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DECOM MANUAL

MANUAL FOR THE DESIGN, CONSTRUCTION, OPERATION, AND MAINTENANCE OF UASB TREATMENT PLANTS FOR DOMESTIC WASTEWATER

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1. INTRODUCTION

1.1 History

The development of the UASB-system for domestic wastewater started in the Netherlands with laboratory-scale experiments, soon followed by pilot-scale experiments. In 1983 a pilot-plant project was started in Cali-Colombia in which the technical, social and financial feasibility of the application of the UASB-system was studied for domestic wastewater under (sub)tropical conditions. This project was financed by the Dutch Ministry of Foreign Affairs, the research and technology department (DPO/OT) of the Directorate General of International Cooperation (DGIS) and was carried out by HASKONING, Royal Dutch Consulting Engineers and Architects in cooperation with the Agricultural University of Wageningen, Holland. In Colombia the project partners were the University of Valle (UniValle), Public Works of Cali (EMCALI) and INCOL Ltda, a local consultant.

The promising results of the feasibility study led to an extension of the project to scale up the UASB-technology to full-scale level. The extension also included the preparation of a manual for design, construction, operation and maintenance of UASB treatment plants for domestic wastewater in warmer climates, based on the experiences with the pilot-plant and the full-scale plant.

1.2 Objectives of the DECOM manual

The Design, Construction, Operation and Maintenance manual, or DECOM-manual as we name it, is based on the first experiences with UASB-treatment for domestic wastewater. The 4 year pilot-plant research with a 64 m^3 (1000 p.e.) UASB-reactor in Cali, Colombia, provided much information on design criteria and operation and maintenance aspects.
The experience gained in the design, construction, start-up and operation of a 1200 m^3 (30,000 p.e.) UASB-plant in Kanpur, India, a 1000 m^3 (20,000 p.e.) UASB-plant in Cali, Colombia, and the design of a 6000 m^3 (100,000 p.e.) UASB-plant for Mirzapur, India were used to elaborate this manual.

The presented design criteria apply for UASB-reactors with a treatment capacity above 500 population equivalents in tropical regions.

In Indonesia research has been done with UASB-reactors for on-site treatment. This application differs from the off-site application, presented in this manual, with respect to design parameters and operation/maintenance. Therefore on-site application of the UASB-system is not included in this manual.

The objectives of the manual are the following:
1. Provide the required information to evaluate the UASB-system as an alternative to more conventional sewage treatment systems.
2. Provide the basic design and operational criteria for UASB-plants for domestic wastewater.
3. Serve as a guide for the elaboration of operation and maintenance manuals for UASB-plants for domestic wastewater.

Though the UASB technology now can be considered as a grown-up technology,

it still can be developed further, on the basis of experience to be gained in the future. Certainly not an objective of this manual therefore is to set the mark on UASB-reactor design for domestic wastewater.

1.3 Users

The manual is intended for:

1. Engineers that consider to design a UASB-plant for domestic wastewater. These engineers should possess a good understanding of anaerobic processes and should have basic experience with anaerobic treatment systems.
2. Engineers that wish to evaluate the UASB-process as an alternative treatment solution.

1.4 Structure of the manual

This manual consists of three parts:

PART 1: GENERAL ASPECTS OF ANAEROBIC SEWAGE TREATMENT

This part of the manual sets the context for the more specific parts of the manual. General information is given and for further reading reference is made to widely recognized literature on the subjects. The three chapters of this part of the manual highlight the characteristics of domestic wastewater, explain the principle of the UASB-process and of anaerobic treatment in general.

PART 2: DESIGN AND CONSTRUCTION

In this part of the manual the lay-out and design principles of a UASB-treatment plant and of the UASB-reactor in particular are presented. In a separate chapter specific information concerning the construction of UASB-reactors and the use of construction materials is given.

PART 3: OPERATION AND MAINTENANCE

This part of the manual starts with a treatise on plant management, which is considered the key to a successful plant operation. In other chapters safety and health aspects, maintenance, operation and troubleshooting on UASB-plants is presented.

PART 1

GENERAL ASPECTS OF ANAEROBIC SEWAGE TREATMENT

CONTENTS

1. STEPS IN THE REALIZATION OF A UASB TREATMENT PLANT

The realization of a large project such a the construction of a UASB treatment plant requires careful planning. As there are large amounts of money involved, one should be able to make the correct decision, based on sufficient data. The choice of the process should be motivated on the basis of cost calculations for various alternatives. The basic design should be based on thorough design criteria, estimates and calculations. After the basic design has been prepared, the size of the various units is known, allowing for calculation of the hydraulic profile over the reactor. Only then the preparation of the detailed design can be started..

Site selection

Nobody wants a wastewater treatment plant in his or her backyard. This holds for both aerobic and anaerobic wastewater treatment plants. Therefore, during the selection of the site, the distance to the nearest housing areas always is a very important issue. If the distance is low, treatment of off-gases may be necessary.

The selection of the site of a wastewater treatment system always is a compromise. On one hand, one would like to have the treatment system placed at a location, where the costs of sewers is low, and on the other hand, it is impossible to build a treatment plant in the middle of a city. Future possibilities for treatment plant extension should always be taken in mind in the choice of a suitable site. A further constraint to the site of a treatment plant are the possibility to discharge the effluent. The site should preferably close to a river with a large enough flow that the effluent has as little effect as possible on the original river water quality. Of course, the soil should of course be suited for the construction of the plant.

If possible, a wastewater treatment plant should be operated under gravity flow as much as possible. If the site selection allows for a location where this is possible, this location should be preferred over other locations. Last, but not least, should the land prices be an element in the selection of the site.

Data collection

Before the system choice can be prepared and the design can be initiated, first there should be sufficient data available on the topographical situation, and on the wastewater. These data need to be representative for the actual wastewater situation. Data to be acquired are flow data and data on the concentration of parameters important for the design. If, for one reason or the other, only limited data are available, the design necessarily has to be conservative. In Chapter 2 wastewater data are discussed in more detail.

System choice

It is imperative that the choice for some kind of treatment system is based upon a sound analysis of various alternatives. Although this manual is not engaged with the system choice, it should be noted that anaerobic treatment of domestic wastewater may not always be a suitable alternative. In the system choice, the complete system, post-treatment, air treatment and biogas use (in larger plants) should be evaluated. In the system choice the effluent regulations will play an important role. If, for instance, nitrogen concentrations in the effluent must be

very low, then a denitrification system might be a viable alternative. In such a case anaerobic treatment would reduce too much BOD.

In the system choice, cost effectiveness will play an important role, as will the capacities for the various treatment systems to comply with the effluent regulations.

Preliminary design

After the system choice has been completed (in which also assumptive design has to be made for cost comparison), the actual preliminary design should take place. This includes the process design. During this phase the size of the various units is calculated, based on wastewater data, design criteria, and design assumptions. These calculations should be reported in such a way, that other technologists can follow the line of reasoning in the calculations, and that the calculations follow logically from data, criteria and assumptions. The preliminary design also includes the choice on crucial points of the UASB system, such as the type of feed inlet system and the gas collectors.

Hydraulic profile

Based on the process design and topographical data of the selected site, the hydraulic profile of the treatment plant can be calculated. This quite awkward calculation should always be performed by a civil engineer specialized in this kind of calculations. The calculation of a hydraulic profile over a wastewater treatment plant is beyond the scope of this manual. Therefore, the reader is referred to more specialised literature.

Detailed design

Only after the completion of the process design and the hydraulic profile, the detailed design can take place. The detailed design will include the actual building of the various units, in terms of construction materials, wall thickness, piping between various units *etcetera*. This manual is not meant as a treatise on how to build a wastewater treatment plant, so this kind of information is not supplied in this manual.

Specified design

The specified design should be such that a constructor would be able to construct the plant. This specified design will include calculations on the concrete thickness, construction drawings, detailed electrical and mechanical design. and equipment specifications.

Tendering

The construction documents should include the calculations on concrete, construction drawings, detailed electromechanical design and equipment specifications. On the basis of the construction documents the tender documents can be prepared and a suitable constructor can be selected.

Construction

The actual construction of the plant is the final step in the realization.

2. WASTEWATER COLLECTION AND WASTEWATER CHARACTERISTICS

A wastewater treatment plant is part of a complete system of sewage collection, transport, treatment and final disposal or re-use. Each of these components contains variables that influence the design and the operation of the treatment plant. In the following paragraph these variables will be presented as far as they interfere with the design and operation of anaerobic treatment plants.

2.1 Sewerage system

1. Presence of industrial wastewater

Wastewater from densely populated areas is frequently collected in a sewer system. In many residential areas certain types of house-industry can be found (dyers, tanneries, service stations etc.). So, depending on the industrialization of the service area, the sewage contains more or less industrial wastewater.

The significance of industrial discharges for the design and operation of the treatment plant is determined by the type of industry involved, the composition of the wastewater produced and its final concentration in the sewage.
In any case a sound study on the industrial discharges should be carried out in order to anticipate possible influences on the performance of the plant. This aspect will be discussed in § 4.2 and 4.3.

2. Presence of infiltration water or storm water

Sewerage systems may be designed as:
- separate sewers, in which wastewater and storm water are collected in different conducts,
- combined sewers, in which the same conduct is used for both wastewater and storm water.

Even in sewerage systems designed exclusively for sewage transport, storm water from roofs, patios, streets and overflows from storm sewers may discharge into the system through erroneous connections. Moreover, sewerage systems often are not water tight, causing infiltration of ground water into the system. In case the sewer is located above ground water level, seepage of sewage to the underground occurs.

In § 2.2 and 2.3 the relevance will be discussed of the type of sewerage system and the presence of infiltration- and storm water in the sewage.

2.2 Flow characteristics

There are no generally applicable thumb rules for estimating design flows of a sewer system. In the handbooks (see § 2.5) several methods for the estimation of the flow are given. In each situation the most appropriate method should be used.

For existing sewer systems the best method to determine the flow rate of the sewer is to carry out continuous flow measurements. These measurements should last at least a week and should provide statistically reliable data on the minimum, maximum and average flow in the dry weather situation during the working week

and in the weekend (Figure 1C). It is important that measurements are repeated under rain-weather conditions, in order to estimate the storm water flow. This is also necessary for separate sewer systems, since erroneous storm water connections exist in practically every sewer system.
Figure 1 shows an example of a 6-day continuous sampling. From the individual daily flow curves (Figure 1A) an average daily flow curve can be derived (Figure 1B).

The shape of the discharge curve depends on many factors, such as:

- length of the sewer system
- type of system
- buffer capacity of the system
- water consumption and water consumption pattern

Usually a morning peak and an early evening peak can be distinguished (Figure 1B). Depending on the length of the system this peak will arrive more or less retarded at the sewer out-fall. Depending of the buffer capacity of the sewer system the peak will be more or less levelled off.

When it is not possible to carry out flow measurements due to a lack of reliable measuring devices or inaccessibility of the sewer, another but less reliable approach can be followed:

- determination of drainage area, rainfall etc.
- estimation of population in drainage area,
- estimation of water consumption in drainage area, (water meter reading where possible)
- taking a certain ratio between water consumption and sewage collection (0.7-0.9),
- assuming that the maximum flow rate (m^3/h) is 10% of the estimated daily wastewater quantity (m^3/d),
- estimation of storm water flow and frequency,
- estimation of infiltration/seepage.

Of course a future increase of the flow has to be considered for population growth, expected increase of water consumption etc.

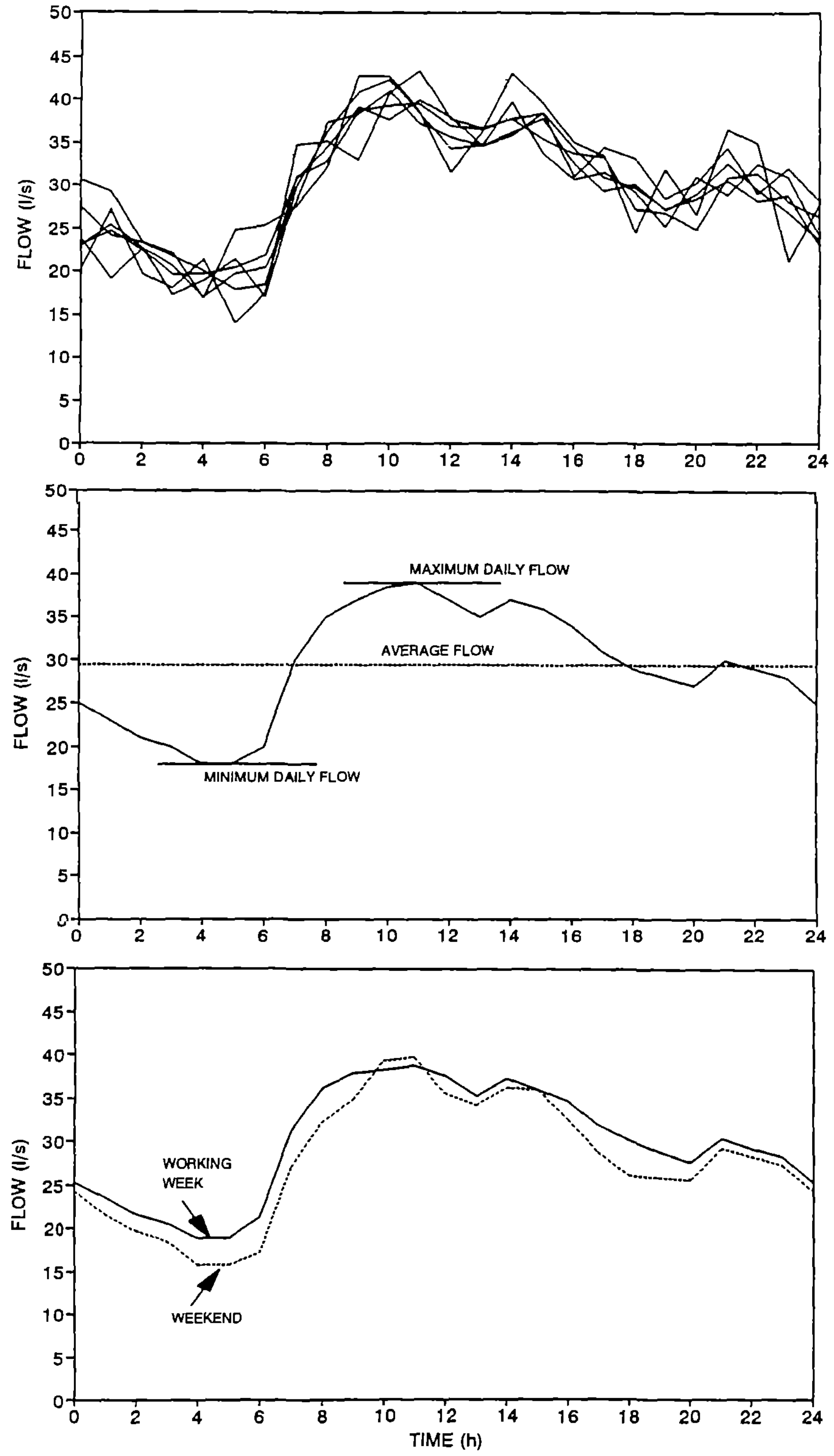

Figure 1. Individual flow curves (top, 1A) and the average daily flow curve (middle, 1B) from flow measurements. Bottom (1C): difference in flow during the week days and over the weekend.

