. This is not only to minimise heat losses from the pipes, but also to prevent them from freezing a situation which could be dangerous if gas pipes were ever blocked up by ice.

However, the biggest heat loss from a digester comes when the digested sludge is removed from the digester. At this point it may have a temperature of 35°C, and unless this heat is recovered (e.g. in a heat exchanger), it will be wasted. The amount of heat could be up to ten times that lost through the walls of an insulated digester. Apart from insulation the only other measure which will conserve energy is to situate the digester in a sheltered place, because as the wind speed increases so does the rate of heat loss from the surface (the transmittance coefficient is increased three fold for a wind speed of 24 km/hr).

4.4.6 Shape and Dimensions - Ground Area - Choosing a Site

Once the volume of the digester has been calculated, next important to decide upon its shape and dimensions. Most vertical digesters are cylindrical, and the smaller sizes tend to be taller than broader, tall and thin digesters certainly occupy
less space, but the engineering problems become greater the taller the tank. The cylindrical shape is usually chosen for a number of reasons. A cylinder has no corners or dead spots and so mixing will be more efficient; it also offers a small surface area per volume, which is important for minimising heat losses; the ground space which a cylindrical tank occupies is less than that required by a cube shaped tank; and lastly it is a fairly easy shape to construct, whether it be made of steel, concrete or butyl rubber.

One of the most important considerations when designing the digester is the foundation. The larger the tank, the more weight of sludge and the greater the pressure upon the foundations. Obviously a digester should never be built upon unstable or marshy ground without adequate precautions. Similarly the supports for the walls must be sufficient; one of the reasons why digesters are sometimes sunk in the ground is to make use of the support offered by the surrounding earth.

Horizontal digesters are usually cylinders (or semi-cylinders), which are laid on their sides. Although they occupy more land space than the vertical type, the pressure of the sludge is spread over a larger area. This means that the foundations and wall supports do not have to be as strong. As a result the cost of construction can be considerably lower.

The ground area that the digester will occupy is the first criterion, which must be applied to any prospective site. As well as considering the tank, the sizes of the gasholder, holding tanks, pump and boiler house must be estimated. Spaces between the various tanks and access to them must be allowed for when deciding the total land area. The size of the gasholder is calculated by multiplying the hourly rate of gas production by the length of storage time required. Most gas holders (except the butyl pillow tank ones) will be upright cylinders, and the dimensions can be estimated in the same way as for a digester. The holding tanks are also sized from the required storage capacity, but on many farms there will already be tanks in use, which will serve this purpose. If at all possible existing facilities such as tanks or lagoons should be used, and the position of these may well be the decisive factor in siting the whole system.

In practice the actual site for the digester will probably be fairly obvious, but factors such as the distances, and final use of the gas, the lie of the land, and, ease of access for maintenance and removal of sludge, should all be taken into account. Most
important of all the digester should be situated in a place, which will allow room for any foreseeable increases in production.

It is an ideal time, when planning a digester, to reconsider the whole waste collection system. Indeed a digester cannot really be planned without regard to the method of transferring the waste from its source to the anaerobic tank. In this respect the lie of the land is important, for it will determine the need for pumps or scrapers in channels. In order to use the slopes to the best advantage, the digester may be sunk into the ground. If they are not fed from a manually filled header tank, however, vertical digesters above ground will almost certainly need a pumped feed, unless the unit is below the level of the animal house. In horizontal digesters the sludge requires a much smaller head to displace it down the tank, and as a result the need for pumping will not be so great.

The area around a digester, however, should not be too steep, for if there are spillages of slurry and could cause pollution. For this reason digesters should not be situated on the banks of a river or lake. It is a good idea if some nearby ground is available for use in emergencies to empty the whole system quickly. One or two fields should be the minimum space between the digester and the river to cater for these rare occurrences.

For when spillages do occur, an adequate water supply is essential to clean up the digester area, although again care must be taken not to hose the spilt sludge down into the river. A good water supply is also necessary for both diluting the waste if it is too strong and for cleaning the equipment regularly.

