ANAEROBIC TREATMENT OF VERY LOW STRENGTH AND COLD INDUSTRIAL AND DOMESTIC WASTEWATERS

G. Lettinga
Department of Environmental Technology,
Agricultural University, Wageningen, The Netherlands

INTRODUCTION

In the light of the urgently required development of sustainable technologies, it is of big importance to develop and to implement low-cost effective protection methods and technologies. These methods should combine:

- technological plainness with a sufficient treatment efficiency for all pollutants, and
- recovery and/or preservation of resources particularly offering the feature to improve agricultural produce.

Regarding the principle advantages of anaerobic digestion as a wastewater pre-treatment method, a big challenge is to demonstrate the feasibility of the anaerobic treatment for very low strength and relatively cold industrial and domestic wastewaters, e.g. of sewage under more severe climatic conditions.
Since 1989 the feasibility of anaerobic pre-treatment for sewage using the UASB-concept under tropical conditions has been demonstrated at small and very big full scale. Developing countries can become self-sufficient in protecting their environment from pollution due to discharge of untreated domestic wastewater. However, apart of the engineers directly involved in the research, the design, construction and operation of these anaerobic treatment plants, there remains an obstinate reluctant attitude outside this small circle. Particularly from the side of the established wastewater pollution control world the scepticism is very big, despite the excellent results obtained in one step pilot plant and in the installed full scale installations under tropical conditions.
Research in the field of anaerobic treatment at our university (WAU) started in 1970, originally concerning medium strength industrial wastewater, since 1976 sewage and domestic wastewater and low strength wastewaters as well. The research also includes work on specific post-treatment methods, viz. microaerophilic methods like biological sulphide removal.

ANAEROBIC TREATMENT OF VERY LOW STRENGTH WASTEWATERS

Introduction

In order to be able to apply very high organic and hydraulic loading rates and to achieve a satisfactory treatment efficiencies, e.g. for very low strength wastewaters, the main conditions to be met for high rate anaerobic wastewater treatment reactors are:

1. **High retention of viable sludge in the reactor under operational conditions.** For sludge bed reactors it is necessary to cultivate a well settleable immobilized type of sludge.
2. **A sufficient contact between viable bacterial biomass and**

waste water should. For this purpose Expanded Granular Sludge Bed (EGSB) systems look the proper approach.

3. **High reaction rates and absence of serious transport limitations of substrate and metabolic end-products.** The size of the biofilms/aggregates should remain relatively small and the accessibility of the organisms inside the aggregate sufficiently high, consequently the pore structure sufficiently open.
4. **The viable biomass should be sufficiently adapted and/or acclimatized.** If this condition is not sufficiently met, the sludge characteristics may deteriorate.
5. **Prevalence of favourable environmental conditions for all required organisms inside the reactor under all imposed operational conditions.** The specific substrate utilization rate of an anaerobic sludge strongly depends on factors like temperature, pH, presence/absence of nutrients and trace elements, presence of toxic and/or inhibitory compounds. With respect to the specific activity of anaerobic bacterial consortia, particularly also the effect of metabolic intermediates and end-products has to be considered. This is because the degradation of 'more complex' organic compounds in anaerobic digestion proceeds via a number of sequential steps requiring the presence of different bacterial organisms/consortia. Regarding the fact that generally a variety of very different organisms participate in the degradation of more complex compounds, the existence of micro-niches within the system with very specific environmental conditions is an absolute pre-requisite, in order to achieve a flourishing growth of the required very different organisms. For this immobilization of biomass is an essential factor, particularly for treatment systems whose capabilities rely on micro-ecological principles like is the case in anaerobic digestion processes.

ANAEROBIC SLUDGE BED REACTORS

Anaerobic Sludge Bed (ASB) reactor systems, like the well-known UASB- (Lettinga et al, 1980, 1983b) and the Expanded Granular Sludge Bed (EGSB-) reactor concepts (Lettinga et al, 1986) belong to the more popular systems.

<u>Sludge retention in ASB-reactors.</u>

The required high sludge retention in ASB-systems needs the formation of a *well settleable flocculent sludge* or - better - the formation of a *granular sludge*. A flocculent type of sludge generally will develop on wastewaters containing a high SS-content, such raw domestic sewage. Flocculent sludge bed UASB-reactors can not be operated at liquid retention times (LRT) below app. 4 hrs, but this is not too long for treating raw domestic sewage. In starting-up UASB-reactors treating sewage it presently is common use to delegate the seeding to the active anaerobic biomass (and SS) present in the raw waste water. In that case a period of 4-5 months is required to complete the start-up. Particularly in tropical countries generally a relatively high concentration of viable anaerobic biomass will be present in the sewage.