2.3 Composition of domestic wastewater

The composition of wastewater varies considerably from one situation to the other and depends on the water consumption, the level of sanitation, the type of sewer and the retention time in the sewer system, the climate and cultural habits.

The composition of sewage is complex as well as variable. In sewage a large variety of organic compounds is present and it is impossible (and meaningless) to characterize them all. Usually the concentration of organic compounds in a sewage is expressed in terms of BOD or COD. Some inorganic compounds, e.g. nitrogen, phosphorus, sulphate, chloride and pH, are also used to characterize sewage. A schematic general composition of domestic sewage is presented in Figure 2. In Table 1 some ranges of the characteristic components are presented for high, medium and low concentrated sewage. The term strength of a sewage generally applies for the BOD-concentration of the wastewater and can be characterized as presented in Table 2.

Table 1. Typical composition of domestic wastewater (Lit. 3). All values except settleable solids expressed in mg/l (= g/m^3)

	CONCENTRATION		
PARAMETER	Strong	Medium	Weak
Total solids	1200	720	350
Dissolved, total	850	500	250
Fixed	525	300	145
Volatile	325	200	105
Total suspended solids	350	220	100
Dissolved	75	55	20
Fixed	275	165	80
Settleable solids (ml/l)	20	10	5
Biochemical oxygen demand BOD (5 d, 20°)	400	220	110
Total organic carbon TOC	290	160	80
Chemical oxygen demand	1000	500	250
Total nitrogen (as N)	85	40	20
Organic	35	15	8
Ammonia	50	25	12
Nitrites	0	0	0
Nitrates	0	0	0
Total phosphorus (as P)	15	8	4
Organic	5	3	1
Inorganic	10	5	3
Chlorides[1]	100	50	30
Alkalinity[1]	200	100	50
Grease	150	100	50

1 : Values have to be increased by the amount present in the drinking water

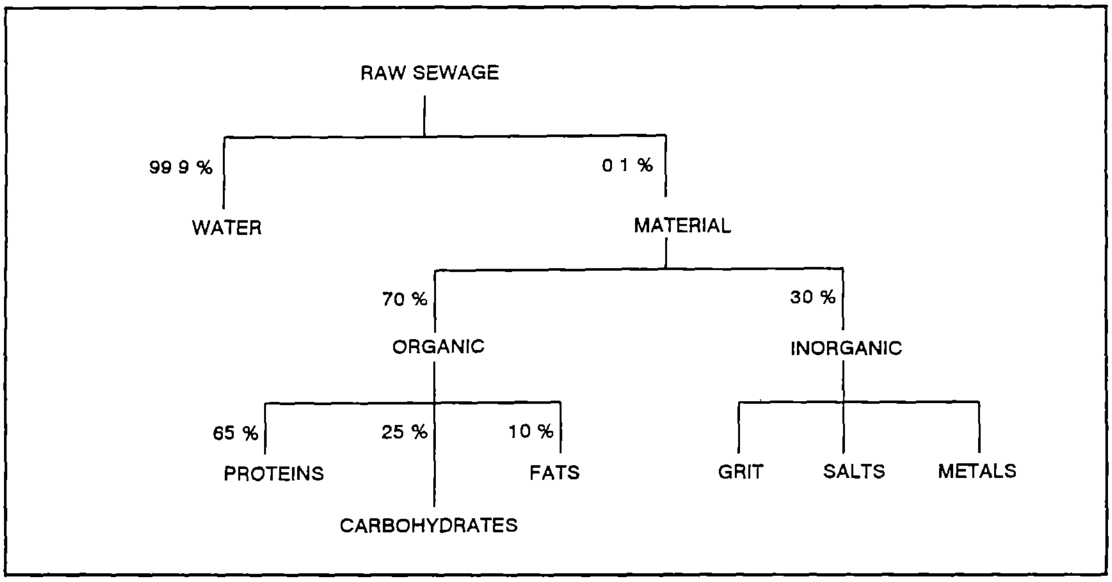

Figure 2. Schematic representation of the composition of sewage (Lit. 4).

Table 2. Characterization of the strength of sewage.

Strength	BOD (mg/l)
low	200
medium	350
strong	500
very strong	750

An indicative parameter for the pollution load per capita is the BOD. The per capita BOD-production varies from one country to the other. The variations are largely due to differences in quantity and quality of sullage that is discharged with the wastewater, rather than of body wastes. Also variations in diet are important. Some typical figures are presented in Table 3.

A suitable value for tropical developing countries is 40 g BOD per capita per day. For conversion to COD a COD/BOD-ratio of 2.5 can be used. Thus, 100 g COD per capita per day can be taken as a typical value. The nitrogen production is approximately 8 g N per capita per day.

The concentration of domestic wastewater is governed largely by the type of sewer. The water consumption on its turn depends on geographical location, climate, size of the community and degree of sanitation (number of taps per household). This can only be determined reliably by surveying each area separately. The average recovery rate is in the range of 70% - 90%. Apart from the influence of the water use of the community, the strength of the wastewater is influenced by infiltration in the sewer from the subsoil and by inflow from drains and overflows from the storm sewers.

Table 3. Typical BOD-production (in g/d) per capita for different regions.

Country	BOD/capita day
Colombia	28-40
Zambia	36
Kenya	23
S.E. Asia	43
India	30-45
Rural France	24-34
U.K.	50-59
USA	45-78
Europe	54

When the wastewater flow and consumption has to be estimated for a projected situation, data from comparable settlements in the same region can be used.

Although this manual is primarily prepared for UASB plants treating domestic wastewater, it has to be considered that sewer systems often contain a mixture of domestic and industrial wastewater, especially in larger sewer systems. Certain components or physico/chemical conditions as water temperature and pH may influence the performance of a treatment plant, especially when the contribution of industrial wastewater to the sewage flow is significant. It should be mentioned here, that it is general practice to demand from industries to control the pH of the wastewater between 5 and 9 and to keep the temperature below 40°C, before discharge into the municipal sewer.

When industrial wastewater is discharged, a careful evaluation of its composition and possible impacts on the treatment process should be made. Of special importance are the heavy metals. Although their concentration in the sewage may be low and their effects on the treatment process limited, they accumulate in the sludge, making it unsuitable for agricultural use or even unacceptable for land site disposal (See also § 4.3).

Industrial wastewaters may also contain high concentrations of sulphates. These will be converted into hydrogen sulphide during the treatment process. Hydrogen sulphide H_2S is an obnoxious gas which should be removed as much as possible before biogas is released in the air. H_2S can cause odour problems in the surroundings of the treatment plant. Air treatment is advised if high concentrations of sulphate are present in the wastewater.

2.4 Health aspects of municipal wastewater

Sewage contains all types of pathogens excreted by the population. The pathogens in sewage are classified in the group of excreta-related pathogens, consisting of bacteria, viruses, protozoa and helminths, which cause a variety of diseases. Table 4 shows some pathogenic organisms that are commonly found in wastewater.

The pathogens in sewage constitute a health hazard and any decision about the treatment, disposal and use of sewage must take this hazard into account.

Table 4. Pathogenic organisms commonly found in wastewater. (Lit. 5)

ORGANISM	DISEASE	REMARKS
Ascaris spp, *Enterobius* spp	Nematode worms	Danger to man from wastewater effluents and dried sludge used as fertilizer
Basillicus anthraces	Anthrax	Found in wastewater. Spores are resistant to treatment.
Brucella spp	Brucellosis. Malta fever in man	Normally transmitted by infected milk.
Entamoeba histolytica	Dysentery	Spread by contaminated waters and sludge such as fertilizer. Common in hot climates.
Leptospira iceterohaemorrhagiae	Leptospirosis (Weil's disease)	Carried by sewer rats
Mycobacterium tuberculosis	Tuberculosis	Isolated from wastewater tuberculosis and polluted streams. Wastewater is a possible mode of transmission. Care must be taken with wastewater and sludge from sanatoriums.
Salmonella paratyphi	Paratyphoid fever	Common in wastewater and effluents in times of epidemics
Salmonella spp	Food poisoning	Common in wastewater and effluents
Schistosoma	Schistosomiasis	Probably killed by efficient wastewater treatment
Shigella spp	Bacillary dysentery	Polluted waters are main source of infection
Taenia spp	Tapeworms	Eggs very resistant, present in wastewater sludge and wastewater effluents Danger to cattle on land irrigated or land manured with sludge
Vibrio cholerae	Cholera	Transmitted by wastewater and polluted waters
Viruses	Poliomyelitis, hepatitis	Exact mode of transmission not yet known. Found in effluents from biological wastewater treatment plants

2.5 Literature for further reading

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3. BACKGROUND OF ANAEROBIC WASTEWATER TREATMENT

3.1 Microbiology of wastewater treatment

In a biological wastewater treatment system, the principal process is the absorption and consumption of wastewater components by microorganisms. These microorganisms can be yeasts, fungi, protozoa, bacteria and methane bacteria. Generally the bacteria and the methane bacteria (which are not bacteria in the true sense, but a completely different group of organisms) are the main functional group of organisms in a wastewater treatment plant. The parameters and descriptions will not change significantly, if other microorganisms are involved. So, if in the rest of this manual reference to bacteria will be made, other biological groups are meant as well.

3.1.1 The complex nature of anaerobic degradation

Anaerobic degradation normally takes place in a number of different steps. These steps are illustrated in Figure 3. The characteristics of each group of bacteria, those performing hydrolysis, acidification, acid-formation and methane formation are all different. There is, however, no reason to describe these groups into much detail. For the understanding of the process the groups can be described in short as follows.

Hydrolytic bacteria are acid-forming bacteria which have the ability to excrete enzymes which are able to hydrolyse large compounds like cellulose, proteins and fats into smaller fragments that are able to enter the bacterial cells, which the original compounds cannot. Actually hydrolysis is an enzymic rather than a bacterial process. The hydrolytic bacteria will use the products of the hydrolysis just like other acid-forming bacteria would.

Acid forming bacteria perform quite well known fermentation reactions. They convert sugars originating from the hydrolysis of polymers like starch, hemicellulose and cellulose, and a lot of other compounds into butyrate, propionate, acetate, lactate, ethanol, hydrogen and carbonate. In the conversion of proteins amino acids, other organic acids, and ammonia and hydrogen sulphide will be formed.

Acetate forming bacteria convert small organic acids and alcohols into acetate, hydrogen and carbonate. The thermodynamics of these reactions are quite complex, and it suffices to know that the hydrogen concentrations has to be exceedingly low (below 100 ppm for most conversions, of which the conversion of propionate is the most delicate) to yield energy for the bacteria. The hydrogen concentration is kept that low by two types of bacteria; hydrogen consuming methane bacteria and sulphate reducing bacteria. The last group will be dealt with later.

Methane is produced by the methane bacteria. They can only use acetate and hydrogen + carbonate (or methanol) to produce methane. So all methane formation has to come via acid-formation, followed by acetate formation.

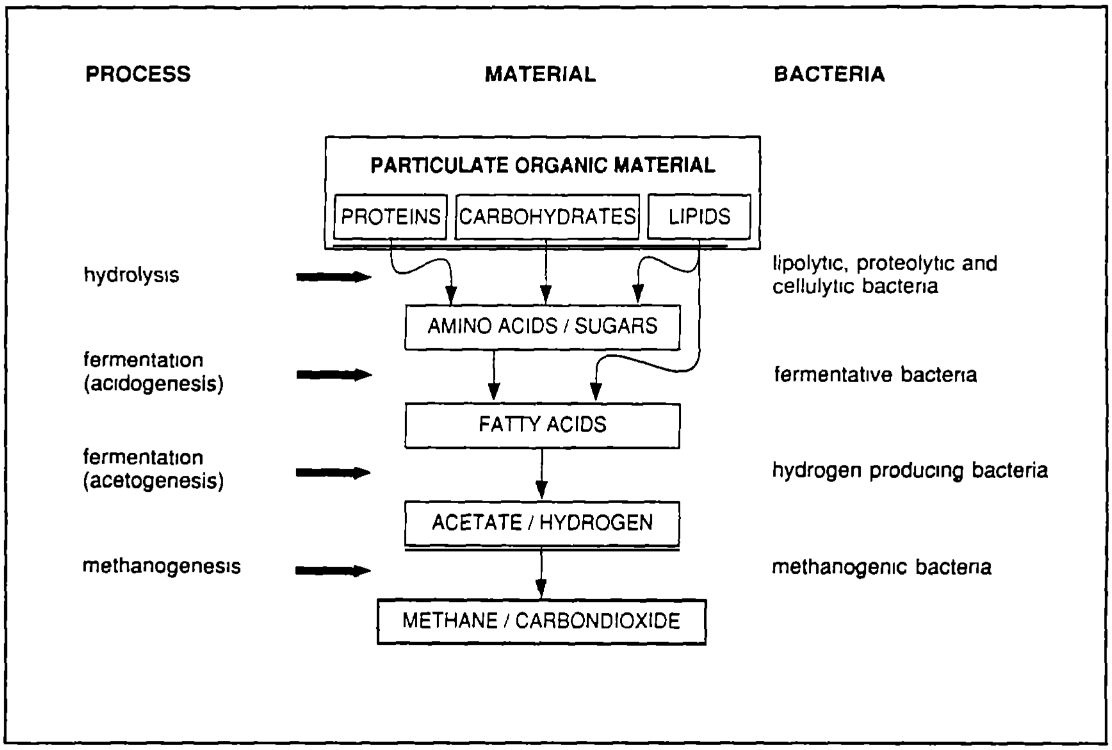

Figure 3. Degradation processes during the anaerobic degradation of waste and wastewater.

A few characteristics of the various bacterial groups should be remembered when dealing with anaerobic wastewater treatment:

1 Hydrolysis of large compounds like proteins, and biopolymers such as cellulose are converted into smaller units by enzymes. Very often, the rate at which this hydrolysis is taking place is not influenced by the amount of bacteria or bacterial enzymes, but by the available surface of the large molecules, where the enzymes can attack. This implies a virtually constant rate of hydrolysis.

2 Acid forming bacteria produce acids! Therefore, they can lower the pH. Normally, the acid forming bacteria are very tolerant to low pH, but most other bacteria are not. Acid forming bacteria also have the highest growth rates of the bacteria involved in anaerobic process.

3 Acetate forming bacteria are extremely sensitive to hydrogen. Under normal conditions namely the conversion of propionate to acetate is extremely sensitive. Generally the conversion of propionate into acetate is the first conversion affected when the conditions are not good. So propionate often is the first volatile fatty acid to appear in the effluent.