The other essential service is of course electricity, although if the biogas is used for generating, this may not be quite so important. Nevertheless there will be occasions when the digester is out of action or being started up, when outside electricity supply is necessary to power the pumps, stirrers or even a simple light bulb. Perhaps a two-digester system could cover this eventuality.

Finally the digester must be easily accessible in all weathers, for sludge removal, whether by wheelbarrow or tanker, has to continue all the year round. The site has to be reasonably conspicuous, so that maintenance etc. is not forgotten, but also out of the way of vandals. It should also be fairly sheltered from the wind, but not so close to animal and human habitation as to become a potential danger if gas leaks out.
4.4.7 Digester Design - Check List

1. Waste characteristics
   - Volume produced per day.
   - Weight of volatile solids produced per day.
   - Moisture content.
   - Nitrogen content.
   - C/N ratio.

2. Can the waste be digested as it stands?
   - Size of digester.
   - Retention time.

3. Does the waste need further treatment?
   - Dilution.
   - Concentration.
   - Chemical addition, e.g. Lime
   - Addition of more organic material to alter the C/N ratio.
   - Large solids shredding or maceration.
   - Adjusted size of digester/retention time.

4. Site for digester
   - Is the lie of land used to the best advantage?
   - Are pumps needed; if so at what point: input to digester, sludge recirculation through heat exchanger, output from digester.
   - Is the waste pumpable, and are the pumps protected from large solids by means of a filter?
   - What happens in the event of pump breakdown? Need for stand-by pumps?

5. Pipework for sludge
   - at least 3" in diameter.
• Easily drained and cleaned out.
• Flexible system, to allow for changes in operation.
• Must not siphon sludge from the digester giving a negative pressure inside. Insulation.

6. Digester vessel
• No waste or hidden spaces.
• Provision of portholes and manholes for sampling and access.
• All moving parts, e.g. stirrers, recirculating sludge pumps, to be outside the digester to give ease of maintenance.
• Facilities for scum and sediment removal.
• Pressure relief valve for excess gas production.
• Thermometer, thermostat.
• Heat losses. Heat-exchanger needed/size of boiler?
• Insulation.
• Protected against corrosion.

7. Gas holder and gas pipework
• Gasholder to maintain pressure of about 8" water gauge.
• Pressure relief valves.
• Good ventilation.
• Pipework - must have non-return valves.
• Condensate traps.
• Flame traps.
• Leak proof.
• Insulation.
• Protected against corrosion.

8. Safety
• Digester system built on firm ground - not marshy, etc.
• Electrical fittings near digester should be flame-proofed and maintained in good condition.
• Pumps, valves, boilers etc, if housed, should have adequate ventilation to allow gas to escape if leaks occur.
• Earth digester, gasholder and pipework.

9. Uses for the gas

• Is gas use balanced against gas production?
• Is gas holder sized correctly to even out irregularities?
• In the event of digester breakdown, what alternative sources of energy are available?
• Scrubbing and compression?

10. Uses for the sludge

• Is the production of sludge balanced carefully against the disposal of the sludge?
• What is the rate at which sludge can be applied for maximum utilisation of the fertiliser content by the crops?
• What happens when sludge cannot be removed, e.g. due to very wet weather conditions?
• Does the sludge need concentration by settlement and supernatant removal; if so what happens to the supernatant?
• Where can sludge in the digester be put in an emergency without creating pollution? Sacrifice land?