The situation is more critical for completely soluble low strength wastewaters. In that case little if any wash-out of viable sludge from the treatment system can be accepted, because of the absence of viable biomass in the raw wastewater. Therefore for treating such types of wastewaters, on the one hand virtually all the bacterial biomass growing in, should become immobilized in some way or another, whereas on the on the other hand the erosion of this immobilized biomass should remain as low as possible under all conditions imposed to the system. The crucial objectives to be accomplished for high rate anaerobic reactors in treating very low strength soluble wastewaters are **"to force the immobilization of the proper bacterial biomass and to persist this immobilization under all possible circumstances"**. It will be clear that the limiting factor both with respect to the sludge retention and applicable loading potentials of the system will be the hydraulic rather than the organic loading rate. With respect to the sludge retention the controlling factors therefore are:

- **sludge settling characteristics under all possible conditions that may prevail in the system,**
- **the mechanical strength of the sludge aggregates,**
- **reactor design, particularly the height of the reactor, the construction of the feed inlet distribution system and of the gas-solids separator.**

Regarding the existence of various syntropic conversion reactions in anaerobic digestion processes, for high rate anaerobic treatment systems it is essential **immobilize 'well balanced bacterial ecosystems'**. In this way the detrimental effect of higher concentrations of specific intermediates can be kept at a minimum, and the environmental factors like pH and redox potential optimal.
The insight in the mechanism of the sludge granulation process for anaerobic treatment, mesophyllic and thermophilic as well, has been elucidated sufficiently for practical application (e.g. Hulshoff Pol et.al.,1986, 1987; Wiegant, 1986, Wu Wei-min et al., 1985, 1987, 1991; Fang, 1994). For practice it is not necessary to understand the complexicity of the granulation phenomenon in detail. The granulation process in essence finds its ground in the fact that bacterial growth is delegated to a limited number of growth nuclei. Our insight in the granulation has been compiled in Table 1.

The **slow first start-up** of an anaerobic reactor system frequently is still considered as one of the major drawbacks of anaerobic treatment. It indeed is a rather delicate, and to some extent time consuming process, taking 3-5 months depending on the availability of seed sludge and the quality of the seed material. Such a period certainly is not too long, because already during the start-up an increasing amount of wastewater will become treated. This generally is a considerable improvements compared to the situation before.

The process of *sludge granulation* certainly is not restricted to anaerobic treatment, but also *will proceed in other biological treatment processes*, provided the proper reactor system is used and the system is operated in the correct way.

Table 1. Sequential steps in sludge granulation.

1. Proper growth nuclei, i.e. inert organic and inorganic bacterial carrier materials as well as bacterial aggregates, are already present in the seed sludge or raw sewage.
2. Finely dispersed matter, including viable bacterial matter, will increasingly rinsed out from the system, once the superficial liquid and gas velocities become higher. Film and/or aggregate formation then will become strongly reinforced.
3. The size of the aggregates and/or thickness of the biofilm is limited, it depends on the intrinsic strength (binding forces and the degree of bacterial intertwinement) and the external forces exerted on the particles/films (e.g. shear). Therefore at due time the particles/films will fall apart, in this way providing a next generation. The first generation(s) of aggregates, viz. 'filamentous' granules mainly consisting of long multi-cellular rod shaped bacteria, are quite voluminous and in fact still more floc than granule.
4. The secondary growth nuclei, at least when retained within the reactor, will grow in size again, but also in bacterial density. Growth will not be restricted to the outskirts but also proceeds inside the aggregates. At due time these sludge particles will fall apart again, evolving a third generation, etc.
5. Gradually the granules will 'age' or 'mature'. This process of aging (maturing) represents the main reason why the rather voluminous "filamentous granules", predominating during the initial stages of the granulation process, disappear and are displaced by dense 'rod' granules. In a matured granular sludge, filamentous granules will be absent.

The course and speed of the granulation process, consequently the ultimate characteristics of the granular sludge formed, will depend on a number of specific properties of the organisms involved in the granulation process, like:

- **specific characteristics of the organisms**, like morphology, substrate specificity, hydrophobicity, surface charge, ability to produce specific polymers, sensitivity.
- **growth rate of the organisms.** Results obtained sofar in granulation studies with the acidogenic organisms are less positive than with methanogens, who grow significantly slower than acidogens. The risk of the development of voluminous flocculent sludge looks rather big with acidogens. This particularly is true when filamentous organisms are involved and when the substrate concentration in the bulk of the liquid is relatively low, because growth then will be restricted increasingly to the outskirts of the aggregates. The selection pressure on the system should be reinforced substantially in order to accomplish granulation in that case.
- **death rate and decay rate** of the organisms are factors of crucial importance. In systems operated at a solids retention times (SRT) significantly exceeding the death and decay rate of **part** of the organisms growing in, a bacterial sludge consortium will develop with a relatively low content of that specific organisms, even when their growth rate is very high compared to other organisms participating in the degradation process, e.g. acidogenic organisms. Latter organisms have a considerably higher death and decay rate than methanogens. The effect of this has been completely ignored by supporters of the so-called **two-step**

treatment process, which is based on spatial separation of the acidogenic and methanogenic phases. (Pohland et al,1971). With a non-acidified wastewater, acidogenic bacteria will grow in rapidly, but major part will dye and then degrade, due to the high sludge age used in high rate reactors. In stead of two-step reactors, it looks recommendable to apply staged anaerobic treatment systems, where in the separate reactor modules a specific sludge can develop (Van Lier, 1994a). These systems lead to a higher treatment efficiency and higher process stability.

