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ADVANCED REACTOR DESIGN, OPERATION AND ECONOMY

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ABSTRACT

Of the high rate anaerobic wastewater treatment systems the UASB (Upflow Anaerobic Sludge Blanket) reactor has found the widest application. Therefore the attention with respect to design, operation and economy will be focussed on this reactor type.
In designing a UASB reactor specific attention is needed for the GSS (Gas-Solids Separator) device and the feed inlet system.
For soluble wastewater generally no phase separation is required. Only for wastewaters high in suspended solids pre-acidification in a separate acidification reactor can be beneficial.
Increasing attention is given to the development of modified UASB systems, such as a combination of a sludge bed reactor and an anaerobic filter.
Other possible modified UASB systems may be found in a FS (Floating Settling) UASB reactor, the EGSB (Expanded Granular Sludge Bed) reactor and the UASB IC (Internal Circulation) reactor.
As many factors are involved in the costs of a UASB reactor, only some rough data on reactor costs are presented.

KEYWORDS

Anaerobic wastewater treatment, UASB reactor, design, operation, economy, phase separation.

INTRODUCTION

High rate anaerobic treatment processes have to be properly designed and operated in order to achieve the optimal benefits of these processes. Regarding the required optimal design it is of big importance that the process performs satisfactorily under all operational conditions which can be expected for the specific situation where the process has to be employed. For this purpose a certain overcapacity is required in order to accomodate for peak loads and environmental stress situations. Regarding the limited experience available at full scale, UASB plants installed so far have been designed at a rather conservative loading rate. However, as many of these plants showed a very satisfactory performance at significantly higher (peak) loads, the confidence in the process of designers has gradually increased. For this reason new plants installed for the same type of wastes presently generally are designed at significantly higher loading rates. Moreover, based on laboratory research as well as full scale experiences, modified systems are under development.

Apart from the design of the system, it is of eminent importance to understand the digestion process itself. Each wastewater has its own characteristics, and generally requires its own typical approach. This also is true for wastes originating from the same industrial activity. For instance sugar beet wastewater in the Netherlands differs from that in Germany significantly in Ca^{2+} content. As a result processes applied satisfactorily in the Netherlands for sugar beet wastewater, perform much poorer -even unsatisfactorily- in Germany.
Specific measures must be taken to avoid problems.
As far as reactor construction is concerned, high rate anaerobic treatment systems certainly are simple and inexpensive. However, for their satisfactory performance it is essential that in each country or region adequate skilled man power in the anaerobic digestion process itself is (or becomes) available.

DESIGN OF ANAEROBIC TREATMENT PROCESSES, THE UASB PROCESS

As our experience particularly concerns the UASB process, the discussion will be focussed on this system.
It will be clear that the basic requirements underlying the process should be met for its proper performance. However, the extent to which this should be the case depends on the type of wastewater treated.
Assuming that the start-up of the process will be made properly, the following aspects deserve serious consideration in the design:

1. GSS device
2. Feed inlet system
3. Reactor dimensions
4. Modular design of the anaerobic treatment system
5. prevention of corrosion
6. One-step or two-step application