4.4.8 Materials used for constructing the digesters

Table 4.5 shows some of the advantages and disadvantages of different materials, which can be used for the various parts of the digester system.
<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Comments on use</th>
<th>General comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>Tank (collecting/settlement)</td>
<td>Can withstand high pressure</td>
<td>Generally very strong, durable and easy to handle.</td>
</tr>
<tr>
<td>1 Steel</td>
<td>Pipework</td>
<td>High thermal conductivity.</td>
<td>Wastewater treated (painted, formerly zinc coated, etc) will corrode.</td>
</tr>
<tr>
<td></td>
<td>Reinforcement</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Digester</td>
<td></td>
<td>High cost and when in large tanks will need suitable foundations to support.</td>
</tr>
<tr>
<td></td>
<td>Gas holder</td>
<td></td>
<td>Weight will not corrode but its use is restricted to its high cost</td>
</tr>
<tr>
<td></td>
<td>Fittings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Stainless</td>
<td>Specific fittings and areas where corrosion is likely, e.g. pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>valves and controls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>Tanks</td>
<td>It may need a trench bag to contain it</td>
<td>Robust, generally strong and readily available but can be attacked by acid.</td>
</tr>
<tr>
<td></td>
<td>Digester</td>
<td></td>
<td>Very heavy, few resistant, needs no maintenance. Easily moulded. Additives may</td>
</tr>
<tr>
<td></td>
<td>Foundation work</td>
<td></td>
<td>improve the properties, e.g., sulphate-metalling</td>
</tr>
<tr>
<td>Butyl Rubber</td>
<td>As a free standing ‘pillow’ tank (closed)</td>
<td></td>
<td>Cheaper. Versatile with a long life compared with other impermeable membranes.</td>
</tr>
<tr>
<td></td>
<td>Disgester</td>
<td></td>
<td>An ideal leak-proof membrane.</td>
</tr>
<tr>
<td></td>
<td>Gas holder</td>
<td></td>
<td>It will need insulation if used in a digester. It expands to accommodate increased</td>
</tr>
<tr>
<td></td>
<td>Collecting tanks</td>
<td></td>
<td>gas production. Not attacked by most wastewaters but attacked by organic solvents,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>e.g., paraffin</td>
</tr>
<tr>
<td></td>
<td>Lagoons</td>
<td>Soil conditions dictate suitability of a lagoon depending upon slope of sides</td>
<td>Not suitable for very large installations unless given adequate structural support.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(never more than 45°) and height of water table. Butyl will need securing in an</td>
<td>Impervious to both gas and liquid. Will burn easily once ignited. Butyl may be</td>
</tr>
<tr>
<td></td>
<td></td>
<td>anchor trench around periphery</td>
<td>reinforced with nylon, giving strength with flexibility.</td>
</tr>
<tr>
<td></td>
<td>Lay-flat piping not less than 3” OD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastics</td>
<td>General impermeable lining</td>
<td>Not as suitable as butyl</td>
<td>Cheaper than butyl but not such long life. Plastic is more susceptible to damage.</td>
</tr>
<tr>
<td>Polythene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVC sheet</td>
<td>Preformed tanks</td>
<td>Usually only for small tanks owing to cost</td>
<td>A strong material which is completely corrosion resistant. It is versatile in</td>
</tr>
<tr>
<td>Glass fibre</td>
<td></td>
<td></td>
<td>operation but can be extremely costly.</td>
</tr>
<tr>
<td>Pipework</td>
<td>Widespread use for sludge and high pressure work</td>
<td>Large diameter for sludge (not less than 2”, preferably more)</td>
<td>Durable and abrasion resistant. Should be protected against corrosion. Very heavy</td>
</tr>
<tr>
<td>Steel</td>
<td>Gas pipes</td>
<td>Standard use in gas installations</td>
<td>and expensive</td>
</tr>
<tr>
<td>Copper</td>
<td>Boiler pipework and fittings</td>
<td>Good thermal conductance for heat exchanger and scale resistant. Compression</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>fittings, etc. make copper pipe easy to use for DIY. If connected with</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Use</td>
<td>Comments on use</td>
<td>General comments</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-------------------------------------------------</td>
<td>------------------------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Plastic Pipe (UPVC or ABS)</td>
<td>All types of pipework</td>
<td>High pressure applications</td>
<td>Corrosion free, suitable for high and low pressure, cheap and ideal for DIY work. Fittings are either glued, screwed or push-fit depending upon pressure. Long pipes need support. Electrically non-conducting. Fragile and not to durable. Cheaper to install. Expensive to install. Corrosion resistant. Only large diameter 3&quot;.</td>
</tr>
<tr>
<td>Pitch fibre</td>
<td>Very liquid wastes only e.g. supernatant</td>
<td>Tamper only for drainage</td>
<td></td>
</tr>
<tr>
<td>Saltglaze</td>
<td></td>
<td>Unsuitable for pressure work</td>
<td></td>
</tr>
</tbody>
</table>
4.4.9 Insulating materials

Insulating materials work on the basic principle of preventing the air from moving to or from the insulated surface. They usually consist of finely divided fibres or particles which, being loosely packed, contain a large volume of static air. The commercially sold insulating materials such as fibreglass wool, expanded polystyrene (balls or blocks), expanded polyurethane, vermiculite and cork are long-life, resistant materials, which take good advantage of the trapped air principle.