Along with the gradually increasing employment of anaerobic treatment relatively big amounts of a high quality (granular) excess sludge will become available. This material represents an almost *ideal seed* for start-up new installations. The start-up then can be completed within a few days. The main condition to be met is to keep sludge loading rates well below 50 % of its maximum substrate utilization rate during the first weeks in order to allow the sludge to adapt to the new situation, especially for waste waters significantly different in composition and strength compared to the wastewater on which the sludge was cultivated. Regarding this important feature of anaerobic sludge, there *in fact doesn't exist any other biological treatment system which can compete with the anaerobic process concerning the rate of start-up.*

Because of the big practical importance of reactor start-up with granular seed sludge, granular sludge growth and the occurrence of granular sludge deterioration has become a major field of research. Comprehensive investigations in this field have been made by Alphenaar (1992, 1993b, 1994). Important conclusions of his work are summarized in Table 2.

<u>Need for good sludge-wastewater contact.</u>
The required sufficient contact between retained sludge and wastewater can be achieved by using sophisticated feed inlet distribution systems and by expanding the granular sludge bed. Sludge bed expansion in case of very dilute wastewaters can be accomplished easily by applying sufficiently high superficial upflow velocities (as applied in EGSB-systems). For medium and high strength wastewaters gas mixing is the more important tool to meet this condition.

Complete utilization of all retained viable biomass.
In order to use indeed **all the immobilized bacteria**, the substrate should penetrate throughout the whole biomass. This requires a very high substrate transport rate within the immobilized biomass at a relatively very low substrate concentration gradient. Although this on itself already would be rather particular, for getting a complete supply of substrate throughout the aggregate the situation is even more extreme, because on its way to centre of the aggregate the solution is continuously exposed to active biomass which will result in a rapid depletion of substrate.

Table 2. Factors affecting granular sludge growth and deterioration. (Alphenaar, 1992,1993b, 1994).

1. Dispersed acidogenic organisms present in the feed solution can initiate flotation of granular sludge. This phenomenon seems to be related to the breakdown of acidogenic sludge, but the real cause sofar is unclear.

Since finely dispersed acidogenic bacteria present in the feed can act as carrier material for in-growing methanogenic organisms and these particles are hardly retained in the anaerobic reactor, it is obvious that higher concentrations of acidogenic organisms in the feed can be quite detrimental for the sludge retention of the system, consequently for the stability of the anaerobic treatment process.

2. A non or only partially acidified sucrose feed (less than 70 %) initiates the growth of a fragile type of granular sludge with a layered structure. This was also found by Fang (1994) and Thaveesri (1994). The accumulation of biogas within and around the aggregates (e.g. between the layers) causes the (granular) sludge floatation.

3. Changes in the composition of the non-acidified fraction of the substrate may result in granular sludge disintegration. The disintegration seems to be more serious in case the acidogenic organisms are more homogeneously distributed over the granular sludge.

4. Contrary to carbohydrate substrates, an excellent quality of granular sludge is always produced on a substrate consisting of non-acidified gelatine or other soluble proteins.

5. The size of the granular sludge is related to the imposed sludge loading rate. When imposing a lower loading a decrease of the strength of the granular sludge will occur.

6. P-limitation results in a decrease of the methanogenic sludge activity. The effect is completely reversible. Phosphate is well available for methanogenic granular sludge at very low phosphate concentrations (< 0.1 mg P/l).

7. Despite the presence of empty places (holes) in larger granules, the porosity of larger sludge granules is lower than that of smaller granules. Substrate transport in the granule seems not to be related directly with the porosity.

Considering the above, there exists a **need for a high specific substrate utilization rate at very low substrate concentrations.** According to Monod kinetics the substrate affinity factor k_m is a crucial factor, i.e. its value should be as low as possible, also at low temperatures. High values of k_m obviously would limit the loading potentials of the system very seriously, unless a relatively low treatment efficiency would suffice.

Mathematical kinetical models for anaerobic treatment sofar in fact exist merely for dispersed cultures, not for immobilized biomass. In latter case external and internal mass transfer processes play an important role in addition to the factors dictating the rate of conversion in dispersed types of biomass. Both for the substrate(s) and end-product(s) there generally exist concentration gradients in immobilized biomass. Mass transport inside biological matrices generally is considered to result merely from diffusion according to Fick's law (Pavlostathis S.G. and E. Giraldo-Gomez, 1991).