4 Methane is formed either from acetate, or from hydrogen and CO_2. Most methane bacteria can only degrade one of the two substrates. Both degradation processes and the bacteria involved behave quite differently.

One of the principal differences between anaerobic and aerobic treatment is, that colloidal matter does not seem to be adsorbed by anaerobic sludge. This implies that colloidal COD, in contrast with aerobic treatment, does not undergo any conversion.

3.1.2 Sulphate reduction

One of the problems with anaerobic treatment of wastewater is the occurrence of sulphate reducing bacteria. These bacteria oxidize small organic compounds, notably the products of the acid-forming bacteria, like propionate, lactate, ethanol and hydrogen with the use of sulphate as an electron donor. The sulphate thus is reduced to sulphide, which is toxic and can end up in water and the biogas in the form of gaseous hydrogen sulphide H_2S. This H_2S is very obnoxious, and very corrosive. Moreover, high concentrations of sulphide can be very toxic to methane-forming bacteria.

Under anaerobic conditions there is normally a competition for hydrogen between sulphate reducing and methane bacteria, which generally is won by the sulphate reducing bacteria. With the conversion of acetate the situation is less clear. It seems that the outcome of the competition between sulphate reducing and methane bacteria depends on the sulphate concentration. In most situations one can expect sulphate reduction to precede the methane forming reactions. This means that there is no way to avoid the production of H_2S during anaerobic wastewater treatment.

If large amounts of H_2S are expected, from high sulphate concentrations in the wastewater, provisions should be made to remove the H_2S as much as possible. H_2S can be removed before the actual treatment, by employing an acidification reactor in which significant sulphate reduction already will take place. It can be removed from the off-gases from acidification and UASB reactors and gutters by air treatment in compost filters. H_2S in the biogas can be removed before use by scrubbing the biogas.

4. THE UASB CONCEPT

4.1 The history of the UASB concept

The development of the upflow anaerobic sludge blanket (UASB) reactor dates back from the early 1970's. The basic idea of the UASB reactor is shown in Figure 4.

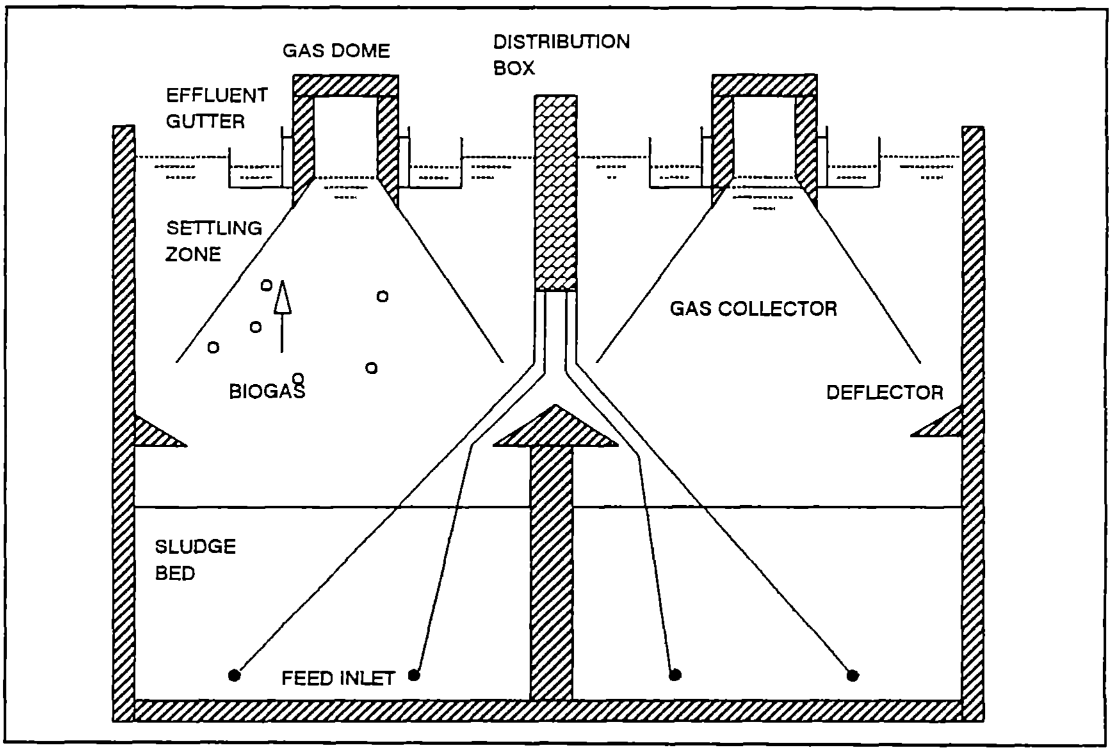

Figure 4. Schematic representation of the upflow anaerobic sludge blanket (UASB) process. The wastewater is entered via the *distribution boxes* and the *feed inlet* points. The wastewater soluble and degradable organic material then undergoes conversion to biogas in the *sludge bed,* where also wastewater solids accumulate and undergo degradation. The wastewater continue its way towards the top of the reactor, where it leaves the reactor via the *effluent gutters*. The gas is collected in the *gas collectors*. The *deflectors* are used to direct the biogas into the gas collectors.

The UASB concept initially has been developed for the anaerobic treatment of industrial wastewaters, with a moderate to high COD and BOD. The basic idea is, that flocs of anaerobic bacteria will tend to settle under gravity, when applying a moderate upflow velocity. In this way no separate sedimentation tank is necessary. Basically, the anaerobic bacteria can develop and settle in the reactor compartment, whereas the wastewater organic compounds are consumed by the bacteria during passage of the wastewater through the sludge layer. During anaerobic degradation of the organic components biogas is formed, consisting of methane CH_4, carbon dioxide CO_2, hydrogen gas H_2, hydrogen sulphide H_2S, and traces of ammonia NH_3. Nitrogen gas N_2, and even some oxygen O_2 may be stripped out of the liquid phase as a result of the biogas production. This biogas

can be used as an energy source, and for this reason the biogas is collected in gas collectors. The liquid-gas interface area underneath the gas collectors should be large, in order to give the sludge particles to which biogas bubbles are adhered the opportunity to lose the biogas and settle back into the reactor compartment.

The zone between the gas collectors is a zone where virtually no gas bubbles will be present in the liquid. Here the sludge particles which have been carried with the water flow between the gas collectors can settle back into the reactor compartment.

The wastewater passes the reactor from bottom to top. In order to guarantee sufficient contact between the incoming wastewater and the bacteria in the sludge layer, the wastewater has to be fed evenly over the bottom of the reactor. Further mixing will be brought about by the production of biogas. If the concentration of solids in the wastewater is not too high, some accumulation of solids will take place without harming the efficiency of the conversion of wastewater organic compounds into biogas. With high concentrations of solids in the wastewater, however, the inert wastewater solids may replace active bacteria and process deterioration will occur.

Since the early 1980's, the UASB reactor has become increasingly popular. Especially for the treatment of highly concentrated wastewaters from agricultural industries, like the potato processing and the sugar manufacturing industry, with COD values up to 30,000 mg/l, the concept has been employed widely. Currently it is the most widely applied process for anaerobic treatment of industrial wastewater.

4.2 The UASB reactor for treatment of domestic wastewater

Domestic wastewater differs from most industrial wastewaters in two respects: ***1*** the concentration is much lower, and ***2*** the fraction of suspended solids, compared to the total COD, is very high. In addition, the temperature of domestic wastewater, in contrast to that of industrial wastewater, is related to the ambient temperature. In the treatment of domestic wastewater both the dissolved organic matter and the suspended solids have to be degraded or removed, in order to have an adequate treatment. The UASB reactor serves both these purposes by acting as a settling tank for the suspended solids, and as a highly efficient bio-reactor for the degradation of the dissolved wastewater pollutants. During the treatment process, suspended solids in the wastewater will be degraded anaerobically. In this way the reactor compartment of a UASB reactor also acts as a digester with respect to the wastewater solids. The differences between UASB reactors for industrial and for domestic wastewater treatment is shown schematically in Figure 5.

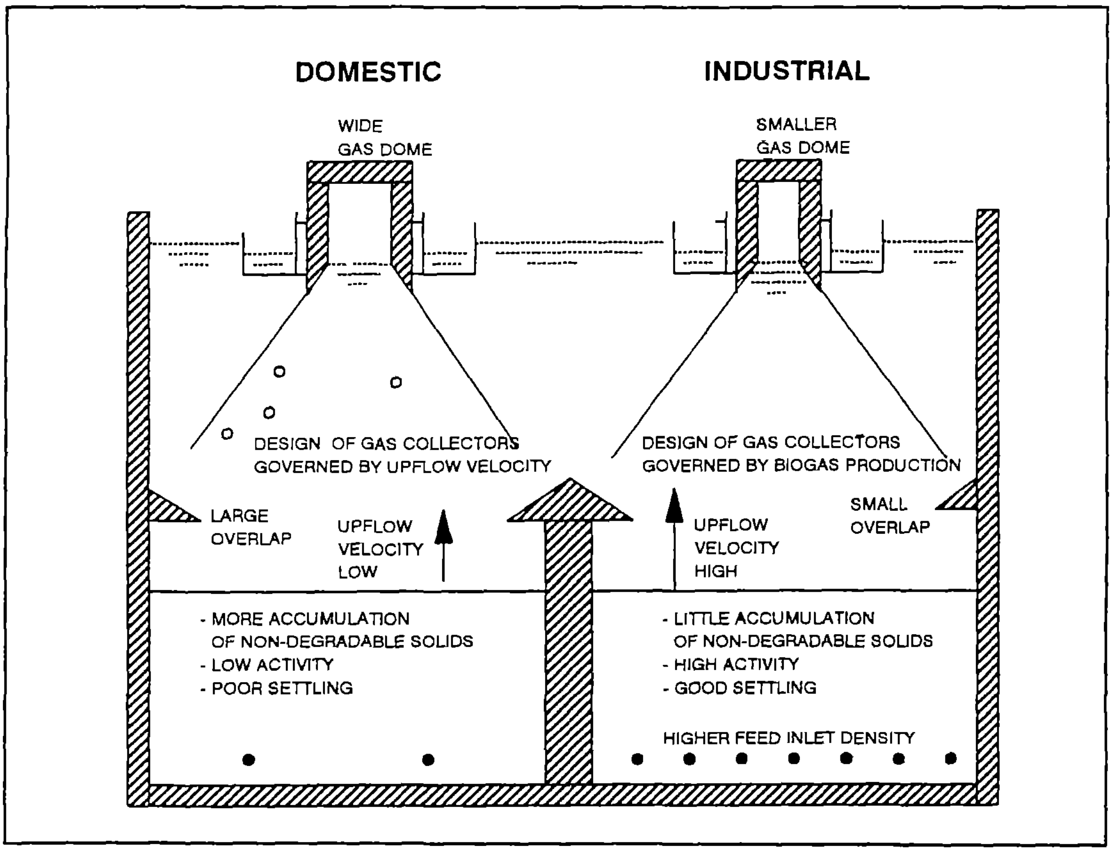

Figure 5. Differences between UASB reactors for (generalized) industrial and for domestic wastewater. Note that for industrial wastewaters with high protein contents, the gas domes also will be wide, and that in treatment of concentrated wastewaters the liquid upflow velocity will not be higher than in domestic wastewater treatment.

The use of the UASB reactor for the treatment of domestic wastewater asks for design criteria which differ considerably from those for UASB reactors treating industrial wastewater. With moderate to high strength industrial wastewaters, the amount of biogas produced will be high. The dimensions of the reactor will be largely dictated by the maximum activity of the anaerobic bacteria and by the maximum biogas production the reactor can allow for. The maximum activity of the sludge containing the anaerobic bacteria will depend primarily on the temperature and the amount of suspended solids in the wastewater in relation to the degradable dissolved COD.

In the treatment of domestic wastewater, the settling of the wastewater suspended solids is of primary interest. So the design criteria are largely dictated by the maximum upflow velocity the solids can withstand before being washed out of the reactor. A second important design parameter is the average time the solids spend in the reactor, the solids retention time (*SRT*). This average time has to be large enough to permit the growth of all relevant anaerobic bacteria.

In conclusion it can be stated that a UASB reactor for the treatment of anaerobic wastewater is completely different from a UASB reactor for industrial wastewater, with a totally different design.

The application of the UASB reactor for domestic wastewater is as yet limited to warmer climates. With cold temperatures the conversion of dissolved organic matter and the anaerobic degradation of suspended solids proceed too slowly and the reactor merely acts as a settling tank. To date, UASB reactors for the treatment of domestic wastewater have been installed in India, Colombia, Brazil, and Portugal. In China experiments are performed with treatment at lower temperatures, employing the UASB concept for the removal of solids in a first (hydrolizing) reactor, and treatment of the soluble organics in a second UASB reactor.

4.3 Applicability of UASB process for treatment of domestic wastewater

Experiences gained with laboratory, pilot-scale and full scale reactors learn that the application of the UASB process for domestic wastewater treatment is feasible, both technically and financially. The experiences with full-scale UASB-plants for domestic wastewater until now have shown clearly that the technical and economical feasibility of a treatment system is not a guarantee for a successful introduction of a treatment system.

Successful implementation depends on a careful evaluation of alternatives, a thorough knowledge of the biological and physical processes involved, an appropriate design and construction, and an adequate management, operation and maintenance of the plant.
A UASB-plant for domestic wastewater operates within certain margins with respect to the influent characteristics and the effluent quality. The most important factors are described below.
The presence of industrial discharges in the sewage is admissible, provided that the industrial discharges do not contain inhibitory or toxic compounds in such concentrations that they disturb the biological processes (see Chapter 5.3).
The temperature of the wastewater is of great importance. Anaerobic digestion has an optimum temperature range of 30 - 35 °C, but lower temperatures can be allowed. Until now there is only pilot experience with UASB treatment of domestic wastewater at average water temperatures below 16°C. Below 20°C no full-scale experience is available yet (see Chapter 5.2).
The UASB-reactor principally reduces the organic contamination of the sewage. Nitrogen and Phosphorus are removed only partly and form a pollution load at discharge on surface water, especially because the nitrogen is discharged as ammonium. Before discharge, post-treatment may be required, depending on the discharge regulations.
Pathogen removal in the UASB-system is limited as well, though the removal of helminths eggs is fairly efficient. If the hygienic quality of the effluent is important it is advised to apply a specific disinfection post-treatment method.

4.4 Treatment efficiencies

In practice the efficiency of wastewater treatment systems is expressed in terms of reduction of COD, BOD and TSS. The average treatment efficiencies, obtained from the 4 years operation of the 64 m^3 pilot-plant at 25 °C, in Cali, Colombia and from a one year intensive monitoring of the 1,200 m^3 UASB-plant are presented in Table 5.

Table 5. Average treatment efficiencies obtained in the Cali pilot-plant and the Kanpur demonstration plant (several years of operation).