4.4.10 Legal Aspects and Grants

There appear to be no legal restrictions at present preventing people from building and operating anaerobic digesters to produce methane. There are, however, a number of legal requirements, which have to be considered especially if a permanent digester is planned.

The first point is co-operation with the Local Authority Planning Department. For industrial purposes planning permission for waste treatment should be sought. The Local Authority will be able to advise as to whether permission is required in particular instances. The Local Authority also administers the law for controlling the public nuisance of smells and odours. The Local Environmental Health Officer can only insist on measures to control smell, e.g. anaerobic digestion.

Building Regulations approval may also be required (again from the Local Authority), but since there are no specific regulations for anaerobic digesters, as there are for septic tanks for example, this may not be a problem. However, the Local Authority may well refer this to the technical section of the Regional Water Authority, who would in any case be better able to advise on the suitability of construction of an anaerobic digester.

The Regional Water Authority has control over the discharge of effluents, both industrial and agricultural, to watercourses and to sewers. The pollution control board has brought together many of the clauses relating to water pollution.

Tannery wastes are treated as industrial ones for the incentive with other grants. The Ministry of non conventional energy sources operate on various Energy Saving Loan Schemes for industry. This applies to projects costing not less than Rs.5.0 crores and is available for such things as the installation or modification of
plant so as to enable waste organic materials to be used as a fuel. A regional
development grant under the Industry Act could perhaps be applied for. The grant
would only be given if the digester forms part of a recognised development in specific
regions. Success in obtaining official aid will depend entirely upon the situation.

4.4.11 Cost-Benefit Analysis

It is impossible to carry out a meaningful cost-benefit analysis of the anaerobic
digestion system without reference to particular cases; however, set out below are
some of the items which ought to be costed, and balanced against the benefits, in
order to discover whether a project is viable on grounds of economy and energy.

Obviously not every item will apply in each case, for the list merely gives
guidelines for the would-be methane producer. Apart from the gas and the fertiliser
produced, the other benefits may be difficult to assess, perhaps even negligible in
some cases. If they do pose difficulties, the best approach is probably a comparison
with the cost of alternative treatment, if this is necessary.

Another uncostable benefit, if a digester is built and run successfully, the
problems that have been already solved will be of enormous benefit in furthering the
development and spread of the process in the future.

1. Calculation of Cost Advantage:

A. GAS:
a) Net annual gas production in cu.ft. (Gross production less process usage)
b) BTUs per cu.ft.
c) Energy value (a x b) BTUs
d) Existing cost per unit of energy i/BTU
e) Annual Cost Saving (c x d)

B. FERTILISER:
f) Incremental N availability (units/ton)
g) Existing cost per unit of N
h) Fertiliser cost advantage per ton (f x g)
j) Annual tonnage produced
k) Annual Cost Saving (h x j)

l) Total annual tangible cost advantage (e+k)

C. INTANGIBLE COST ADVANTAGES:
Pollution control
Reduced odour
Improved disease control
Eased pasture management due to reduced souring Possible sale of dried material

4.4.12 Economical and environmental issues

Because batch systems are technically simple, the investment costs are significantly (ca. 40%) less than those of continuously-fed systems. The land area required by batch processes is however considerably larger than that for continuously fed dry systems, since the height of batch reactors is about five-fold less and their OLR two-fold less, resulting in a ten-fold larger required footprint per Ton treated wastes. Operational costs, on the other hand, seem comparable to those of other systems.