The GSS device

In order to achieve the highest possible sludge hold-up under operational conditions, it is necessary to equip the UASB reactor with a proper GSS device. Such a device is always required, or at least very beneficial, also in the case the reactor contains merely a granular type of sludge. As explained elsewhere (Lettinga et al., 1980) the design of the GSS device can be fairly simple. As a matter of fact various approaches are presented in the reactor lay-out shown in Figure 1. The first objective of the device is to separate the biogas as effectively as possible from the mixed liquor, in order to maintain satisfactory settling conditions in the settler compartment. For this purpose it may be beneficial to install separate vertical baffles beneath the gas collector near the apertures. In this way heavy liquid turbulences can be quenched to some extent. In order to facilitate the collection and discharge of the biogas, and to reduce the occurrence of scum layer formation in the gas collector, a liquid-gas interface of sufficient surface area has to be maintained here. This surface area should be smaller at lower gas production rates in order to provide sufficient mixing here for preventing scum layer formation.
Currently various designs for the GSS device are available, most of which perform satisfactorily. It is impossible to provide general design criteria, due to an incomplete insight into the performance of existing systems and a lack of comparative performance data between the various systems.
It may be clear that the design of the GSS device to some extent will be dictated by the characteristics of the wastewater, the type of sludge present in the reactor, the applied loading rates, the expected gas load and the dimensions of the reactor.
In treating very dilute wastes it is essential to achieve an almost complete retention of the viable sludge under all possible operational conditions. A sophisticated Gas-Solids Separator system is required in this case.
Special measures have to be taken in treating industrial effluents containing higher concentrations of proteins and/or fats, because the presence of these compounds stimulates flotation of the sludge and consequently the wash-out of viable biomass. Moreover serious foaming may occur in the gas collector with wastes being high in protein content, so that the release of the biogas from the reactor becomes difficult. In order to avoid problems in these cases antifoam sprayers should be installed in the upper part of the gas collector.

Feed inlet system

In order to take maximal benefit of all the retained sludge in a UASB reactor it is essential to avoid channelling in the sludge bed as much as possible. The risks for channelling are greatest when the process is applied to cold and/or dilute wastewater. The gas production generally will be too low then for adequate sludge bed mixing. Moreover, the risks for channelling will increase with a decreasing number of feed inlet nozzles at the bottom of the reactor, but also with increasing settleability of the sludge.

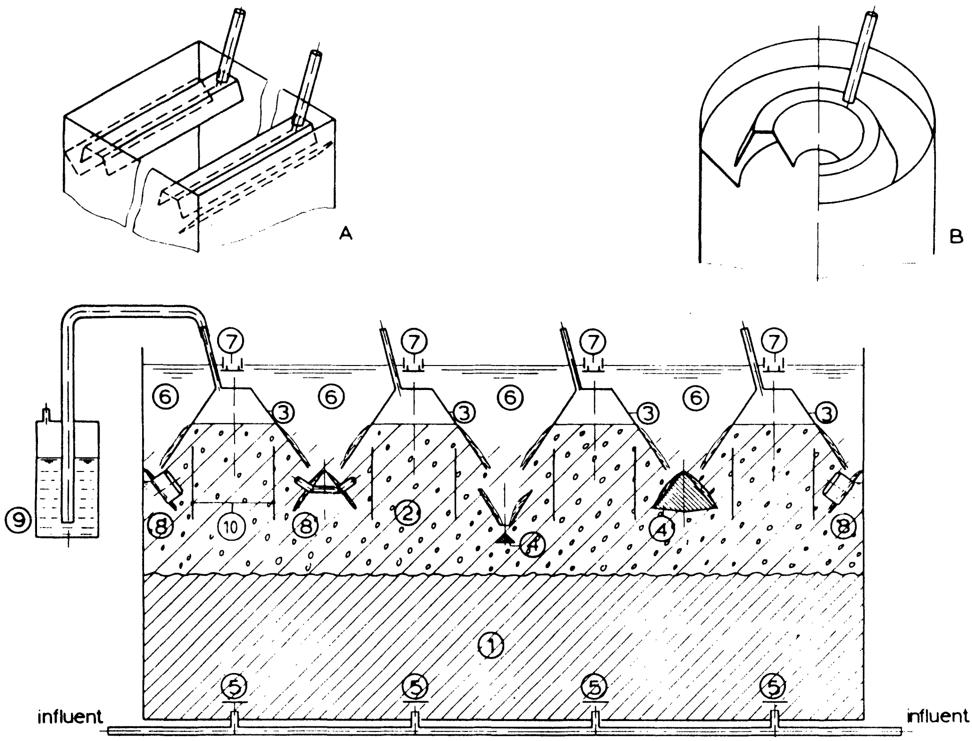

Fig. 1. Various UASB reactor configurations (A = rectangular; B = cylindrical. 1 = sludge bed, 2 = liquid phase + gas, 3 = gas collectors, 4 and 8 = different designs to direct the gas into the gas collector, 5 = feed inlet system, 6 = settling compartment, 7 = overflow, 9 = water seal).