PARAMETER	Cali	Kanpur
COD total / total	65 %	70 %
BOD total / total	80 %	69 %[1]
TSS	75 %	79 %

[1] The BOD-measurements of the effluent were influenced by relatively high HS concentrations.

The values vary with the composition of the sewage. The Cali sewage is low-strength and septic. The Kanpur plant treats domestic wastewater, containing a relatively large fraction of tannery wastewater. This wastewater contains high concentrations of chloride, sulphate and chromium.
The reduction of the nitrogen- and phosphorus-concentration is around 20 %. The pathogen-reduction has been found to be around 50 % for bacteria. A typical composition of influent and effluent of the Cali 64-m^3 pilot plant and the Kanpur plant is given in Table 6.

Table 6. Typical composition of influent and effluent of the Cali pilot plant and the Kanpur plant. All values are expressed in mg/l (= g/m^3)

	PILOT PLANT		KANPUR PLANT	
CONSTITUENT	influent	effluent	influent	effluent
BOD_5^{20}	150	30	165	50
CODtotal	290	100	460	135
TSS	160	40	515	57
VSS	85	25	-	-
N-total	14	13	45	40
organic	5	1	10	2
ammonia	9	12	35	38
P-total	1.5	1.2	3	2
sulphate	-	-	165	70
alkalinity	-	-	120	145

The biological conversion in a UASB-reactor is indicated by the specific gas production, which is defined as the methane or biogas production in m^3 per kg COD. Quite often it is expressed as the amount of biogas per kg COD removed. In a well-operating system the value of the biogas production varies between 0.15 and 0.25 m^3/kg COD removed. A low specific gas productions indicates that a large fraction of the COD accumulates in the sludge. High values indicate that a large fraction of organic pollutants is converted into biogas and that the sludge production will be low.

4.5 Literature for further reading

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2. Louwe Kooijmans, J. Lettinga, G. and A.F M. van Velsen, Applications of the UASB-process for treatment of domestic sewage under sub-tropical conditions, the Cali case WPCF-conference, Amsterdam, (Sept. 1986).
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5. PROCESS THEORY

5.1 Introduction

In the operation of a biological wastewater treatment plant, it is essential to have a basic insight in the processes underlying both the design and the operation of the plant. In this part of the manual the functioning of the sludge, which is the most important ingredient of a biological wastewater plant, is explained in detail. The important parameters upon which a design has to be based are presented and explained.

With the aid of the information given in this chapter, the biological parameters and design criteria of the anaerobic treatment processes, and the functioning of these processes, can be understood and controlled.

This part of the manual can by no means be a handbook on the microbiology of anaerobic wastewater treatment systems. If a more detailed knowledge of the biological processes is needed, the reader is advised to refer to more detailed literature on biological treatment processes, given in the list of references.

5.2 Bacterial growth and decay

5.2.1 Growth

The bacteria in an anaerobic wastewater treatment plant will grow by the consumption of organic compounds. During consumption of the wastewater components, part of the components is converted into new biomass.

In formula this can be described as follows:

$$dX/dt = Y * -dS/dt,$$

in which

X = biomass;

Y = yield coefficient, the amount of biomass formed per unit of BCOD converted (BCOD = biodegradable COD);

S = substrate (wastewater BCOD);

dX/dt and dS/dt denote the changes in amounts of bacteria and substrate per unit of time.

In words, the formula states: the change in amount of biomass over time is directly proportional (via the yield coefficient Y) with the amount of substrate removed over time. The values for the conversion coefficient Y for the various groups of bacteria are presented in Table 1.

The growth rate of bacteria is defined as

$$\mu = (dX/dt) / X,$$

in words: the growth rate of the bacteria is the change in number (or amount) of bacteria over time, divided by the number (or amount) of bacteria present. The unit for the growth rate is h^{-1} or day^{-1}.

The maximum growth rate of the bacteria is denoted μ_{max}. For a given species of bacteria, and a given temperature, this maximum growth rate is fixed. For wastewater treatment at approximately 20°C, the maximum growth rate of the important bacteria is presented in Table 7.

The growth rate of bacteria is primarily dictated by the concentration of the components the bacteria consume. The higher the concentration (up to a certain limit, which will be discussed later), the higher the growth rate of the bacteria, until the maximum growth rate is reached. If the concentration is zero, the growth rate will be zero. Usually this relation is described in a hyperbolic function:

$$\mu = \mu_{max} * S / (S + K_s),$$

in which K_s is called the substrate half-saturation constant. The substrate half-saturation constant for BCOD in general is hard to define, because BCOD generally consists of a large number of different components which all have different constants. Approximate K_s-values, suited for design purposes are presented in Table 7.

5.2.2 Maintenance and decay

Just like all other organisms, bacteria need energy to sustain themselves. Also, they die after a certain period of time. In practice, there is no distinction in the parameters between maintenance and decay of the bacteria. The amount of energy needed to sustain the bacteria is directly proportional with the amount of bacteria, so the formula for the conversion of substrate has to be extended:

$$dX/dt = Y * -dS/dt - bX,$$

in which b is the coefficient for maintenance and decay, with day^{-1} as the unit.

This coefficient is mainly dependent on temperature, but also on the concentration of toxic compounds. In Table 7 a number of values for the decay coefficient are given.
The net yield Y_N depends on the amount of bacteria that have to be maintained on a certain amount of substrate. Y_N is related with the gross yield Y_0 via the solids retention time *SRT*, which is the reciprocal of the growth rate *dX/dt* (see § 4.5.1)

$$Y_N = Y_0 * (1 + b * SRT).$$

Table 7. Values for growth rates, substrate saturation constant and decay rate for various groups of important anaerobic bacteria. Values for growth rates and decay coefficients given are for 20°C. K_s and Y_o do not change significantly within the temperature range of 20-35 °C.

conversion	Y_o kg VSS/ kg BCOD	μ_{max} h^1	K_s mg/l	b h^1
hydrolytic bacteria	0.18	0.1 - 1.0	-	0.1
acid-forming bacteria	0.18	0.1 - 1.0	1	0.1
acetate forming bacteria	0.02	0.01	1	0.002
methane bacteria	0.04	0.01	20	0.002

temperature
Temperature has a distinct influence on the growth rate and the decay rate of all living beings, including bacteria. The higher the temperature the higher the growth

rate will be and the higher the decay rate will be. At a certain temperature, for most bacteria in the temperature interval of 40 to 45°C, the rate of decay will exceed the growth rate, and the net result will be negative growth. Above this temperature the bacteria cannot grow any more.
So, all factors for growth and decay have to be corrected for the temperature. The factors may vary between different groups of bacteria. Generally, the following values can be used:

μ_{max}/μ_{max} at 20°C = $1.07^{(T-20)}$ (day^{-1});
b/b at 20°C = $1.10^{(T-20)}$ (day^{-1}).

The factors just described only hold for mesophilic bacteria, the normal bacteria the grow in the temperature range of 15 to 45 °C. In the higher temperature range of 45 to 65 °C, thermophilic bacteria become active that have totally different characteristics. This manual is not intended to deal with this type of bacteria.

Temperature also has an important effect on the dissociation of several compounds, like ammonia and hydrogen sulphide. This effect will be discussed later.

5.2.3 Nutrients

All growing organisms need more than carbon and energy sources alone. They need nutrients such as N, P, S, to build up proteins and genetic material, essential elements as Fe, Mg, and Ca, which are used in various cell components, and trace elements such as Co, Ni, Cu, Zn, and others, which might be involved as catalysts in essential enzymic reactions. From the build-up of bacterial cells, and those of other organisms, it is not hard to imagine that the amounts of these nutrients needed for growth follows more or less the sequence in which they were given.

In bacterial cells the ratio of carbon to nitrogen, phosphorus and sulphur is approximately C:N:P:S = 100:15:2:1. From this ratio, the need for N, P and S can be calculated, if it is assumed that BOD consists for approximately 50 % of C. In the wastewater, the ratio should be:

$$BOD : N : P : S = (200/Y_n) : 15 : 2 : 1,$$

in which Y_N is the net conversion coefficient, with decay included:

$$Y_N = Y_0 / (1 + b * SRT).$$

This expression shows that the higher the SRT is, the lower the yield coefficient of the bacteria will be.

One can easily see that the amount of nutrients needed for anaerobic wastewater treatment are significantly lower than those for aerobic treatment, as the yield factor for aerobic sludge is nearly ten times as high as that for anaerobic sludge.

In domestic wastewater a lack of nutrients, essential elements and trace elements is experienced only rarely. In industrial wastewater treatment, however, there is often a lack of one or more of the nutrients and essential elements. Especially N and P content of the wastewater should be measured before treatment starts, because dosage of these compounds may be required for operation. If one experiences a slowly decreasing treatment efficiency without any clear cause, one should always check the soluble N and P and S content of the effluent. Soluble

nitrogen compounds (ammonium-N or nitrate-N) and soluble phosphate should always be detectable in the effluent. If not, they should be added in the reactor to give the approximate ratio as presented above.

A special case is the use of flocculating agents. Ferric iron chloride and alum tend to precipitate phosphate, making it inaccessible for bacteria. If flocculation is used before the wastewater enters the reactor, overdosage of flocculant may lead to precipitation of phosphate. This may imply addition of phosphate or phosphorus acid to the incoming wastewater, even though the BOD : P ratio seems to be fine.

If a lack of other minerals is suspected, they can be added from a simple stock solution in a laboratory experiment, to see if there is any effect. Only under extreme conditions a lack of trace elements may be experienced. They are needed in extremely low quantities. For instance, the occurrence of very low concentrations of nickel in steel pipes is more than enough to sustain anaerobic growth.

5.3 Environmental factors affecting reactor performance

Bacteria can only grow well if their basic requirements are fulfilled. These requirements regard the availability of substrate, the temperature, the pH, the concentration of inhibiting compounds, and the need for nutrients and trace elements. Temperature and nutrients have just been discussed, but the others are equally as important.

5.3.1 pH

Bacteria and methane bacteria can only grow within a certain pH range. For methane bacteria this range is rather narrow. They are only active in the range between pH 6.5 and 8.5. Outside this range the activity of the methane bacteria drops off quite sharply. Acid forming bacteria produce acids as their end product. Generally, they are much less sensitive to a lower pH. These bacteria will continue to be active with pH down to 4.5.

One of the main problems in the control of anaerobic waste and wastewater treatment is pH control. As the acid forming bacteria both are much more active, have a higher growth rate and are less sensitive to low pH, the effects of overloading of a system in equilibrium are quite dramatic. A strong increase in the load of neutral compounds, like sugars, may lead to higher growth of acid-forming bacteria than of acetate-consuming methane bacteria. Overloading of the methane bacteria and acetate-forming converting, which consume higher volatile fatty acids, leads to an accumulation of acids which may lower the pH. If the pH becomes lower than 6.5, the activity of acid-forming bacteria still continues; the methane bacteria however will become less active. This negative feedback will eventually lead to still lower pH and ultimately to the death of the methane bacteria.

In the treatment of domestic wastewater the concentrations generally are quite low, and the alkalinity (the buffering capacity of the wastewater) is reasonably high. Therefore, the chances that pH becomes dangerous for the methane bacteria are actually quite low. Only with an extremely inconsiderate start-up procedure these chances exist.

The pH also has an important effect on some other environmental factors, like the concentration of gaseous ammonia and hydrogen sulphide. This is dealt with in the next section.

5.3.2 Inhibiting compounds

ammonia

Ammonia is quite toxic for a large number of bacteria. Ammonia dissociates into ammonium:

$$NH_3 + H_2O \quad <\!\!---\!\!> \quad NH_4^+ + OH^-$$

The toxic effect generally is caused by the free ammonia NH_3, which can enter the bacterial cells, and will dissociate again inside the cell. The cells will have to put energy into the removal of the NH_4^+, and once it is removed, it will be entering again as NH_3. The overall effect is an huge increase in the amount of energy needed for the maintenance of the bacteria.

NH_3 is very toxic for methane forming bacteria, and much less toxic for acid-forming reducing bacteria. To evaluate the effect of NH_3 one has to calculate the NH_3 concentration from the total ammonium-N concentration $(NH_3 + NH_4^+)$-N, pH and temperature. The total ammonium-N concentration is the concentration as it is measured. The fraction F of the total ammonium-N concentration which is in the form of free ammonia NH_3 is calculated as follows:

$$F = \frac{10^{pH}}{(10^{-pKb}/10^{-pKw}) + 10^{pH}}$$

in which *pKb* is the negative logarithm of the dissociation constant of NH_3, and *pKw* the same for water. The values can be found in the Handbook of Chemistry and Physics. In Table 8 values for F are given as a function of pH and temperature. The free NH_3-N concentration will be $F * (NH_3 + NH_4^+)$-N.

Table 8. Fraction F of the total ammonium-N concentration, which is in the form of free ammonia, as a function of pH and temperature.

temperature pH	24	26	28	30	32	34
7.0	0.005	0.006	0.007	0.008	0.009	0.010
7.2	0.008	0.010	0.011	0.013	0.014	0.016
7.4	0.013	0.015	0.017	0.020	0.023	0.026
7.6	0.021	0.024	0.027	0.031	0.035	0.040
7.8	0.032	0.037	0.042	0.048	0.055	0.062
8.0	0.050	0.057	0.066	0.075	0.085	0.096
8.2	0 077	0.088	0.100	0.113	0.128	0.143
8.4	0.117	0.133	0.150	0.169	0.188	0.210
8.6	0.174	0.195	0.218	0.243	0.269	0.296
8.8	0.250	0.278	0.307	0.337	0.368	0.400
9.0	0.346	0.379	0.412	0.447	0.480	0.514

Free NH_3 can be considered quite toxic for methane forming bacteria, and somewhat less for acid-forming bacteria. Free ammonia levels of 150 mg N/l may be considered too high for the anaerobic treatment of wastewater. On the very long run, some adaptation of the methane bacteria to high ammonia levels can be expected. In treatment in UASB reactors, one should not calculate with this

adaptation, without further research.
Finally, one has to realize that the NH_4^+-N concentration in the wastewater has no relation with the actual NH_4^+-N concentration in the reactor. Organic nitrogen containing compounds are generally readily converted into other organic compounds under release of ammonium-N. So the N_{kj}-N contents of the effluent actually gives more information than the NH_4^+-N concentration of the incoming wastewater.

H_2S

With H_2S the situation is even more complex. Basically, the toxic effect of H_2S is comparable to that of NH_3. In the free form it will enter the cell, dissociate there, influence the pH, and thus gets pumped out, only to re-associate again and re-enter the cell. On top of this, H_2S also damages critical cell components. Therefore it is more toxic than NH_3. H_2S can be stripped out of the water phase by the evolving biogas, thereby lowering the actual concentration in the wastewater. Therefore, the calculation of the concentration of free H_2S is influenced by the amount of biogas produced during the treatment of the wastewater. The higher the amount of biogas produced, the lower the H_2S concentration in the water phase will be.