In reality the situation is much more complex, but for two reasons presumably also more favourable, than follows from diffusion considerations:

1. It looks reasonable to assume that in addition to diffusion a convective type of mass transfer will occur in the anaerobic aggregates, particularly in the macro-pores, e.g. as a result of the formation and release of gas bubbles and/or (according to Kato, 1994) as a result of higher hydraulic turbulence in the bulk of the liquid due to imposed high superficial liquid

velocity in the reactor.
2. Secondly a possibly (very) positive effect of the existence of syntropic processes should be taken into account in the degradation (rate) of organic compounds. These syntropic degradation processes are also of crucial importance for the built-up of immobilized balanced micro-ecosystems.
Besides the detrimental effect of biomass-immobilization with respect to transport rates inside bacterial aggregates, on the other hand biomass-immobilization very likely enhances the rate of conversion reactions. As a consequence (apparent) K_m-values for well balanced immobilized micro-ecosystems even may become lower than intrinsic K_m-values found for dispersed cultures. According to results obtained by Kato this indeed seems to be the case for EGSB-systems. Prevailing apparent substrate affinity (K_m-) values in EGSB-reactors were found to be lower than 10 mg COD/L.
Apart from the above kinetical reasons, the substrate utilization rate also could be negatively influenced by the presence of dissolved oxygen, which frequently is the case for very low strength wastewaters. However, according to results of Kato (1993) the detrimental effect of oxygen is neglectable.

TREATMENT OF SOLUBLE SUBSTRATE SOLUTIONS USING EGSB-SYSTEMS.
Based on very promising results of preliminary experiments with expanded granular sludge bed reactors conducted in the early eighties (Lettinga et al, 1983), comprehensive investigations on the anaerobic treatment of very low strength and cold wastewaters were started in 1989 (M.Kato et al,1994, Rebac et al. 1993).
EGSB-systems indeed offer enormous potentials for practice. In experiments conducted in 1 m tall EGSB-reactors (reactor volume: 2.5 L) with dilute VFA-solutions (COD, 1000 mg/l) at temperatures as low as 10 ^oC (Rebac, 1994) space loads up to 12 kg COD/m^3.day at LRT < 1hr were well accommodated (see Fig. 1).
Results obtained with low strength ethanol solution (COD: 100 - 800 mg/l) conducted at 30 ^oC, reveal that EGSB-systems perform very satisfactory at superficial liquid velocities (V_f) ranging from 2.5 to 5.5 m/hr. At V_f-values below 2,5 m/hr the expansion of the bed and the mixing intensity is insufficient for achieving the required contact between sludge and wastewater and/or for enhancing the mass transport of the substrate to position deep inside the sludge aggregates. V_f-values exceeding 5.5. m/hr don't result in a higher efficiency.

The feasibility of high rate anaerobic treatment using EGSB-systems sofar only was demonstrated for:

- Mainly soluble wastewaters consisting of:
  - Solutions of VFA (COD_{infl}: 600-900 mg COD/L, composed of a mixture of acetic, propionic and butyric acid) at ambient temperatures of 10 - 13 ^oC (Lettinga et al. 1986, Kato et al. 1994),
  - Solutions of ethanol (COD: 100-800 mg/l. (EGSB-reactors 2.5 - 4 liter in volume, 1 - 2 m reactor height).
- Partially acidified wastewaters consisting diluted (waste-)beer and malting wastewater (Rebac et al,1993) in a 225 litre, 7 m tall EGSB-pilot reactor,

- Solutions of sodium salts of lauric and capric acid in small scale EGSB-reactors (Rinzema 1988, Rinzema et al. 1989, 1993).

These results can represent a definite breakthrough with respect to the application of anaerobic treatment at low ambient temperatures and for very low strength substrates, and not merely VFA-substrates but very likely also substrates consisting of ethanol and even of more complex soluble (and even partially soluble) compounds.

TREATMENT OF SEWAGE
(De Man et al, 1990; Van der Last et al,1991a,b; Wang Kayun, 1994

With regard to the feasibility of anaerobic treatment systems for sewage the following aspects have to be considered in relation to the imposed loading rates and environmental conditions:

- treatment efficiency (COD,BOD,SS)
- extent of sludge stabilization achieved,
- excess sludge production (in kg and in m^3)

Table 3. Summary of finding of batch recirculation experiments with sewage samples.

1. **For raw sewage:**

- The maximum achievable overall treatment efficiency amounts to about 80 % at 20 °C. At lower temperatures longer contact times are required in order to achieve a similar efficiency.
- Coarse suspended solids (paper filtrable) are removed completely and relatively easily. Flocculent solids accumulate at top of the granular sludge bed. In full scale installations this sludge should be discharged occasionally. The rate of biological degradation of these solids proceeds slowly, and generally is far from complete, especially at lower ambient temperatures and for septic types of sewage.
- The colloidal and supra-colloidal SS-fraction can be removed for 80 - 100 %, but the process proceeds relatively slowly.
- Depending on the type of sewage 55 - 72 % the soluble COD-fraction can be eliminated at temperatures ranging from 10 to 25 °C, but the process needs more time at lower temperatures. The remaining fraction is non-biodegradable (anaerobically and aerobically).

2. **For settled sewage** (average: 42 % soluble, 28% colloidal and 31 % relatively coarse particles).