Consequently more sophisticated feed inlet systems are required when the process is applied at relatively low organic and high hydraulic loading conditions (dilute cold wastewater) and when a relatively shallow and thick sludge bed is present in the reactor.
As the available information is sparse, only rough (tentative) guidelines can be provided for the required number of feed inlet points (see Table 1).

TABLE 1 Rough guidelines for the number of feed inlet nozzles required in a UASB reactor

Type of sludge present	area (m^2) per nozzle	
1. Dense flocculant sludge (> 40 kg $DS.m^{-3}$)	0.5-1	at loads < 1-2 kg $COD.m^{-3}.day^{-1}$
2. Medium thick flocculant sludge	1-2	at loads < 1-2 kg $COD.m^{-3}.day^{-1}$
(20-40 kg $DS.m^{-3}$)	2-5	at loads > 3 kg $COD.m^{-3}.day^{-1}$
3. granular sludge	0.5-1	at loads < 1-2 kg $COD.m^{-3}.day^{-1}$

Apart from the number of feed inlet lines, suppliers of full scale plants employ in their designs specific dimensions of the nozzles, minimum and maximum outflow velocities and sometimes intermittent supply of the feed over the various inlet pipes.
Obviously it is possible to employ feed distribution systems similar to those used in attached sand fluid bed reactors. However, unless higher superficial liquid flows are employed, presumably the installation of a sophisticated feed inlet system will only partially prevent channelling in UASB reactors operated at low organic loads.

Reactor dimensions

The size (volume) of the reactor is mainly dictated by the maximum total daily hydraulic and/or organic load, together with the applicable volumetric loading rates. Therefore the height/area ratio of a reactor is not such a relevant parameter. A more relevant factor is the reactor height. It is difficult to provide figures about the 'optimal' reactor height that have a general applicability. The more dilute the waste, the higher will be the upflow superficial liquid velocity at a specified organic loading rate and reactor height. The type of sludge present in the reactor restricts the maximum permissible superficial velocity, together with the organic space and sludge loading rate applied.
For flocculant sludge reactors maximum superficial velocities of 0.5 $m.hr^{-1}$ can be tolerated at organic space loads up to 5-6 kg $COD.m^{-3}.d^{-1}$, sometimes even up to 1.5 $m.hr^{-1}$. An adequate reactor height in that case is approximately 6 m.
For granular sludge UASB reactors considerably higher superficial liquid velocities can be accepted, even over 10 $m.hr^{-1}$. Therefore in principle much higher reactors can be applied, and presumably will be applied in the near future in specific, modified UASB concepts. However, for conventional systems a reactor height of approximately 6 m looks quite adequate.
The 5500 m^3 UASB reactor at "De Krim" (The Netherlands) treating potato starch wastewater is with its 10 m height the tallest reactor built so far. The experience obtained from this plant and from a few others of about 8 m height, shows that 6 m would have been a more adequate choice. Foaming problems and liquid turbulence will be less serious then.

Modular designs

A modular design of anaerobic reactors offers a number of important benefits over one-compartment systems:

- the (first) start-up of the plant will proceed easier in the case a limited amount of seed sludge is available, because one or two compartments can be started up separately with a sufficient amount of sludge.
- different compartments can be operated in series, which presumably will result in a better overall performance.
- the treatment system can be phased better in the time, and -based on the results obtained in the first phase- the design load might be adapted.

Regarding the possibilities for modular designs, rectangular reactors clearly are in favour over cylindrical reactors.