The calculation of the free H_2S concentration in the water phase includes the calculation of the H_2S content of the biogas. Therefore, it is an important calculation. This calculation is carried out as follows. First the fraction of free H_2S is calculated, analogous to the way the fraction F of free ammonia is calculated. If the amount of biogas to be evolving from one litre of wastewater is known, the distribution of the amount of H_2S over the water phase and the gas phase can be calculated.

The fraction F_S of free H_2S is

$$F_S \quad = \quad 1 / (1 + 10^{pK1} * 10^{pH})$$

Values for F_S are given in Table 9. The total amount of S^{2-} in water and biogas is (per l of water + the amount of biogas, formed from 1 l of water):

$$[S^{2-}]_T = [SO_4]_{in} / 3 \ (mg/l)$$

The total S-concentration in the water phase will be:

$$[S^{2-}]_W = [S^{2-}]_T / (1 + F_S * B / \alpha),$$

in which
B is the amount of biogas formed per l of wastewater
α is the partition coefficient of H_2S.

values of α are presented in Table 9.

The amount of H_2S in the water phase will be

$$[H_2S]_W = F_S * [S^{2-}]_W$$

The amount of H_2S in the biogas formed will be

$$[H_2S]_G = [S^{2-}]_W * F_S * B / \alpha,$$

and its concentration is

$$[H_2S]_B = [H_2S]_G * 0.00066 / (B + [H_2S]_G * 0.00066)$$

Table 9. Values of the fraction F_S of free H_2S, and the coeffieicnt α, as a function of pH and temperature.

temperature	24	26	28	30	32	34
pH α	2.562	2.460	2.367	2.274	2.197	2.120
7.0	0.478	0.464	0.450	0.435	0.422	0.408
7.2	0.367	0.353	0.340	0.327	0.315	0.303
7.4	0.268	0.256	0.245	0.235	0.225	0.215
7.6	0.187	0.179	0.170	0.162	0.155	0.148
7.8	0.127	0.121	0.115	0.109	0.104	0.098
8.0	0.084	0.080	0.075	0.072	0.068	0.064
8.2	0.055	0.052	0.049	0.046	0.044	0.042
8.4	0.035	0.033	0.031	0.030	0.028	0.027
8.6	0.023	0.021	0.020	0.019	0.018	0.017
8.8	0.014	0.014	0.013	0.012	0.011	0.011
9.0	0.009	0.009	0.008	0.008	0.007	0.007

5.3.3 Volatile fatty acids

Although they are used as substrate for methane-forming and acetate-forming bacteria, volatile fatty acids themselves are also toxic to both groups of bacteria. Namely propionic acids can be quite toxic. The free concentration of volatile fatty acids is calculated in the same fashion as explained above for ammonia. Sometimes it is stated that a low pH in itself is not toxic to the methane bacteria, but the free acids which are present at low pH. At neutral pH, the free acid concentration are very low. As a general rule, concentrations of volatile fatty acids should be below 500 to 1000 mg/l.

5.3.4 Specific compounds

A number of other compounds are toxic to the anaerobic conversion processes. Industrial discharges to the sewer system should be screened on these compounds.

In general *chlorinated compounds* are very toxic to methane bacteria. Especially CCl_4, CH_3Cl and CH_2Cl_2 are already toxic in concentrations of 1 mg/l, since they strongly resemble methane. These compounds attach to the places methane is processed in the bacterial cell, thereby inactivating the methane-producing capacity. These compounds are quite volatile and can be stripped from the wastewater by the biogas, when the gas production is sufficiently high. *Cyanide* is very toxic for methane-forming bacteria, but less toxic for the other anaerobic bacteria. Cyanide seems to be converted anaerobically, which may contribute to recovery of the microbial process. As with chlorinated compounds, cyanides mostly originates from industrial sources. Cassava wastewater, however, contains natural cyanide. *Formaldehyde* denaturates proteins. When the concentration of

formaldehyde in the wastewater is such, that there are more bacteria killed than growing, reactor failure will ultimately occur. Formaldehyde is toxic in concentrations above 50 - 100 mg/l, concentrations that are not likely to occur in domestic wastewater. *Sulphite*, in itself toxic at concentrations exceeding 100 mg/l, can be converted by sulphate reducing bacteria into H_2S, which is far less toxic. So, adaptation to high concentrations of sulphite can occur. *Oxygen* is toxic for obligate anaerobic bacteria, like methane-forming bacteria are. Anaerobic sludge, however, always contains facultative aerobic bacteria, consuming oxygen entering the reactor very rapidly. When treating wastewaters with very low concentrations of organic pollutants, the oxygen concentration of the wastewater may become so high (e.g. through pre-mixing etc.) that the settling characteristics of the anaerobic sludge may deteriorate because of the growth of aerobic filamentous bacteria. Under tropical conditions no serious problems related to oxygen will arise, as the solubility of oxygen is low and the bacterial activity is high.

Methane-forming bacteria are sensitive to the concentrations of ions in their environment. A process inhibition by *cations*, like NH_4+, K^+, Na^+, Mg^{2+} or Ca^{2+} can be followed by an adaptation to elevated concentrations of these cations. For instance, the immediate response of methane bacteria to a sodium concentration of 70 mM (1500 mg/l) can be quite dramatic, whereas at a gradual increase sodium-concentrations of 750 mM and more can be tolerated. This holds basically true for all cations. The capacity of anaerobic systems to adapt to high concentrations of a large number of cations has been investigated by Speece *et al* (1986). *Heavy metals* are a group of cations of special interest to wastewater treatment due to their tendency to accumulate in the sludge. Although heavy metals generally are toxic in low concentrations (1-10 mg/l), in practice no problems occur due to the formation of non-toxic metal sulphides. Although in general heavy metals will not interfere with the anaerobic treatment process because of their low concentrations the quality of excess sludge will be influenced. Sludge with high heavy metal concentrations is not suitable for agricultural use. If the presence of heavy metals in significant concentrations is expected, their concentrations in the excess sludge should be assessed.

5.4 Physical processes in UASB treatment

A UASB reactor serves both as a biological reactor and as a settling tank. The biological parts have been dealt with in a qualitative sense in the previous paragraphs. The operation of a UASB reactor as a settling device is equally as important as its biological function, especially in the treatment of domestic wastewater.

The physical events occurring in a UASB reactor are quite complicated. Without biogas production, the reactor would merely serve as a upflow sedimentation tank. I such a tank, filtering effects in the sludge blanket are important for the overall treatment effect. The design of such tanks is mainly governed by the upflow velocity of the water (equal to the surface loading rate in conventional design). This upflow design for conventional tanks generally can be calculated from settling curves. Without exact knowledge of the settling characteristics of the wastewater solids, a quite defensive approach has to be adopted. In the treatment of domestic wastewater, generally upflow velocities of 1.0 m/h are used for the design.

There are, however, quite some differences between a UASB reactor and a settling tank for domestic wastewater solids. There is a complex biology going on,

which alters the characteristics of the solids. Particles become hydrolysed and bacteria will grow using wastewater solids to attach to. Thus, the settling characteristics of the solids will also change. During the bacterial conversions there is biogas produced, increasing the turbulence in the reactor compartment. Moreover, biogas bubbles tend to adhere to sludge particles, which will then tend to rise. They have the opportunity to lose the biogas on their way up, or in the interface between biogas and liquid in the gas collector. If the biogas is not released in time, or the particles are too small to withstand the upflow velocity, the particles will leave the reactor compartment and enter the settling compartment. The entry of the settling compartment is the aperture between the gas-solids-separators. The flow rate of the water near the aperture is much higher than the average upflow velocity over the reactor. If particles just able to settle in the reactor come in the neighbourhood of the aperture, they cannot withstand the upflow velocity and they will enter the settling compartment. In the settler compartment, the velocity decreases again, and some particles may grow into larger particles and return into the reactor compartment. There will be some gravity flow of accumulated sludge from the upper sides of the gas collectors, which serve as the sloped bottom of a sedimentation tank.

5.4.1 Sedimentation theory

Several theories on the sedimentation of sludge particles apply to the sedimentation in UASB reactors. For single particles on their way out, the Stokes law may be applied:

$$V_0 = g * (d_s - d_l) * D^2 / (18 * E),$$

in which

V_0 is settling velocity (m/s)
g is gravity acceleration (9.81 m/s^2)
d_s is density of particle
d_l is density of the liquid
D is particle diameter
E is kinematic viscosity

This law predicts that the settling rate of a sludge particle is related to the its diameter and the difference in density between the particle and the liquid. Note that the difference in density might seem important, but the particle size is the parameter that actually matters.

For the majority of the sludge particles, however, the theory of hindered sedimentation should be applied, for which there is no mathematical formulation. Interesting though these theories may be, they cannot be applied quite well to sludge, because sludge does not consist of particles of uniform size. On the contrary, particle size in the sludge particles differs widely. In Figure 6 an example of the size distribution of digested sludge particles is shown. Although wastewater solids and digested solids from a UASB reactor will differ from the solids from a sludge digester, it will be clear that in the case of domestic sewage treatment, the particle size will also be widely scattered.

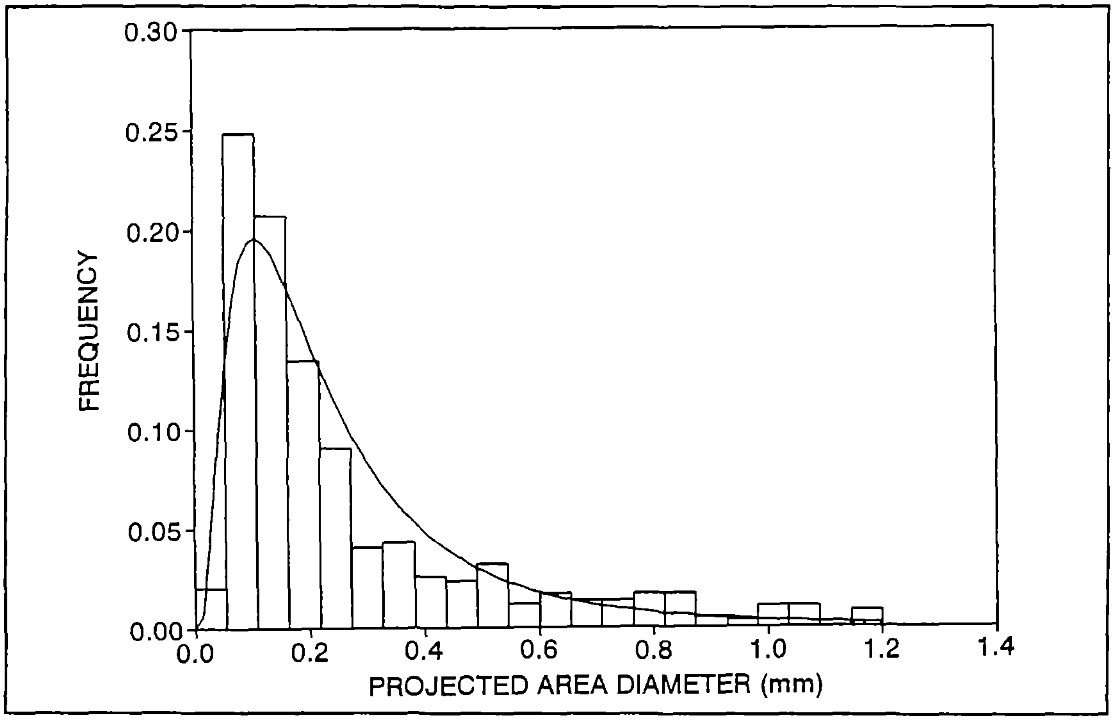

Figure 6. Particle size distribution of digested sludge solids.

From the particle size distribution an idea can be obtained on how the upflow velocity will influence the efficiency of the sedimentation. Each diameter will correspond to a specific settling velocity. Particles with a smaller diameter will tend to be washed out of the system. From the particle size distribution, the distribution of the relative amounts of solids in each diameter class can be made. Of course, due to the nature of anaerobic wastewater treatment, a proportion of the larger particles will leave the system due to adhering biogas particles.

5.4.2 Sedimentation practice

In a UASB reactor, a number of events and parameters will influence its behaviour as a settling tank with the purpose of containing as much solids as possible.

1 *The upflow velocity of the wastewater* in the reactor compartment will be the primary determining factor for the efficiency of the settling of solids. If this parameter (the overall upflow velocity) is not well designed, solids may even not settle if there would be no biogas production at all. The upflow velocity that can be tolerated by the sludge depends on the characteristics of the sludge. With wastewaters with very low quantities of suspended solids and a high concentration of dissolved organic compounds, the sludge may develop in the form of so-called granular sludge. granules, which are particles up to 2 mm diameter. The sludge granules are able to withstand very high liquid upflow velocities up to 4 or even 8 m/h. With the treatment of domestic wastewater, these granules will certainly not develop, and the solids in the wastewater will actually determine the settling characteristics of the sludge. As with the pre-sedimentation of domestic wastewater, the efficiency of the sedimentation of the solids is depending strongly on the upflow velocity. The lower the upflow velocity, the higher the efficiency will be.

2 *The height of the sludge layer* (the sludge blanket) on the bottom of the reactor will have a distinctly positive effect on the efficiency of the retention of solids in the reactor. Of course, if the sludge bed height is too close to the apertures between the gas collectors, sludge will be swept into the settling compartment because of the increased liquid velocity near the apertures. For this reason there is a physically optimum height of the sludge blanket in given UASB reactor for domestic wastewater. The reactor design should thus provide for both an effective sludge bed height and enough distance between the sludge blanket and the apertures between the gas collector to prevent massive sludge washout.

3 *The rate of the production of biogas* will have a distinct influence on the efficiency of the solids settling. The parameter of importance is the volume of biogas per unit of surface area, the biogas loading rate, in $m^3.m^{-2}.h^{-1}$, or m/h, which is the same. If the biogas loading rate is very low, every once-and-a-while very large aggregates of sludge (up to tens of litres) may rise up and release their biogas. This works like an explosion, and it will have a negative effect on the solids in the effluent. If the biogas loading rate is higher, the interface between sludge and liquid will be quite regular. Small gas bubbles will escape all the time, and there will be a regular traffic of sludge particles with gas bubbles adhered moving upward, and particles just having released their gas bubbles moving downward. If the biogas loading rate becomes very high, which is virtually impossible in the treatment of domestic wastewater, the turbulence in the reactor compartment may become too high to have a regular distinction between sludge blanket and overstanding liquid, if the sludge settling properties are not very good. Massive sludge washout may be the result. So, with a highly concentrated substrate one will need a sludge with good settling properties.

4 *The area of liquid-gas interface in the gas collector* will have an influence in the ability of the sludge particles to release any adhered biogas bubbles. The larger the interface area is, the better the release of the biogas will be, and the better the efficiency of solids retention will be. If there is a vivid traffic of sludge particles, near the water surface, they may become a scum layer which may dry out and clog the gas outlet. Therefore, it is suitable to have a reasonably wide top of the gas collector, providing for enough liquid-gas interface.