- The achievable overall COD-reduction using UASB-systems or with combined EGSB-systems + post-settler amounts to 65-84 % (average: 78 %). When providing EGSB-reactors with a wider top-section, flocculent excess sludge can be temporary retained in the reactor, which looks beneficial with respect to the removal of colloidal matter.
- EGSB-systems are quite effective in removing colloidal matter.
- Soluble COD is removed by EGSB-systems for 54 % at the maximum. At lower temperatures these values are slightly lower and/or longer contact times are needed. This also is the case for diluted sewage (rainy weather conditions).
- Evidence was obtained that lower COD_{eff} (approximately 11 % lower) is reached when proceeding an aerobic treatment by an anaerobic pretreatment step (UASB or EGSB).

Extensive investigations have been conducted since 1976 aiming at assessing the feasibility of high rate anaerobic treatment

systems like UASB-, FB-, EGSB- and UHSB- (upflow hydrolysis sludge bed) reactors for treating **raw and/or settled domestic sewage**. Small and big pilot plant scale as well as in bench scale laboratory feasibility studies have been conducted and in the meantime also full scale experience is available.
It is impossible to present and to discuss these results in detail and we'll suffice providing the most relevant findings.

Results of laboratory feasibility studies.

A large number of batch recycle experiments were conducted with settled and raw sewage under a large variety of conditions. In these experiments a batch of wastewater is recycled through a UASB- or EGSB-reactor filled with fresh granular sludge obtained from a full scale UASB-reactor. These assays provide information about the 'Maximum Anaerobic Biodegradability' (AnB_{max}), i.e. the biodegradability after prolonged contact of the wastewater under conditions which are fairly similar to those in full scale UASB/EGSB reactors. The results are summarized in Table 3

Results of Pilot UASB experiments with raw sewage

UASB-reactors varying in volume from 30 up to 20,000 liter and in height from less than 1 m up to 6 m were employed, using both flocculent and granular sludge seed material. Most experiments conducted concerned one-step UASB-systems, but some complementary experiments in two-step UASB-treatment systems were also carried out, as well as some preliminary experiments with an integrated anaerobic-chemical system.

Use of flocculent sludge bed reactors.

Table 4. summarizes the results obtained in 0.03- 6 m^3 UASB-reactors.

Table 4. Experimental results obtained in flocculent sludge 0.03- 6 m^3 UASB-reactors with raw domestic sewage.

COD-reduction tot/tot	COD-reduction filt/raw %	HRT-range hrs	temperature range °C	Conditions
		under dwa-conditions		
ca 65	70-80	8 - 12	18-20	dwa
20-45	45-65	8 - 12	18-20	rwa
60	55-75	> 12	8-12	dwa
	60-75	> 12	8-12	rwa

At temperatures exceeding appr 16 °C a sufficient sludge stabilization can be accomplished.

Use of granular sludge bed reactors.

The results obtained are summarized in Table 5.

Table 5. Treatment efficiencies obtained in 6 m^3 granular sludge UASB reactors with raw sewage from the village of Bennekom.

react.	Conditions Temp.	dwa/rwa	HRT	$E_{t/t}$	$E_{f/t}$	E_{SS}
			uur	%	%	%
120 L	13-18	dwa	ca 7	50-60	70-85	
120 L	13-18	rwa	ca 7	ca 30	45-70	
6 m^3	>12	dwa	7-11	40-50	30-50	50-70
	18-20	rwa	8-12	20-45	45-65	

The best results were obtained in a shallow reactors , i.e. in the 120 l UASB-reactor, which was only 1.5 m tall. This mainly can be attributed to the higher v_f-values needed in the 20 m^3 reactor and very likely to the poorer feed inlet distribution. At temperatures below 12 ^oC either longer liquid detention times are required, or a more sophisticated feed inlet distribution system should be applied in order to improve the contact between sludge and waste water. The results obtained with sewage from a separate sewer system (Lelystad) were very disappointing, presumably mainly due to deterioration of the specific methanogenic activity of the granular seed sludge, i.e from 0.55 to less than 0.002 gr CH_4-COD/gr VSS/day.

Use of EGSB- and FB-systems
Investigations with EGSB- and FB-systems using settled sewage were started in 1986 and those with EGSB, using reactors varying in height from 2 m to 5m, still are continued. The applied superficial velocities (v_f) in EGSB-systems always amounted to appr. 6 m/hr and in the FB-systems up to 12-24 m/hr at the start and 10-12 m/hr after completion of the start-up. These V_f-values were adjusted by applying the appropriate effluent recycle ratio at the imposed HRT.

Results with FB-systems
Results obtained with FB-systems, operated under conditions of $v_f$values exceeding 12 m/hr, clearly indicated that these systems are not feasible for treating settled sewage. However, when operating these reactors under EGSB-conditions, viz. at v_f 6-9 m/hr, a methanogenic biofilm develops on the carrier material, and ultimately even a granular sludge with a relatively high methanogenic activity developed, i.e. appr. 0.4-05 kg CH_4-COD/kg VSS.day at 30 ^oC, which is distinctly higher than the ultimate specific activity of a granular seed sludge when exposed to same sewage in EGSB-reactors.