Fig.4.13 Schematic diagram of various types of reactor system

4.5 Design of Laboratory scale digesters

Based on the requirement and study, different volumes of reactors were constructed with suitable modifications.
4.5.1 BMP SETUP

Anaerobic biodegradability of waste was measured by conducting a Biochemical Methane Potential (BMP) assay. The BMP assay procedure was developed by Owen et al. (1979) to measure the amount of organic matter in a waste that can be degraded in an anaerobic process. The procedure was designed to assure that nutrients, inoculum, substrate toxicity, pH, oxygen toxicity or substrate overloading do not limit the degradation of the substrate in the wastes. To account for biogas production from residual degradable matter in the inoculum, a control containing only inoculum is sampled simultaneously to allow subtraction of biogas not attributed to the substrate. Analyses were run in triplicate.

4.5.2 Apparatus

The laboratory apparatus consisted of 130 ml serum bottles with the initial atmosphere of 50% carbon dioxide and 50% nitrogen gas. The bottles were sealed with butyl rubber stoppers and crimp aluminum caps. Gas production was monitored by water displacement method. The volume of water displaced from the bottle was equivalent to the volume of gas generated. Gas was vented to maintain equilibrium with the atmospheric pressure and the headspace samples were removed for qualitative analysis using a 1 ml gas tight syringe (Hamilton) equipped with a 22 gauge needle. Initial feeding, and sampling from the reactors at the end of incubations was done using an anaerobic chamber. A transfer box with a vacuum/purge cycle was used to move the materials into the anaerobic chamber and to ensure an oxygen free environment. The headspace gas in the anaerobic chamber was 15% carbon dioxide, 5% hydrogen and balance with nitrogen. The serum bottles were incubated statically in a walk-in chamber at room temperature (32 - 37°C). A view of the experimental set up is shown in Fig.4.14.

4.5.3 Experimental design

A batch, screening assay employed in this part of experimental work permits evaluation of a wide range of variables and thus, allows for sorting out of promising configurations. The assay has been designed in part using the principles of
Biochemical Methane Potential (BMP) bioassay, as described by Owen et al. [1979]. The Anaerobically Digested Sludge (ADS) served as one source of anaerobic biomass potentially making it more suitable for inoculation of a high-solid digestion process.

The incubations were carried out for 5–10 weeks depending upon the study, a period much longer than 30 days being normally considered sufficient for assessing methane generation potential in waste digestion. The aim was to provide enough time to determine the ultimate yields of biological conversion of the high solid organic matter by the anaerobic microorganism consortia present in each reactor.

Seventeen experiments were set, including 13 for different combinations of substrate and inocula and 4 for the inocula alone. Out of the 17 experiments involving tannery solid waste, four involved digestion with treated wastewater from aerobic treatment process, and remaining eight involved with primary sludge obtained from the effluent treatment process of tannery liquid waste. The entire system was deoxygenated prior to use applying several vacuum-purge systems using gas headspace replacement system, a gassing manifold. The headspace gas was changed initially with 80% N\textsubscript{2} balance with CO\textsubscript{2}. The reason for setting additional experiments with the inocula was to assess their contribution to the overall amount of methane generated in respective reactors involving these inocula. These experiments are further referred to as control experiments.

Each experiment consisted of six to ten replicate reactors to account for possible variability in digestion rates and methane generation. Prior to biogas release the serum bottles were shaken for 10 seconds, in order to reach the equilibrium between gases present in both, the gas and the liquid phase. The effect of mixing on the overall performance of the system was observed by shaking the bottles manually for 1 minute daily, from the fourth day onwards.

4.5.4 Start up of the reactors

All the feed stocks were prepared and placed into an anaerobic chamber in which the environment is maintained with a gaseous mixture containing 15% CO\textsubscript{2}, 5% H\textsubscript{2} and balance N\textsubscript{2}. Each reactor was fed with predetermined volume of the feedstock and sealed. They were then removed from the anaerobic chamber. The reason for using this particular gas mixture is that carbon dioxide acts as a buffer thereby
reducing the impact of the expected elevated pH. The bottles were then placed in a walk-in chamber set up at 32 – 37°C.