5 *The upflow velocity in the settling zone* will be important for the sludge to return in the reactor compartment. As a large settling zone will imply a small width of the gas collectors, and therefore a limited gas-liquid interface area, one has to find an optimum between points 4 and 5.

6 *The liquid velocity in the apertures* is considered important too. This velocity has an effect on the amount of particles swept into the settling compartment of the UASB reactor.

7 *The angle of the gas collectors* has a distinct influence on the amount of sludge in the settling compartment returning into the reactor compartment. For this reason, the gas collectors are always designed with an angle of between 50 and 60°. This value is well-known from stationary gravity settlers without automatic sludge collection. In this kind of settlers the sludge is just collected because it is sinking into the deeper parts of the settler.

8 *The overlap between the gas deflectors and the sides of the gas collectors,* is there to minimize the amount of biogas entering the settling compartment.

9 *The length of overflow weirs* is important to have an equal effluent outflow. If the weir overflow rate is too high, sludge from deeper parts of the settling compartment may be swept along, thereby decreasing the efficiency of solids settling.

It will be clear that a lot of these more or less hydraulic parameters will be strongly influenced by the characteristics of the solids. Therefore, it is hard to give general values for all types of sludges and wastewaters. For domestic wastewaters the parameter values are presented in Table 10.

Table 10. Important parameters during average flow for the design of UASB reactors for treatment of domestic wastewater.

no.	parameter	minimum	maximum	advised	unit
1	liquid upflow velocity	-	1.0	0.5	m/h
2	sludge blanket height	2.0	3.8	3.4	m
3	biogas loading	-	2.0	1.0	m/h
4	area of liquid-gas interface	10	-	12	% of total
5	upflow velocity in settling zone	-	1.3	0.7	m
6	aperture velocity	-	2.0	1.5	°
7	angle of gas collector sides	45	60	50	m
8	overlap between deflector and collector	0.10	-	0.15	m
9	weir overflow	-	5	2	m^2/h

5.5 Estimation of the sludge production for a specific wastewater

During the design of a UASB reactor, it is very important to have an idea about the sludge production to be expected. First, some reactor parameters will depend on the sludge production, and second, the sludge production itself is very important for the design of the sludge removal facilities.

5.5.1 Solids retention time

The solids retention time in a UASB reactor is hard to calculate beforehand. Without a good idea of the amount of sludge in the reactor, it is impossible to get an idea of the solids retention time. The solids retention time is calculated as: $SS_R / \Delta SS$

$$\frac{\text{amount of sludge in the reactor } (SS_R)}{\text{amount leaving the reactor daily, via effluent or via sludge removal } (\Delta SS)}$$

The solids retention time is $SS_R / \Delta SS$. If the ratio of bacteria to non-bacterial solids in the reactor is identical to the ratio in the effluent, then $X_R / \Delta X$ will be equal to the solids retention time. The solids retention time should be sufficient for the degradation of the solids, and of course it should be sufficient to retain the relevant bacteria in the reactor. The relative rate at which bacteria are removed from the UASB reactor is equal to the reciprocal of the solids retention time. In formula:

$$\mu = dX/dt = \Delta X / X_R$$

$\Delta X / X_R$ = removal rate of bacteria
and
$dX/dt = \mu$ = growth rate of the bacteria.

Now for the bacteria to be retained in the system, their growth rate has to be at least equal to the rate at which the bacteria is removed. This is why the solids retention time in most reactor systems is very important. In a UASB reactor, the *SRT* generally is far higher than necessary to maintain the bacteria in the system. Only if the hydraulic loading of the UASB is quite high and the solids content of the wastewater is also high, it is possible that the volume of the reactor has to be based upon the solids retention time, in stead of any other parameter.

The *SRT* can also be calculated in a different way: if one assumes a fixed reactor concentration of solids, then the sludge production from the wastewater must be equal to the sludge leaving the reactor. So, the solids retention time can be defined as

$$\frac{\text{amount of sludge in the reactor}}{\text{amount produced daily}}$$

With the aid of this approach, some important calculations can be made, as will be shown in the next two paragraphs.

5.5.2 Sludge production and minimum average HRT

For design purposes, an certain average sludge concentration may be assumed. If a fixed *SRT* is considered the minimum for a good solids degradation, the amount of sludge to be allowed to accumulate in the reactor can be defined as:

$$TSS_{ACC} = TSS_{AVG} / SRT$$

in which

TSS_{ACC}	is the amount allowed to be accumulating (g TSS.l of reactor^{-1}.d^{-1})
TSS_{AVG}	is the average sludge content in the reactor (g TSS/l of reactor)
SRT	is the sludge retention time (d).

If there is more accumulation, the desired *SRT* cannot be maintained. For the *SRT*, 10-15 days is an absolute minimum (in industrial wastewater treatment), but 30-50 days is more desirable. The higher the *SRT*, the more stabilized the sludge will be.

The average TSS concentration over the reactor is calculated as follows:

$$TSS_{AVG} = TSS_{BED} * A * (H_R - H_G) / H_G$$

in which

TSS_{BED}	is the average sludge bed concentration
A	is the percentage of the height to the gas collector occupied by the sludge bed
H_R	is the height of the reactor
H_G	is the height of the gas collector

Now the accumulation TSS_{ACC} can be calculated. This possible accumulation of sludge in the sludge bed is equal to the production of bacterial material, plus the amount of TSS in the influent that is not degraded. So, per litre of wastewater the sludge production is :

$$P_{VSS} = VSS_{IN} * (1 - Z/100) + Y_T * BCOD_{IN}$$

in which

P_{VSS} is the amount of VSS produced per litre of wastewater

Y_T is the total bacterial yield coefficient (0.08 to 0.10 kg TSS.kg BOD, depending on *SRT*, and other factors);

VSS_{IN} is the incoming VSS concentration (kg/m^3);

$BCOD_{IN}$ is biodegradable COD_{IN} (kg/m^3);

Z is the percentage degradation that the solids will undergo during their stay in the reactor (10 - 40 %, depending on the type of solids, the *SRT*, and the temperature).

With the ash percentage of the sludge fixed at A_{BED} %, the TSS production will be

$$P_{TSS} = P_{VSS} * (1 - A_{BED}/100)$$

Please note that the contribution of bacteria to the total the sludge production is rather low. With a maximum allowed accumulation of TSS_{ACC} g.m^{-3}.d^{-1}, this means that the hydraulic retention time of a UASB cannot be shorter than:

$$HRT_{MIN} = P_{TSS} / TSS_{ACC} \text{ (days)}$$

So

$$HRT_{MIN} = \{VSS_{IN} * (1 - Z/100) + Y_T * BCOD)\} * (1 - A_{BED}/100) / (TSS_{AVG} / SRT)$$

Z is considered as a constant in this formula, but actually it is not: it is a function of the *SRT* and the temperature. The higher the *SRT* and the temperature, the higher *Z*.

On the average, the solids retention time does not have to be considered in the design of a UASB reactor for domestic wastewater treatment. Beware, however, with high wastewater solids contents or high hydraulic loads!

5.5.3 Estimation of the methanogenic activity

Solely on the basis of the wastewater characteristics and a few considerations regarding the reactor contents, a reasonable estimate of the methanogenic sludge activity in the reactor can be made. This estimate can be used for a check on the reactor loading. Basically, the estimate uses the same information as the estimate of the maximum hydraulic loading of the reactor. First, the amount of sludge produced per litre of wastewater is calculated. This is done as described in the preceding paragraph. Then the amount of methanogenic sludge, which is formed from the wastewater, is calculated. From this, the proportion of methanogenic sludge in the sludge produced is calculated. With the use of a table on the maximum specific activity of purely methanogenic sludge, and the fraction of methanogenic bacteria n the sludge, the maximum methanogenic activity can be estimated.

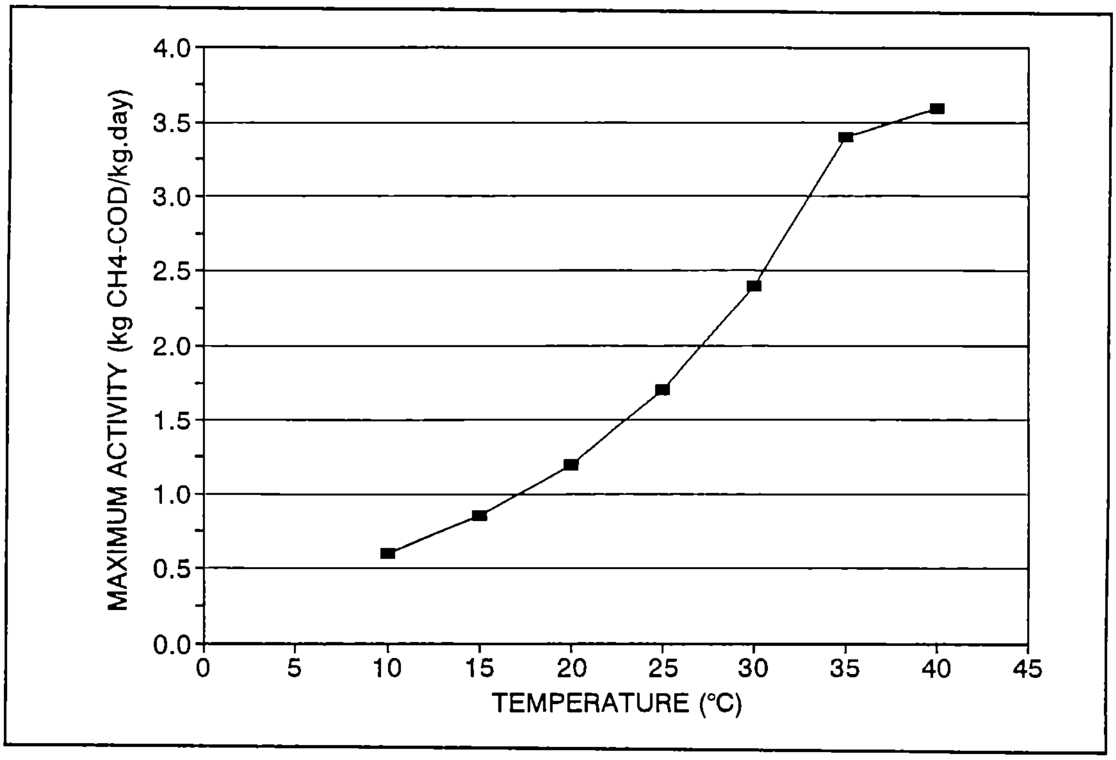

Figure 7. Maximum specific methanogenic activity (in kg CH_4-COD. kg $VSS^{-1}.d^{-1}$) of purely methanogenic sludge as a function of temperature.

The amount of methanogenic bacteria produced per litre of wastewater is

$$M = Y_M * (BCOD_{IN}) * (1 - Y_A)$$

in which

M is the amount of methane sludge (g/l, or kg/m^3)
Y_M is the yield coefficient for methane sludge (g / g BCOD)
Y_A is the yield coefficient for acidifying and hydrolysing sludge (g / g BCOD)

Depending on the *SRT*, the value of Y_M is 0.02 to 0.04, and Y_A is 0.06 to 0.12. So the fraction of methanogenic sludge will be

$$F_M \quad \frac{\text{methane bacteria production}}{\text{total sludge production}}$$

The maximum activity of the sludge will be related to the fraction of methane bacteria in the sludge, and the activity of purely methanogenic sludge, which is a function of the temperature.

$$A_{MAX} = F_M * A_{MAX,METH}$$

For the specific wastewater temperature, now the maximum specific methanogenic activity $A_{MAX,METH}$ can be calculated from Figure 7.

It can be calculated that the amount of non-degradable solids in the wastewater, relative to the total amount of BOD, has a major impact on both the minimum hydraulic retention time and the maximum specific methanogenic activity. In the treatment of domestic wastewater, this calculation may not be very important. In industrial wastewater treatment, however, this calculation gives an insight in the reactor loadings that can be applied. The calculation can be used as a check on the expected methanogenic activity.

PART 2

DESIGN AND CONSTRUCTION

CONTENTS

6. DESIGN OF UASB PLANTS FOR DOMESTIC WASTEWATER

6.1 General considerations

The actual design of a treatment plant follows the evaluations and decision routes taken in the planning phase. These decisions are based on infrastructural, economical, social and technical criteria and are generally taken in the mark of a master plan. The master plan provides a list of demands on the treatment system, including treatment efficiencies, construction costs, operation and maintenance costs, technical complexity, land availability etc.

Based on this information a treatment system can be selected, the site for the treatment plant can be determined and the preliminary and final design can be made. It will be clear that for the evaluation of the UASB technology in a master plan specific knowledge on the system potentials is essential.

For site selection the following general remarks can be made. Sewerage networks are designed in such a way that the flow of sewage is by gravity. Pumping is avoided as much as possible in order to make the network independent of external power and to minimize costs and maintenance requirements.

The location of sewage treatment works depends on the following general principles:

1. The pumping head should be reduced as much as possible.
2. The site should be some distance from the nearest houses in order to avoid visual or odour nuisance. Nuisance by odorous compounds should preferably be avoided by air treatment.
3. The plant should be accessible for transport (trucks).
4. The site should be of a suitable shape and soil conditions should be adequate to support the structures of the plant.
5. The site should be safeguarded against flooding.
6. There should be adequate land available for future extension.

For site selection of any wastewater treatment plant, including a UASB treatment plant, particular attention should be paid to point 2. Anaerobic processes in grit chambers, effluent gutters and the effluent may produce malodorous compounds such as H_2S. Escape of off-gases should be avoided as much as possible. Preferably, treatment of escaping gases should be employed. Some escape of odorous gases virtually always will occur. Therefore, the predominant wind direction has to be taken into consideration in the selection of the plant site.

In a UASB treatment plant the UASB reactor is the key component, as it performs the major reduction of the organic load in terms of BOD, COD and suspended solids. The remaining structures serve to accomplish an optimal functioning of the UASB reactor and to perform additional treatment steps.

The most simple treatment plant consists of a wastewater supply system (pumping), a pre-treatment (screens and grit removal) and a UASB reactor. Apart from this 'minimum' lay-out, some additional structures may be required which are determined by the effluent standards (post-treatment, disinfection), nuisance reduction (air treatment), disposal of side products (sludge and gas treatment) and location factors (See Figure 8). This will be discussed in detail in § 1.2.

A UASB reactor for domestic wastewater is a relatively plain treatment system, as it does not contain any mechanical parts. This can be seen in the basic design of a UASB reactor (see Part 1, Figure 4). The process control equipment required

for a proper operation of a domestic UASB reactor is low. These features play a role in the evaluation of the UASB process as a wastewater treatment alternative.