Results with EGSB-systems
In *one-step EGSB-systems* using granular sludge cultivated on paper wastewater, appr. 45 % COD-reduction can be accomplished under dwc-conditions at temperatures exceeding 13 ^oC and at HRT as short as 2 hrs. This 45 % COD-reduction represents 85 % of the anaerobically biodegradable COD. The efficiency increases only slightly upon increasing the HRT from 2 to 7 hrs. The acetoclastic activity of the granular sludge improves during the experiment from 0.17 to 0.25 kg COD/kg VSS.day at 30 ^oC.
During winter time (average temperature 9.4 ^oC) the efficiency drops down to appr 20 %.
The performance of the system strongly depends on the quality of the granular sludge used. So it was found that the same treatment

efficiency (up to 43 % of the soluble fraction) can be achieved at less than 1 hr liquid detention time using a granular sludge cultivated on settled sewage itself.

A significantly better performance is obtained in using a *two-step EGSB-treatment* system operated at the same overall liquid detention time, i.e. a COD-reduction of 55 % instead of 45 %. This higher efficiency mainly can be attributed to the improved removal of colloidal and finely dispersed matter in the second step. A further improvement of the treatment efficiency can be accomplished by equipping the EGSB-reactor with a more sophisticated GSS-device.

Formation of active granular sludge

The experiments with the reactors supplied with inert carriers (sand and basalt) conducted under EGSB-conditions revealed that an excellent type of granular sludge can be cultivated on settled sewage via biofilm formation on these carrier particles. Important with respect to granulation is retain biomass aggregates. It was also shown that granulation proceeds well at appr. 20 °C using digested sewage as seed, provided the reactor is operated at HRT= 5 hr and V_f = 8 m/hr. After 1 month small granules were already observed in both reactors investigated, and after two months the reactors contain granules with a diameter of approximately 1 mm. Like observed in the granulation in UASB-reactors the first generations of granules are mechanically rather fragile, but gradually they mature to more rigid aggregates. The VSS-content of the aggregates gradually increases up to appr 70 -80 %, and the methanogenc activity reaches values as high as 0.31 kg COD/kg VSS.day.

CONCLUSIONS AND DISCUSSION OF RESULTS OBTAINED WITH RAW SEWAGE

Anaerobic wastewater treatment based on the upflow sludge bed principle like the UASB-system belong to the category **"grown-up environmental technologies"**.

For practical application presently sufficient insight is available in the sludge immobilization (i.e. **granulation**) process. The understanding of the factors controlling granular sludge growth and/or deterioration is growing rapidly. In anaerobic treatment the immobilization of balanced bacterial eco-colonies is essential. Such balanced bacterial communities enhances the rate of degradation of acetogenic and acidogenic organic substrates very signifantly, because the concentration of intermediates is kept sufficiently low and the environmental conditions optimal. In addition to well known factors, like seed sludge characteristics, process and environmental conditions, the morphology and growth rate of the organisms, factors of big importance with respect the ultimate characteristics of sludge aggregates comprise the death and decay rate of the organisms. These factors have been almost completely ignored in all contemplations of *two-step* high rate treatment systems. Regarding their high sludge hold-up, **death and decay rate** should be considered. Organisms with a relatively high death and decay rate, such as acidogenic bacteria, will constitute only a minor fraction of the sludge, even despite their relatively high growth rate. Therefore for cultivating a sludge with a high specific methanogenic activity on non- or slightly acified wastewaters there doesn't exist any need for *'phase separation'*.

The most recent variant of the sludge bed concept, the **EGSB-system**, offers big practical prospects, particularly for very low strength wastewaters (COD<< 1000 mg/l) and for lower temperatures, i.e. as low as 10 °C. In the EGSB-system not merely all the retained sludge is contacted with the wastewater, but also a substantially bigger fraction of the immobilized viable biomass participates in the process, as a result of the prevailing extraordinary low values of the apparent substrate affinity for the sludge. The relatively very high substrate affinity of the granular sludge in EGSB-systems may lead to a reconsideration of the theories developed for mass transfer in immobilized biomass. It looks necessary to account for the positive effect of the presence of balanced bacterial ecosystems in anaerobic granular sludge, and the existence of convection flows in the pores which greatly may enhance the rate of mass transfer in the immobilized biomass. Convection flows may be caused by gas bubble formation. A positive consequence of the prevailing high substrate affinity in EGSB-reactors, is that significantly higher loading rates can be accommodated in these systems with wastewaters containing lipids and/or higher fatty acids, as compared to conventional UASB-reactors.

A distinct improvement in the anaerobic reactor technology can be obtained by **staging the reactor**, so that mixing up of the sludge will not occur and a plug flow pattern is approached. A staged process will provide a higher treatment efficiency and a higher process stability. This particularly will be the case for thermophilic systems, because substrate inhibition, viz. especially also by intermediates, is relatively more important here than for mesophyllic processes.