FIG 4.14 EXPERIMENTAL SET-UP FOR METHANOGENIC ACTIVITY TEST
4.5.5 DESIGN AND CONSTRUCTION OF SINGLE AND TWO PHASE SYSTEM

4.5.5a Single-Phase System

The single-phase reactor had an active liquid volume of 6.5 liters (Total 10 liters) and an overall height of approximately 40 cm and 73 cm diameter. The system was operated with a pH ranging between 7.1 and 7.8 and a HRT greater than 30 days. The effluent port was located at 7th and 23rd cm below the liquid level in the reactor. The single-phase reactor was batch fed with solid and liquid wastes from tannery and the feed volume varied depending on the desired OLR and strength of the waste.

4.5.5b Two-Stage System

The two-stage system shown in figure 4.15 consisted of separate reactors for acidogenic phase and methanogenic phase. The acidogenic and the methanogenic reactors were cylindrical in shape and, each having a 4 and 10 litre total volume respectively. Typically in a two-phase system, the acidogenic reactor is smaller than the methanogenic reactor since the required HRT for acidogenesis is less than that for methanogenesis. The first reactor is having active volume of 3.50 L to operate under acidogenic phase. The second reactor is having a working volume of 6.5 L operate as methanogenic phase reactor. The pH in the acidogenic phase was 5.4±0.87 and the HRT was maintained between 9 and 10 days. The acidogenic phase reactor was fed with mixture of tannery solid and liquid wastes and the volumetric feed rate to the reactor was maintained for the required HRT. In the methanogenic phase, the pH was between 7.1 and 7.8 with a HRT of 20 days. The sampling port for acidogenic reactor was located at top of the reactor and for the methanogenic reactor at 7 and 23 cm below liquid surface. The first reactor in the two-phase system was fed with mixture solid and liquid wastes from tannery, and the digested material drained from the first phase reactor was fed to the second reactor.
4.6 CONCLUSIONS

In the last 25 years, a remarkable evolution has occurred in the attitude towards the reactor digestion of solid wastes. The scepticism with respect to the feasibility has changed towards a general acceptance that various digester types are functioning at the full scale in a reliable way. Most existing full-scale plants were designed with a single-stage reactor and reflect the relative newness of the technology. It can be expected that one-stage systems will continue to dominate the market, but that the reactor designs will be improved and matched to more specific substrates. This should provide far more reliable plants. Many companies also offer several versions of one technology, or propose both wet and dry systems. Two-stage systems may start playing a more and more important role, especially if treatment of industrial wastes is to be combined with that of biowaste and hygienisation may require a separate treatment step at higher temperatures. Batch systems also still need to make a breakthrough, but chances are that hygienisation as well as safety requirements will make these systems more difficult to introduce. Batch systems may be more successful in developing countries due to the low investment costs.

At present, it is not possible to single out specific processes as all-round and optimally suited under all circumstances. Indeed, as discussed, many variables have to be taken into consideration and a final evaluation for a specific site will need to be made. There is and will continue to be room for technical diversity in this domain of waste treatment. Yet, practice shows that initial investment costs are of crucial importance. This factor, rather than the overall operating costs or performance...
characteristics often determines the outcome of a public tender. In view of the fact that such investments should serve at least several decades, it is to be hoped that decision makers will learn to have long-term foresight in these matters.

It must be recognized that anaerobic digestion of solid wastes still has to compete vigorously with aerobic composting. This is in part related to the fact that composting is a long established technology which generally requires less initial investment. However, current energy prices and targetted reduction of fossil fuel combustion in the coming decades will draw increasingly more attention towards anaerobic digestion. Indeed, the amount of gas potentially recovered from the solid wastes is substantial at the level of a country. In the framework of the Kyoto agreements, many countries have agreed to stimulate the production of methane from wastes, e.g., by subsidizing the electricity from biogas. The latter certainly will be a major support for anaerobic digestion of complex wastes. The Ministry of Non-conventional Energy Sources, Govt of India has set the goal in the National level to increase the fraction of electricity produced with renewable ressources (excluding large hydroplant) from 3.2% in 1997 to 12.5% in 2010. Electricity generated from industrial solid waste by means of anaerobic digestion can make a significant contribution towards this goal.