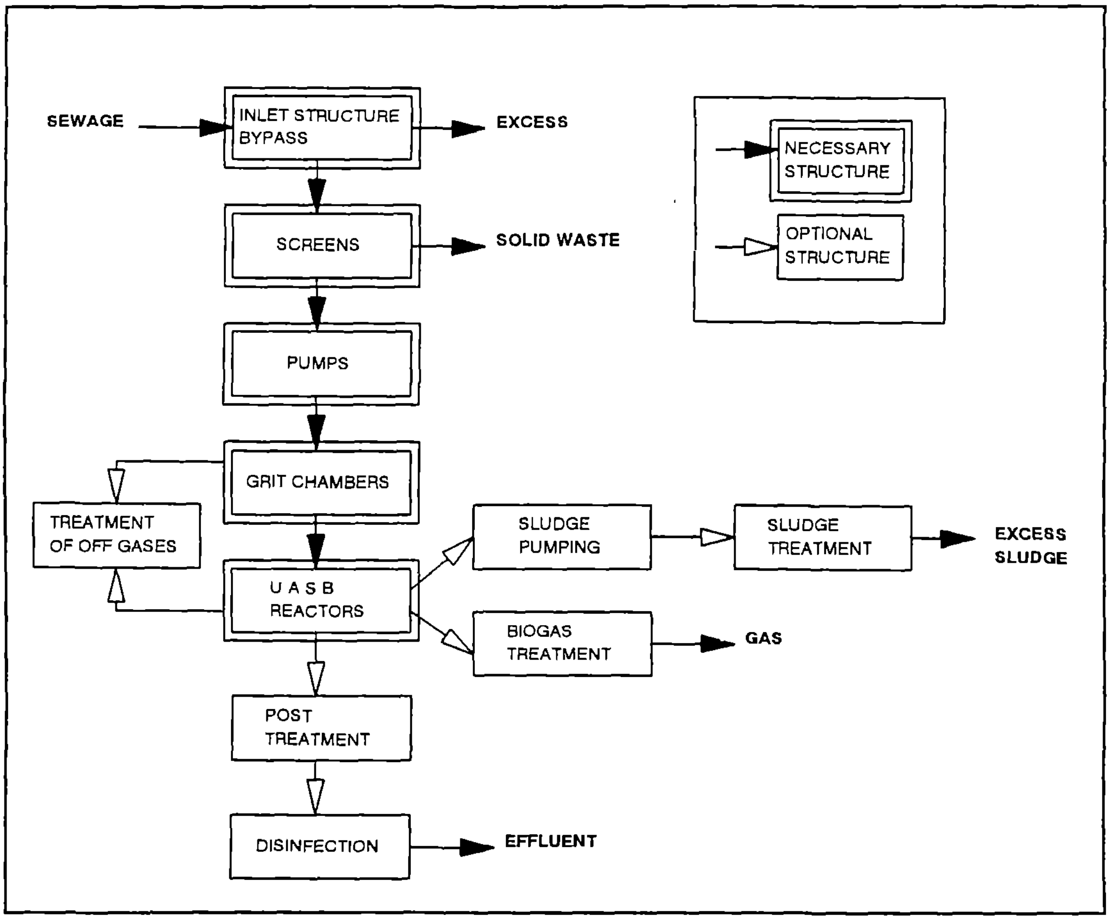

Figure 8. Lay-out of a UASB treatment plant. Optional structures are indicated by single boxes and open arrows.

1. Mechanical and technical plainness

The nature of the design of the UASB reactor, without moving parts, makes the UASB reactor very suitable for implementation in areas with a low level of infrastructure, where factors like electricity and skilled personnel for operation and maintenance are not readily available or too expensive. Obviously, additional structures of the UASB treatment plant should be consistent with the general concept of the UASB reactor. Thus, mechanical equipment should be avoided when possible and, if necessary, should be in accordance with the technical competence of the available service personnel.

It will be clear that with increasing plant size the convenience of operation and maintenance personnel requirement will favour further automatization of the plant and will allow more sophisticated equipment.

2. Phased construction feasible

Financial considerations may favour a phased construction of a treatment plant. The UASB concept makes it possible to phase the construction in time. A UASB reactor provides a major reduction of the organic pollution load. As a first phase this reduction can be already sufficient to improve the quality of the receiving

water body substantially. In subsequent phases, a post-treatment system can be added to polish the effluent.

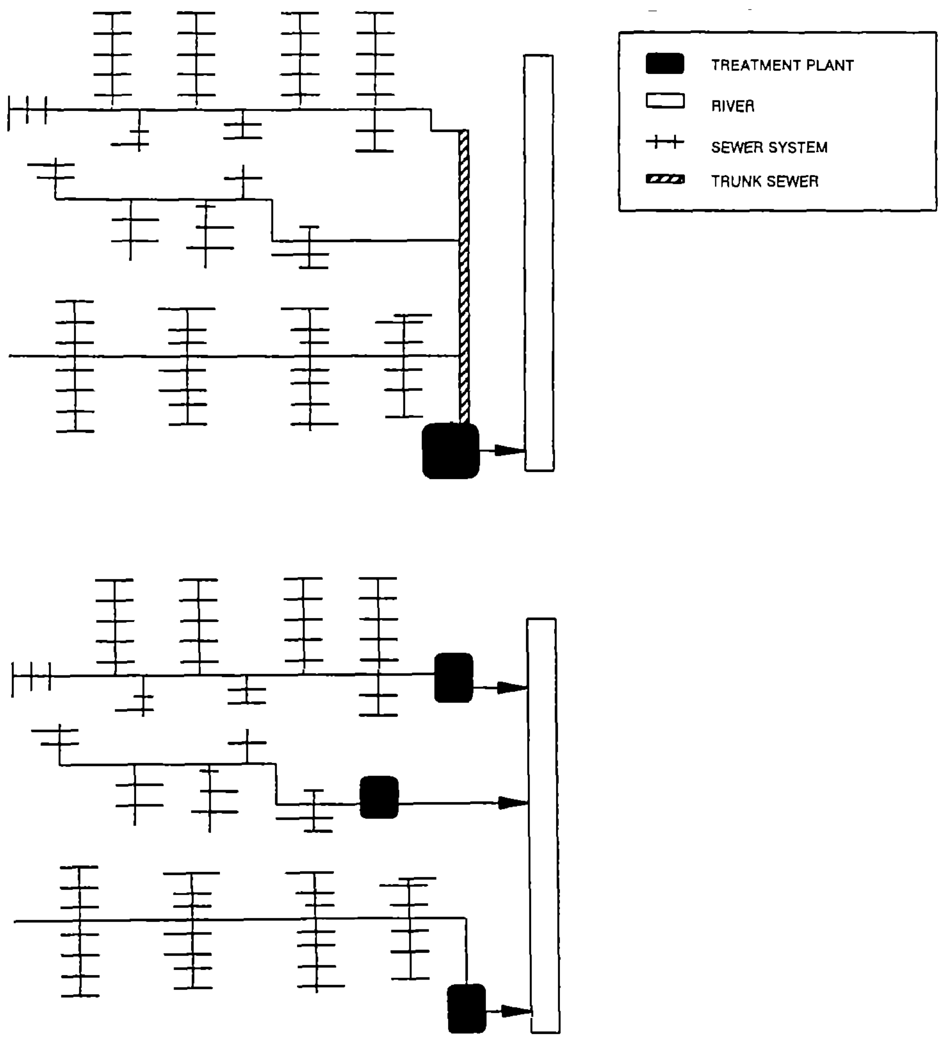

Figure 9. Example of a centralized versus a decentralized approach.

3. Decentralization feasible

In conventional aerobic treatment plants there is a tendency to centralize sewage treatment, because large plant sizes relatively reduce costs of mechanical equipment such as pumps, aerators or compressors and control equipment. Furthermore the costs of operation and maintenance of the equipment are relatively lower.

In a UASB plant the contribution of the mechanical equipment to the total construction costs is low. UASB treatment plants require less complicated operation and maintenance. As a result, the costs of construction and operation depend less on the size of the plant and thus the difference in costs between one

large treatment plant and a number of decentralized treatment plants is small. Regarding the high costs of collection systems, decentralized treatment in UASB reactors often may be more feasible than centralized treatment.

The above allows the following considerations:
- Phase the implementation of treatment works. In the first phase a complete treatment module is constructed for the actual situation and in subsequent phases additional modules are constructed to account for population growth.
- Decentralize the treatment scheme. The construction costs of a central sewer, that connects various outfall points to the treatment plant may be higher than the construction costs and operation of a larger number of treatment plants connected to small diameter sewer systems. Cost evaluations should be made for these two alternatives and should refer to the costs of both sewage collection and treatment. Figure 9 illustrates the centralized versus the decentralized approach.

6.2 Design of a UASB treatment plant

In Chapter 6.1 features of the UASB system were discussed as far as they play a role in the selection of treatment methods. In this chapter the components of a UASB treatment plant (Figure 8) will be described to the level of preliminary design. For most of these structures the design criteria are well defined and can be found in the handbooks mentioned in Chapter 6.3. Only criteria that are relevant for UASB treatment facilities will be mentioned in this chapter.
The detailed design criteria for UASB reactors will be discussed in Chapter 7.

6.2.1 Wastewater supply

A UASB reactor for the treatment of domestic wastewater is basically designed on hydraulic criteria. Therefore, the flow rate to the plant is bound to the limits set in the design and the flow should be controlled to avoid exceeding its maximum.

For a short while (up to two hours) even the design maxima may be exceeded by some 30 %. When the wastewater is pumped, the capacity of the pumps sets the maximum flow rate. Excess wastewater has to be drained through an overflow system in the sewer, or stored in a buffer basin. When the plant is gravity-fed, the flow rate should be limited by means of an overflow device to its maximum and the remainder is to be drained or led to a buffer basin for later treatment. The same structure can serve for flow measurements when appropriately designed.

It must be possible to bypass the plant completely for maintenance purposes. The simplest form is to install a slide valve at the sewer outfall. Then, the entire system is out of operation. The capacity of the overflow structures of the sewer system, therefore, must be sufficient to drain all sewage. If this is not possible for longer periods, the wastewater has to be pumped and discharged permanently. The structures before the pumps and the pumps themselves can only be taken out of operation for the time permitted by the storage capacity of the sewer system. Gravity fed plants should be provided with a bypass. The overflow device in many situations can be designed in such a way that both functions, overflow and bypass, can be realized.

6.2.2 Screening

A sewage treatment plant is located at the end of a pipe that often is used as a general waste disposal system. Therefore, wastewater may carry large objects such as wood, plastics, cloth etc. that may damage or obstruct equipment or structures in subsequent stages of the treatment. These objects are removed by screening.

In a UASB plant it is important to remove even relatively small objects, down to 15 - 25 mm in size, to allow for a proper functioning of the influent distribution system. The distribution system is a gravity fed system, working with overflow weirs and low pressure falls and is therefore sensitive to obstructions.

It is recommended to use double screening: course screens, followed by fine screens, as a sole fine screen will require frequent raking. It is recommended to place only the course screen before the pumps and the fine screen after the pump, at a location where the screen is more accessible for operation. Screens should always be provided with a bypass, in order to avoid flooding of the plant in case of obstruction of the screens.

The spacing between the bars of the course screen can be between 50 and 80 mm. This value is determined by the specifications of the pumps. For the fine screen bar spacings between 15 and 25 mm are recommended.

6.2.3 Pumping

In some situations the topographical conditions are such that the treatment plant can be fed by gravity and pumping is not necessary. It is clear that the elimination of pumps from a plant considerably simplifies its design and reduces costs of construction and operation and maintenance. Therefore, gravity flow is to be preferred when the site permits it. The elimination of pumping should not be the starting point of the design, however, thereby making operational aspects or safety factors points of minor interest. A careful evaluation should be made of cost reduction versus operational costs and maintenance aspects.

It is good practice in wastewater treatment to pump the sewage from the sewer outfall to its highest point, after which the entire plant is operated under gravity. The static head of the influent pumping can be calculated from the hydraulic profile of a treatment plant. In Figure 10 the schematic flow diagram of the Cali demonstration plant is given. The hydraulic profile of this plant is presented in Figure 11.

An important aspect in this respect is the invert level of the UASB reactor; it can either be constructed above ground level or in the ground. As all elements that require access for operation and maintenance are located at the top of the reactor, digging the reactor partially in the ground is favourable for an easy operation of the reactor. A free board of 1 meter has found to be practical.

Local conditions may favour the construction of the reactor at ground level, such as the soil structure, the ground water level, future implementation of post-treatment and gravity feeding of other components of the plant.

It is preferable to use locally available pumps that can be locally maintained and repaired, and of which spare parts are easily procured.

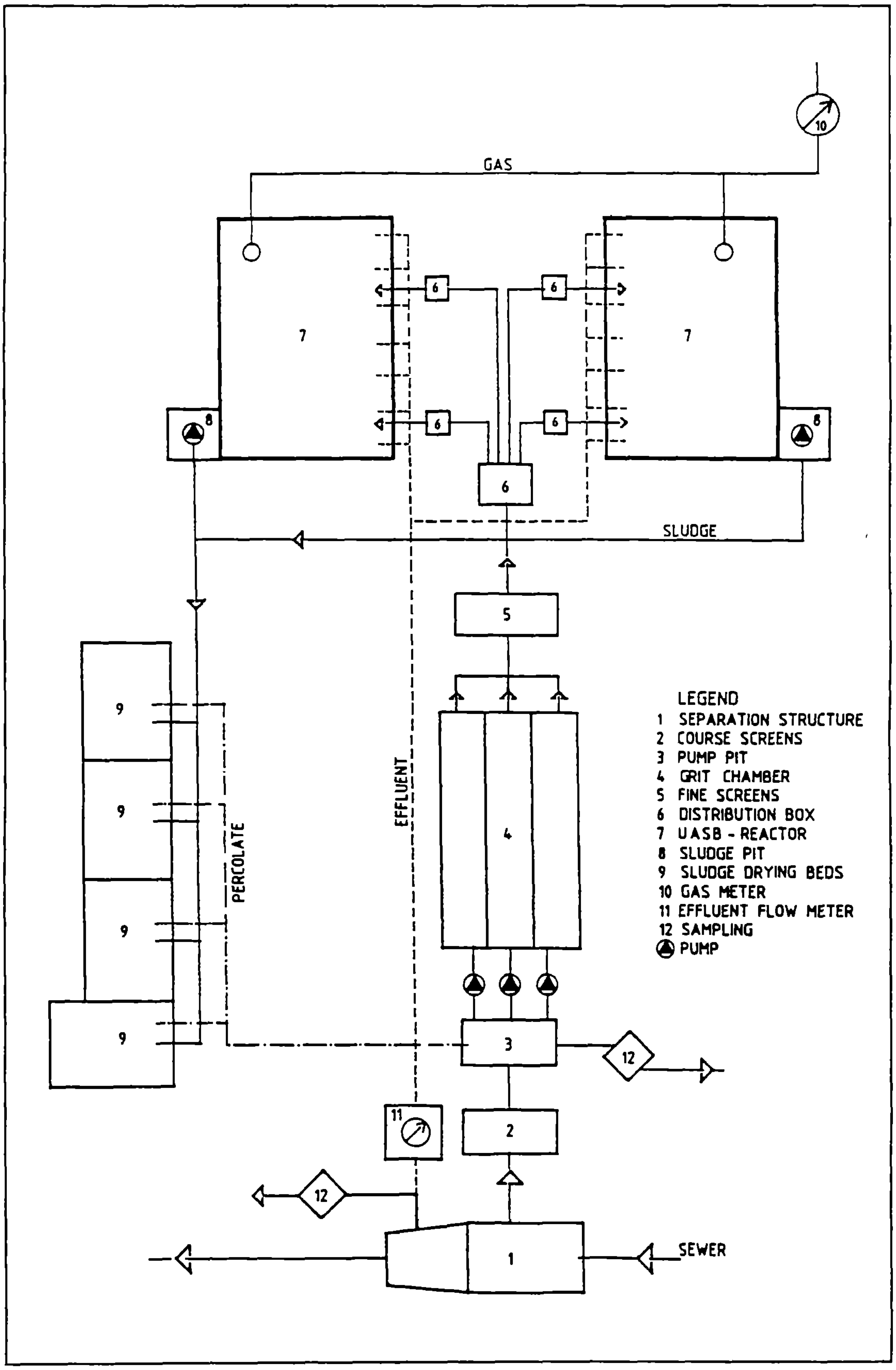

Figure 10. Schematic flow diagram of the Calı-Vivero plant.