Comprehensive pilot plant investigations and results obtained in full scale reactors reveal that conventional (one-step) UASB-systems (4-5 m tall) can provide 65-75 % COD-reduction on **raw sewage** at temperatures exceeding 20 °C at hydraulic retention times 4-6 hrs. Also under moderate temperatures of 12-18 °C a substantial COD-reduction can be achieved, provided the sewage is distributed as evenly as possible at the bottom of the reactor, the daily average v_f remains below 0.5 m/hr (i.e. the height of the reactor should not exceed 3 m). Preferentially the installations should consist of two or three compartments operated in sequence. Flocculent sludge UASB-reactors should not considered as inferior relative to granular sludge bed reactors, neither for the removal of soluble COD nor for finely dispersed solids. The removal of colloidal and supra-colloidal matter represents the main limiting factor with respect to the treatment efficiency of anaerobic treatment systems. The excess sludge production strongly depends on the loading regime applied and on the operational temperature. At temperatures exceeding appr. 16 °C and when the system is properly operated, a satisfactory sludge stabilization can be accomplished and the excess sludge production then amounts to 10 kg DS/P.E./year. Under these conditions the thickening characteristics of the sludge are satisfactory, so that easily TSS-values exceeding 8-10 % can be

obtained.
Anaerobic treatment to our opinion could represent an attractive option for moderate climates, though not (always) especially for COD-removal, but for improving the performance of the aerobic treatment process with respect to P- and N-removal by increasing the VFA-concentration and for removing and stabilizing SS from the raw waste water.
Such a first VFA-producing and SS-removal treatment step obviously also could be used as a first module of compartmented sludge bed reactor system, because the VFA in the effluent of this first module can be removed quite efficiently in a second (e.g. granular sludge) UASB- or EGSB-reactor. A serious drop in specific methanogenic activity of the granular sludge in this reactor then will not occur. The prospects of EGSB-systems for treating settled or pre-treated sewage look promising.

Literature

Alphenaar P.A., W.J.H. van Berkel, G.Lettinga, P.A., M.C. Perez, (1992).Determination of the permeability and porosity of anaerobic sludge granules by size exclusion chromatography. Applied Microbiology Biotechnology, **36**: 795-799.
Alphenaar, P.A., G.Lettinga, M.C. Perez, (1993a). The influence of substrate transport limitation the porosity and methanogenic activity of anaerobic sludge granules. Appl. Microbiol. Biotechnol. 39: 276-280.
Alphenaar P.A., G.Lettinga, A.Visser, (1993b). The effect of liquid upward velocity and hydraulic retention time on granulation in UASB reactors treating waste water with a high sulphate content. Biores. Technol. 43, 249-258.
Alphenaar, P.A.(1994), Anaerobic granular sludge: Characterization and factors affecting its performance. PhD-Thesis, Wageningen Agricultural university, June, 1994.
De Man de, 1990, Final Report "Anaerobic Treatment of raw sewage using granular sludge UASB-systems", Wageningen.
Hulshoff Pol, L.W., G. Lettinga, C.T.M. Velzeboer, W.J. de Zeeuw, (1983a). Granulation in UASB reactors. Wat Sci Technol 15:291-304.
Hulshoff Pol L.W., J. Dolfing, G. Lettinga, K. van Straten K. & W.J. de Zeeuw. (1983b). Pelletization of anaerobic sludge in anaerobic sludge bed reactors on sucrose containing wastewater. In: Klug MJ & Reddy CA (eds) Current perspectives in microbial ecology. Proc. 3rd int. symp on microbial ecology. 7-12 August 1983. American society for microbiology, Washington DC UAS, 636-642.
Hulshoff Pol, L.W. & G. Lettinga, (1986). New technologies for anaerobic wastewater treatment. Wat. Sc. and Technol, 18, 41-53.
Hulshoff Pol, L.W., K Heynekamp & G.Lettinga, (1987). The selection pressure as a driving force behind the granulation of granular sludge, in "Granular Anaerobic Sludge; Microbiology and Technology", Proceedings of the GASMAT-workshop, 25-27, October, 1987, Lunteren, 146-153.
Hulshoff Pol L.W. (1989). The phenomenon of granulation of anaerobic sludge. Ph.D. Thesis Agricultural University Wageningen, The Netherlands.
Iza, J., P.A.Garcia, I.Sanz & F.Fdz-Polanco, (1987). Granulation results in anaerobic fluidized bed reactors, in "Granular Anaerobic Sluige; Microbiology and Technology", Proceedings of the GASMAT-workshop, 25-27, October, 1987, Lunteren,
Kato, M. (1994). The anaerobic Treatment of low strength Soluble Wastewaters, PhD-thesis, Wageningen Agricultural university.
Kato, M.T., J.A.Field, P.Versteeg, G.Letting, (1994). The feasibility of expended bed granular sludge bed reactors for the anaerobic treatment of low strength soluble wastewaters. Biotechn. & Bioeng., 44, 469-479.
Lettinga, G. S.W. Hobma, A. Klapwijk, A.F.M. van Velsen & W.J. de Zeeuw (1980). Use of the Upflow Sludge Blanket (USB) reactor concept for biological wastewater treatment. Biotechnology and Bioengineering, 22: 699-734.
Lettinga, G., P. Grin, S.W. Hobma, L.W.Hulshoff Pol, R. Roersma, S. Sayed,

A.F.M. van Velsen, W. Wiegant & W. de Zeeuw (1983a). 'Upflow Sludge Blanket Processes'. Proceedings Third International Symposium On Anaerobic Digestion, 14-19 August, 139-158, 1983, Boston, USA.