Prevention of corrosion

Little if any corrosion problems will be found beneath the liquid-gas interface, because neither the liquid nor the sludge is aggressive under normal operational conditions.
However serious corrosion problems frequently occur at the liquid-gas interface(s), particularly in the settler due to the presence of oxygen. These corrosion problems become especially serious when the effluent solution contains H_2S, because this compound is rapidly converted to H_2SO_4 in the presence of air-oxygen as a result of biological activity. Locally very low pH values may result from this oxidation process and consequently metals and concrete may become seriously attacked. It is therefore essential to use either adequate coating materials to protect corrosive construction materials or to use non-corrosive construction materials such as stainless steel or plastics.

One-step and two-step process configurations

In treating more complex types of wastes a two-step treatment process might have some benefits. Such a two-step system consists of a first reactor for liquefaction and/or acidification and a second reactor for methanogenesis. Whether or not this system is more practical and economical than a one-step process is questionable. It should be understood that generally liquefaction is the rate limiting step in the overall digester process, and consequently that relatively large reactor volumes are required for liquefaction. Although the second reactor can be comparably small, it will be obvious that the investment costs for a two-step process may exceed significantly that of a one-step process, even when the total reactor volume required in latter case is bigger.
A specific benefit claimed for phase separation, even in the case of merely soluble types of wastes, is the presumed higher stability of the two step over a one-step system (Cohen, 1980, 1982; Breure, 1986). However, this is more appearance than reality, because it only applies when a constant product composition in the effluent of the acidogenic reactor can be guaranteed. Latter is not possible when the wastewater fluctuates in composition and strength and this frequently is the actual situation in practice. Therefore, we are of the opinion that for soluble types of wastes there exist little if any reasons to use a separate acidogenic reactor. For the sake of process stability we recommend to apply in a one-step process a safe overcapacity of appr. 40-50%. This doesn't mean that some pre-acidification of the wastewater could not be beneficial. The point is that for a partial pre-acidification a separate acidogenic reactor generally is not required, because acidogenesis already will proceed to a sufficient extent in the feed supply lines, holding tanks, etc.
Valid reasons for applying phase separation for soluble wastes might be found in the removal -if possible- of toxic and/or hazardous compounds in an acidogenic reactor. An example is the potato starch treatment plant in "De Krim", where a 1700 m^3 acidogenic reactor has been placed in front of the 5500 m^3 methanogenic reactor. The main objectives of the first reactor are to remove SO_3^{2-} and proteins.

In treating partially soluble wastes application of a separate first reactor for liquefaction and acidogenesis might be profitable. In order to be able to convert SS (suspended solids) COD into methane, the anaerobic treatment systems should meet the following two conditions:
1. the biodegradable SS present in the wastewater should be efficiently entrapped,
2. sufficiently long sludge retention times should be maintained to allow the complete hydrolysis of these entrapped solids.

It will be clear that the loading potentials of the anaerobic treatment system will be dictated now by factors like:
1. the efficiency of the system towards the removal of suspended pollutants which in turn is chiefly dictated by the various relevant characteristics of these pollutants, e.g. their settling, flocculation and adsorption characteristics,
2. the rate of hydrolysis, which depends strongly on the nature (size, shape and composition) of the SS, but also on the extent to which excreted exo-enzymes remain available for hydrolysis, e.g. are not being washed out.

It will be obvious that the loading potential of the system may drop down significantly depending on the characteristics of dispersed pollutants and the constraints set on the required SS removal efficiency and extent of sludge stabilization. When applied mainly for the removal of soluble pollutants high rate systems still can be applied at very high loading rates. Main part of the SS then will not be eliminated from the waste and proper post treatment processes have to be implemented for that purpose. High rate granular sludge bed reactors will exert a rather poor efficiency toward the removal of SS. When a high overall COD treatment efficiency is pursued, these systems look less adequate for partially soluble wastes. This is also the case for FB systems, downflow AFF reactors and upflow AF systems. FB and AFF reactors are ineffective in removing suspended solids, while AF reactors suffer from clogging problems. However, flocculant sludge bed UASB reactors can be employed more profitably for partially soluble wastes such as slaughterhouse waste (COD: 1500-2200 $mg.l^{-1}$, 40-50% insoluble COD) (Sayed, 1984).

The same is true for granular sludge bed UASB reactors, provided they are operated at loads below approximately 3 kg $COD.m^{-3}.day^{-1}$ as in the case of flocculant sludge bed systems. A fairly satisfactory removal of suspended solids can be achieved in both types of sludge bed reactors. Moreover, depending on the operational temperature, the entrapped biodegradable solids can be stabilized to a considerable extent. It therefore can be concluded that UASB systems are suitable for one-step anaerobic treatment of partially soluble wastes. The specific benefits of low-rate granular sludge bed reactors over flocculant sludge bed reactors are:

1. excess flocculant sludge produced will accumulate above the dense layer of granular sludge. This enables its separate discharge from the reactor, which is particularly important when the biodegradable fraction of the dispersed solids in the wastewater is poor. These solids will not mix up with the active methanogenic sludge, such as will be the case in flocculant sludge bed reactors.
2. a high volumetric methanogenic activity can be retained in the reactor, which leads to a more complete breakdown of the biodegradable compounds.

It will be obvious that in a two-step treatment system, all the above constraints exist for the first reactor. Depending on the performance, the investment and operational costs of such a "liquefier", a two-step treatment system might be more or less attractive than a one-step process for partially soluble wastes.

MODIFIED UASB SYSTEMS

Modified UASB concepts are investigated currently in various laboratories. Some of these systems resemble more a modified upflow AF, because they consist of an anaerobic sludge blanket in the lower part, combined with an AF system in the upper part of the reactor. According to Pipyn and Verstraete (1985), Guiot et al. (1984), Wang Zu Xu et al. (1985) and van den Berg (1985) the potential of such hybrid blanket systems looks good, because they show a satisfactory performance at space loads up to 28 kg $COD.m^{-3}.day^{-1}$ (v.d. Berg et al., 1985). Despite these good results we doubt about the real practical feasibility of these systems. From our experience the installation of a GSS device is necessary, at least very desirable, in order to maintain the sludge bed easily beneath the support material. And even then, the use of UASB reactors with support material supplied to the settler compartment, is from our experience rather disappointing.

In experiments in a 6 m^3 pilot plant with domestic sewage using such a system, we observed that floating sludge particles/flocs are easily forced through the AF. In our opinion this phenomenon must be distinctly more serious when the installation of a GSS device beneath the AF has been omitted. Therefore our confidence in these "Captured Anaerobic Sludge Bed" (CASB) reactors is not great.

Good results are also claimed for polyurethane carriers (PRC), but reliable results of pilot and full scale plants so far have not been published.

APPLICATION OF THE UASB PROCESS AND FUTURE DEVELOPMENTS

Soluble wastes

In applying the UASB system to mainly soluble wastes generally very high space loading rates can be and frequently are satisfactorily accommodated once the reactor has filled up with a granular type of sludge. Some relevant experimental results are shown in Table 2.

TABLE 2 Results obtained with UASB reactors using granular sludge (mainly soluble wastes)

Substrate characteristics			Experimental conditions					COD reduction	
type	COD	soured	reactor volume	volume of sludge bed	COD sludge load	temp	COD load	total	filtered effluent
	mg/l	(%)	(l)	(l)	(kg.kg VSS^{-1}. day^{-1})	°C	(kg.m^{-3}. day^{-1})	(%)	(%)
VFA	1000 C_2 1000 C_3	100	30	15-20	2.3	30	62		80-90
alcoholic	51% methanol 27% ethanol 12% propanol	0	2.7	~ 1.5	0.6-0.7	30	22		> 95
	10% butanol		28	~ 10	0.7	30	14		85-90
potato processing	2.5-4.2		6000	< 2000	0.27	19	3-5	88	95
	3.3-5	6-16	6000	< 2000	0.65	26	10-15	86	95
	3.5-4.5		6000	< 2000	0.97	30	15-18	83	95
	3.5-7.1		6000	~ 4000	1.45	35	24-45	84	93