Lettinga, G., P. Grin, S.W. Hobma, L.W. Hulshoff Pol, P. de Jong, R. Roersma & W.J. de Zeeuw,(1983b). Design, operation and economy of anaerobic treatment. Wat. Sc. and Technol., 15, 177-195.

Lettinga, G. & L.W. Hulshoff Pol, (1986). Advanced reactor design, operation and economy. Wat. Sc. and Technol., 18, 99-108.

Pavlostathis S.G. and E. Giraldo-Gomez, (1991). Kinetics of anaerobic treatment. Wat Sci Technol 24:35-59.

Pohland,F.G. & S. Ghosh, (1971), Anaerobic stabilization of organic wastes; two-phase concept. Environmental letters, 1, 255.

Rebac, S., M.T.Kato & G.Lettinga, (1994). The application of an upscaled EGSB-type reactor for the anaerobic treatment of low strength brewery-type wastewater. Internal report 1993.

Rinzema,A. (1988) Anaerobic Treatment of Wastewater with High Concentrations of Lipids or Sulfate, PhD Thesis, Wageningen Agricultural University.

Rinzema,A., A. Alphenaar & G. Lettinga, (1989). The effect of lauric acid shock loads on the biological and physical performance of granular sludge bed UASB reactors digesting acetate, J. Chem. Technol. Biotechnol. 46: (4), 257-266, (1989)

Rinzema,A., A. Alphenaar & G. Lettinga, (1993a). Anaerobic digestion of long chain fatty acids in UASB-reactors and Expanded Granular Sludge Bed reactors. Process Biochemistry, 28: 1993, 527-537.

Van der Last, A.R.M. & G. Lettinga, (1991a). "Anaerobic treatment of domestic sewage under moderate climatic conditions using upflow reactors at increased superficial velocities." Paper presented at the sixth International Symposium on Anaerobic Digestion, Sao paulo, 12-16 May.

Van der Last, A.R.M., (1991b). Anaerobic Treatment of settled sewage using an EGSB- and a Fluidized Bed process. Final report of an investigation at pilot plant scale dealing with the assessment of the use of these systems in the Netherlands, June 1991. (Agricultural University, Department of Environmental Technology, Wageningen. (in Dutch).

Van Lier, J.B., C.T.J.M. Grolle, K.C.F. Conway de Macario, A.J.M.Stams & G. Lettinga, G. (1992). Start-up of a thermophilic Upflow Anaerobic Sludge Bed (UASB) reactor with mesophyllic granular sludge. Appl. Microbiol. and Biotechnol. 37: 130-135.

Van Lier, J.B., F. Boersma, M.M.W.H. Debets & G. Lettinga, (1994a). 'High Rate' thermophilic anaerobic wastewater treatment in compartmentalized upflow reactors. p. 338-347, In: Paper Pre-prints of the Seventh International Symposium on Anaerobic Digestion, Cape Town, January 23-27, 1994, South Africa.

Van Lier J.B., N. Groeneveld & G. Lettinga, (1994b) Characteristics and development of thermophilic methanogenic sludge in compartmentalized upflow reactors. Biotechnol. and Bioeng. *submitted.*

Wiegant, W.M. & A.W.A. De Man. (1986b). Granulation of biomass in thermophilic anaerobic sludge blanket reactors. Biotechnol. Bioeng. 28, 718-727.

Wiegant, W.M. (1986). Thermophilic anaerobic digestion for waste and wastewater treatment. PhD. thesis, Department of Water Pollution Control, Agricultural University, Wageningen, The Netherlands.

Wang Kayun, 1994, Integrated Anaerobic and Aerobic Treatment of Sewage. PhDthesis, Wageningen Agricultural University.

Wu Wei-min, Hu Ji-cui & Gu Xia-sheng (1985). Properties of granular sludge in upflow anaerobic sludge blanket (UASB) reactor and its formation (1985). Proc. 4th int. symp. on anaerobic digestion, Guang Zhou, China 11-15 nov 1985.

Wu Wei-min, R.F. Hickey & J.G. Zeikus, (1991). Characterization of metabolic performance of methanogenic granules treating brewery wastewater - Role of sulfate reducing bacteria. Appl Environ Microbiol 57: 3438-3449.

Wu wei-min (1987) Granular sludge in upflow anaerobic sludge blanket (UASB) reactor and its properties. Water Treat 2:148-157.