Considering that in most of the experiments the sludge bed only occupied approximately 60% of the total reactor volume and that at temperatures of 38-40°C the maximum specific sludge activities are approximately twice as high as compared to 30°C, it will be clear that even significantly higher space loads can be applied. However, under conditions of very high sludge loads, appropriate adjustments have to be made to the design of the GSS. These adjustments are required because an increasing fraction of the granular sludge will be redispersed in the liquid medium above the sludge bed due to the marked turbulence (mixing) brought about by rising gas bubbles from the sludge bed and particularly also due to the increasing tendency of the granules for flocculation. The main feature of the modified Gas-Solids Separator should be to retain both floating as well as settling granular anaerobic sludge in a highly turbulent environment. No attempts should be made in such a "super high rate system" to retain finely dispersed sludge, nor to combat the flotation tendency of sludge granules. Adapted designs for the GSS device in such high rate granular sludge bed reactors are under development.
Super high rate granular sludge bed reactors of this type should be designated as Floating Settling granular sludge UASB modifications (FS UASB).
Results of small pilot scale experiments made in the laboratory indicate that granular sludge bed reactors operated in expanded bed mode by applying high superficial liquid velocities combined with high sludge loading rates, probably have attractive practical potential (Lettinga et al., 1983; Rinzema, 1986).
These Expanded Granular Sludge Bed reactors (EGSB) approach the conventional FB systems, except that any inert carrier material is not used and that a complete fluidization of the granular sludge bed is not required. Superficial liquid velocities in the range 5 - 15 $m.hr^{-1}$ look applicable. It is impossible in such systems to achieve a substantial removal of dispersed matter from the wastewater. In the EGSB reactors adjusted designs for the GSS device can be employed. The high superficial liquid velocities can be achieved by applying effluent recycle.

Another possibility to achieve a high superficial liquid velocity has been proposed in an ingenious concept based on Internal Circulation introduced recently, viz. the UASB IC reactor. In this reactor concept liquid and sludge recirculation are accomplished by employing the impulsive forces from the evolved biogas (Vellinga et al., 1986).

Partially soluble wastes

From what has been explained before, it will be obvious that anaerobic treatment proceeds easiest for soluble types of wastes. Generally a high quality anaerobic sludge will develop in that case. The methanogenic fraction of the sludge will be relatively high, particularly for wastes which mainly consist of VFA pollutants. The situation becomes more complex for wastes which contain an increasing fraction of insoluble pollutants. As mentioned before generally the hydrolysis step is the rate limiting factor in the degradation of insoluble compounds, especially at lower ambient temperatures. Consequently in order to convert these pollutants to methane, the following conditions have to be met in the anaerobic treatment system:

1. the biodegradable dispersed pollutants should be efficiently entrapped in the anaerobic reactor.
2. the average sludge retention time should be sufficiently long to allow for the complete hydrolysis of the entrapped pollutants.

Both these conditions in fact imply that the operation at high organic space loads is impossible for partially soluble wastes in one-step anaerobic treatment systems. Satisfactory overall treatment efficiencies and a sufficient sludge stabilization can only be achieved at moderate loading rates, i.e. in the range 0.5 - 5 kg COD.m^{-3}.day^{-1} depending on the waste characteristics, the temperature and type of sludge present in the reactor. However, such moderate loading rates still can be very attractive in practice, because all the other principle advantages of anaerobic treatment still apply.
A possibility to increase the loading capacity of the anaerobic treatment system could be found in employing a separate first reactor for liquefaction and acidogenesis. However, it is rather questionable whether or not anything is gained in this way. The two conditions mentioned above still have to be fullfilled, now especially for the first reactor. The difficulties to achieve the goals are not less, and the costs of such a two-step system presumably are higher. Although the UASB process was originally developed for the treatment of mainly soluble low- and medium-strength wastewaters, it would be a serious misapprehension to conclude that the process would be applicable only to these categories. Satisfactory results have been obtained with complex wastes, e.g. with slaughterhouse (Sayed, 1984), domestic sewage under tropical conditions (Schellinkhout, 1985) and calf fattening wastes (Schomaker, 1986).

COSTS OF ANAEROBIC TREATMENT

Many factors are involved in cost scenarios of anaerobic treatment. It is therefore impossible to provide exact figures. However, on the basis of available information a rough estimate can be made. We have made such an estimate for a 1000 m^3 and a 5000 m^3 UASB plant for seasonal and continuous operation at a design load of respectively 10 kg COD.m^{-3}.day^{-1} and 15 kg COD.m^{-3}.day^{-1}. The results of these calculations are presented in Table 3, together with the assumptions made. Concerning the investment costs of UASB reactors, very recent information revealed that 1000 m^3 reactors can be installed for US $ 400,000 in the Netherlands, including start-up, seed sludge (exclusive land, pipings and buildings).

TABLE 3 Rough Cost Estimate of Anaerobic Treatment

Assumptions made in the estimate

COD load	: 10 and 15 kg $m^{-3}.day^{-1}$
treatment efficiency	: 90% COD reduction
methane yield	: 0.9 kg COD-methane/kg COD-removed
methane production ($m^3/m^3{}_r/y$)	: 1550 at a load of 15 kg COD/m^3/day 1030 at a load of 10 kg COD/m^3/day
interest and redemption	: 15% of the capital costs
maintenance and renewals	: 2% of the capital costs
energy requirements	: 10% of the methane production
investment costs	: 1000 m^3 plant --- $ 500,000 - 750,000 5000 m^3 plant --- $ 2,000,000 - 3,000,000

OPERATION COSTS (in $ 1000 x)

I. Continuous operation (365 day/year, 24 hrs/day)

	1000 m^3 plant	5000 m^3 plant
interest + redemption	75 - 112.5	300 - 450
maintenance + renewals	10 - 15	40 - 60
labour + supervision	15	40
analyses + control	15	40
Total costs	115- 147.5	420 - 590
Costs of methane gas ($/$m^3$ STP)[a]		
1. load: 15 kg COD/m^3/day	0.08 - 0.105	0.06 - 0.085
2. load: 10 kg COD/m^3/day	0.125- 0.160	0.09 - 0.125

II. Seasonal operation (3 months/year, 24 hrs/day)

	1000 m^3 plant	5000 m^3 plant
interest + redemption	75 - 112.5	300 - 450
maintenance + renewals	3 - 5	15 - 20
labour + supervision	5	15
analyses + control	5	15
Total costs	88 - 127.5	335 - 500
Costs of methane gas ($/$m^3$ STP)		
1. load: 15 kg COD/m^3/day	0.25 - 0.36	0.19 - 0.29
2. load: 10 kg COD/m^3/day	0.38 - 0.55	0.29 - 0.43

a) net methane gas production

CONCLUDING REMARKS

Anaerobic treatment is now feasible for a wide variety of wastewater, including very high strength and very low strength wastes. The process can be applied both under optimal mesophilic, but also under suboptimal mesophilic and even psychrophilic temperature conditions, very soon presumably also under thermophilic conditions (Wiegant, 1986). However, as anaerobic organisms are susceptible to a large number of factors, and while industrial wastes generally vary considerably in composition, strength, temperature from location to location, each wastewater needs its own approach. Although the technology is simple, proper application requires guidance by skilled experts, particularly during start-up.

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