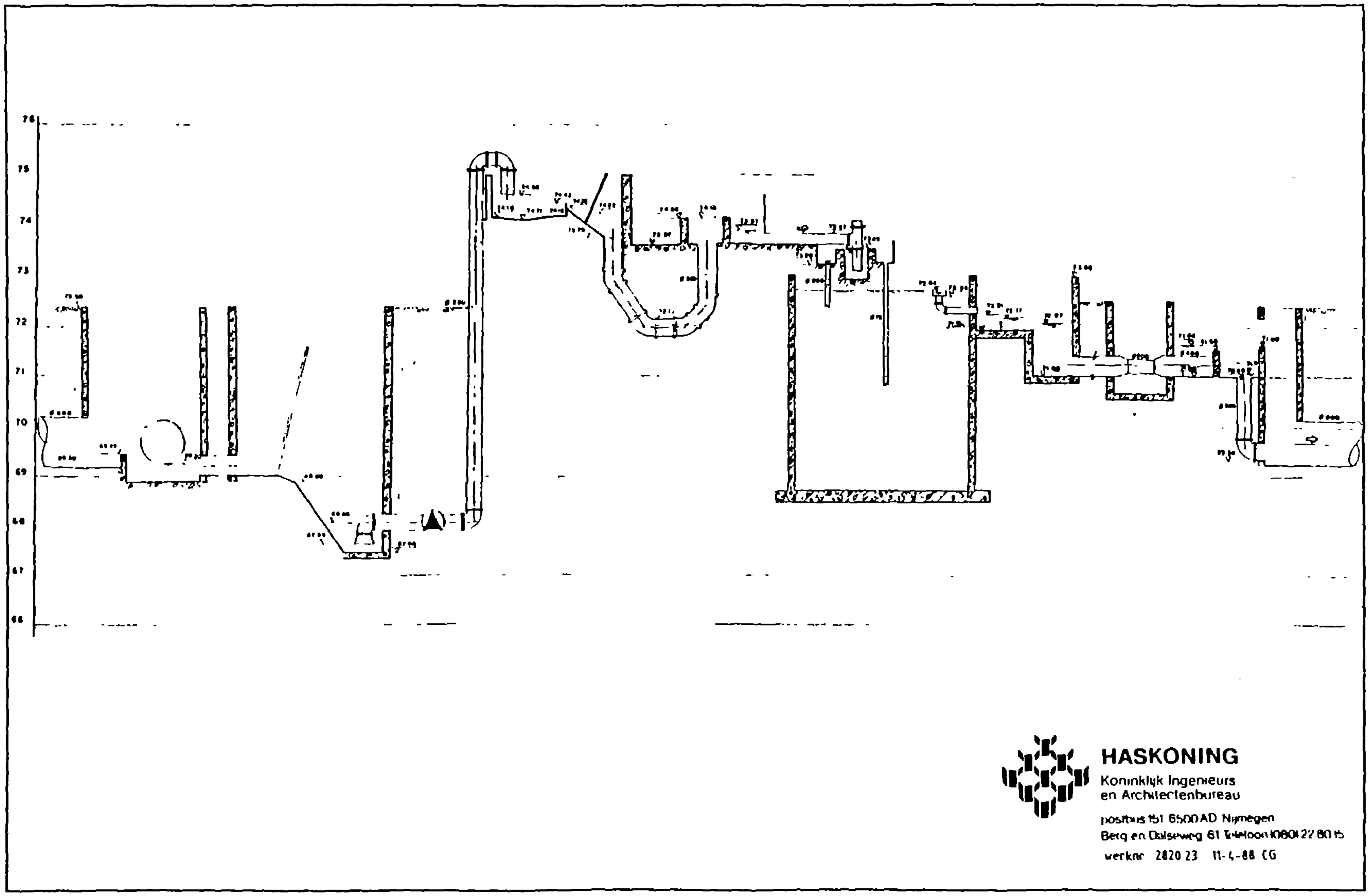

Figure 11. Hydraulic profile of the Cali-Vivero plant.

6.2.4 Grit removal

Wastewater contains a fraction of highly settleable solids. This material is mainly inorganic, the so-called grit. Due to its tendency to settle in places with a low flow velocity, it will accumulate in the reactor and will, in time, reduce the capacity of the reactor. This will make a tedious cleaning operation necessary.

The grit is a weight on the operational labour of a plant as it will tend to cause clogging of tubes and should therefore be removed as far as possible at the head of the plant. Various types of grit chambers are in use such as the Dorr type, the Geiger type and the vertical type. Taking into account easy operation and maintenance and simple construction, the open horizontal flow type is recommended (Figure 12). The internal section of this type of grit channels can either be rectangular or parabolic. The choice is determined by the flow pattern of the sewage. If strong variations in a single grit channel are to be expected, the parabolical section is to be preferred. A so-called Suitro weir will serve the same purpose: with this type of parabolic weir the channel can be rectangular, as a constant wastewater velocity is accomplished by application of the weir (see Figure 12).

Since one of the functions of grit removal is the protection of the structures of the plant against excessive wear by abrasion, the best location of the grit chamber would be before the pumps. Normally the depth of the sewer and the inaccessibility of the grit channels are prohibitive and the grit chamber will be designed after the pumps.

It is good practice to construct an additional grit channel. In this manner the channels can be operated alternatingly, thus allowing the cleaning of the channel that is not in operation.

Open horizontal grit chambers are designed for a horizontal velocity of 0.3 m/s and loading rates between 30 and 40 $m^3/m^2.h$.

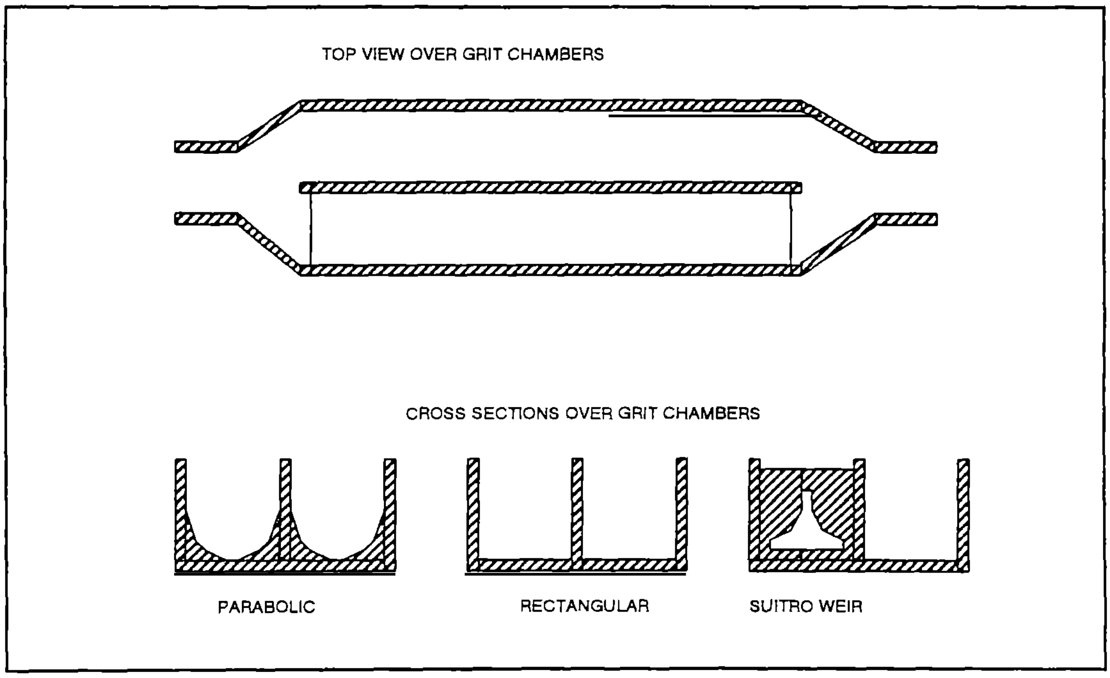

Figure 12. Example of the design of a grit channel and of a rectangular and parabolical section.

Grit production from domestic wastewater varies between 7.5 and 90 l grit per 1000 m^3 wastewater with an average of 30 l/1000 m^3. The storage capacity of grit in a grit chamber is usually designed at 2 to 3 days. The design of grit chambers is not further elaborated in this manual, as it is adequately dealt with in numerous textbooks.

6.2.5 UASB reactor

The detailed design criteria of a UASB reactor for domestic wastewater will be presented in Chapter 3. In this paragraph some general design considerations will be given. The design of a UASB reactor is mainly based on hydraulic principles.

The UASB reactor is hydraulically designed for a maximum flow rate of a given sewer system. The actual flow rate will show variations and peaks. These variations have to be absorbed by the system to a certain level. A UASB reactor for domestic wastewater is capable of operating up to peak flow rates of roughly two to three times the average flow rate. For short periods, even higher flow rates can be allowed. The other structures of the treatment plant should be designed in such a way that the same flow variations can be allowed.

The capacity of the treatment plant is dictated by its service area. This manual copes with the UASB reactor for off-site treatment, starting with sizes from 500 person equivalents (p.e.). Practically there is no upper limit to the capacity of a UASB treatment plant. An important design consideration for large plant sizes will be the number of treatment units.

For reasons of flexibility of operation it is recommended to construct minimally two UASB reactors at each plant site. In this way one reactor can be taken out of operation, while the other unit(s) can be given a temporarily higher loading rate in order to maintain the treatment capacity of the plant. In these unit(s) sludge can be stored for posterior start-up of the reactor. The use of a modular approach is thought to be cost effective at reactor sizes over 500 m^3. A general optimum size of one treatment unit is hard to give. Practical considerations as desired number of treatment lanes, pump sizes, flow increase, manageability etc. will be decisive.

6.2.6 Sludge treatment

In the Cali pilot plant the excess sludge production of a UASB reactor was in the range of 0.3 - 0.4 kg TS/kg TS influent. This is equivalent to 0.02 - 0.04 kg TS/p.e. day. This excess sludge has to be removed periodically from the reactor, once in a period of one or two days for larger reactors to up to a week for smaller reactors.

In a well-performing reactor the excess sludge is well stabilized and does not produce odour upon storage. The sludge does not need further treatment and can be disposed of directly. It may be desirable to dewater the sludge before disposal, when it has to be transported over long distances or has to be dumped on a tipping site.

Various methods are available for sludge dewatering, varying from manually or mechanically cleaned sludge drying beds to filter presses or belt pressure filters. The preference for the system of sludge dewatering depends on the size of the treatment plant, hence on the volume of excess sludge produced and on the availability of land. The most simple form is dewatering on sludge drying beds. This system is preferable as it fits into the concept of a technically simple sewage

treatment system. At large plant sizes mechanical cleaning of drying beds can be considered. If land availability is limited or climatological conditions do not favour the use of sludge drying beds, more compact, mechanical sludge drying methods will have to be employed.

Contrary to aerobic activated sludge and primary sludge, UASB sludge has high settling and thickening properties and sludge can be discharged from the reactor at concentrations between 50 and 100 kg/m^3. This sludge can be concentrated to 150 - 200 kg/m^3 (15 - 20 %) by further settling or natural dewatering.

At present too little experience with dewatering is available to give exact design criteria for sludge dewatering. Experience with the sludge from the Cali pilot plant shows that the sludge can be dewatered in sludge drying beds to a consistency of 40 % in a period of less than 14 days. Bed loadings of 20 kg TS/m^2 were found to be the optimum. The resulting bed loading rates of 10 kg TS.m$_{-2}$.week^{-1} are considerably higher than those for aerobic or primary sludge. In the Kanpur plant, bed loadings were even two times higher. However, these data cannot be used as general criteria for the design of sludge drying beds as the drying characteristics largely depend on local climatological conditions. Until more practical experience is available on design criteria for sludge drying the following procedures can be followed:

- The land reservation for the total size of sludge drying beds should be based on the one third of the land required as calculated with criteria for aerobic sludge. In this way still a rather conservative design is made (anaerobic sludge dewaters far easier than aerobic or primary sludge).
- At construction of the plant only part of the total number of sludge drying beds is constructed and in the first period of operation of the plant the production, loading rates and drying times for the sludge can be fixed.
- On basis of these data the definitive size of the drying beds can be calculated and constructed.

The future experiences will contribute in determining design criteria for UASB-plants.

The possibilities for final disposal of wet or dried excess sludge depends on its quality, legal aspects and demands for the sludge. Especially when good quality anaerobic sludge is not readily available in the region it can be used as seed sludge for the start-up of other anaerobic reactors. If the concentrations of heavy metals in the sludge are below the locally legal levels, as can be expected to hold for purely domestic wastewater sludge, it can be used in agriculture. A limit may be its content of pathogenic organisms. Sun drying of sludge in open drying beds considerably reduces the pathogen content of sludge.

6.2.7 Biogas treatment

The biogas produced by a UASB reactor operating on domestic wastewater has the following average composition: CH_4: 70 - 80 %; CO_2 : 5 - 10 %; N_2: 15 - 20 %; H_2S : < 1 %.

The production of biogas from domestic wastewater is relatively low. It can be estimated at 0.15 - 0.25 m^3/kg COD removed. This is equivalent to 10 - 15 litres biogas per p.e. per day. Due to the low organic load of the reactor, a relatively large fraction of the gas dissolves in the water and leaves the reactor with the effluent. At a temperature of 25°C and a HRT of 6 h, about 50 % of the methane is dissolved in the effluent.

At small plants can be gas released to the air. It even may be considered to construct open gas collectors (Figure 13). Here, a possible odour nuisance should be foreseen and it is strongly recommended to apply open gas collectors only at locations quite distant from urban areas. In any other situation the gas is collected to be blown off via a chimney or preferably via a flare. It is not advised to have release of the biogas without flaring, because of the possible odour nuisance.

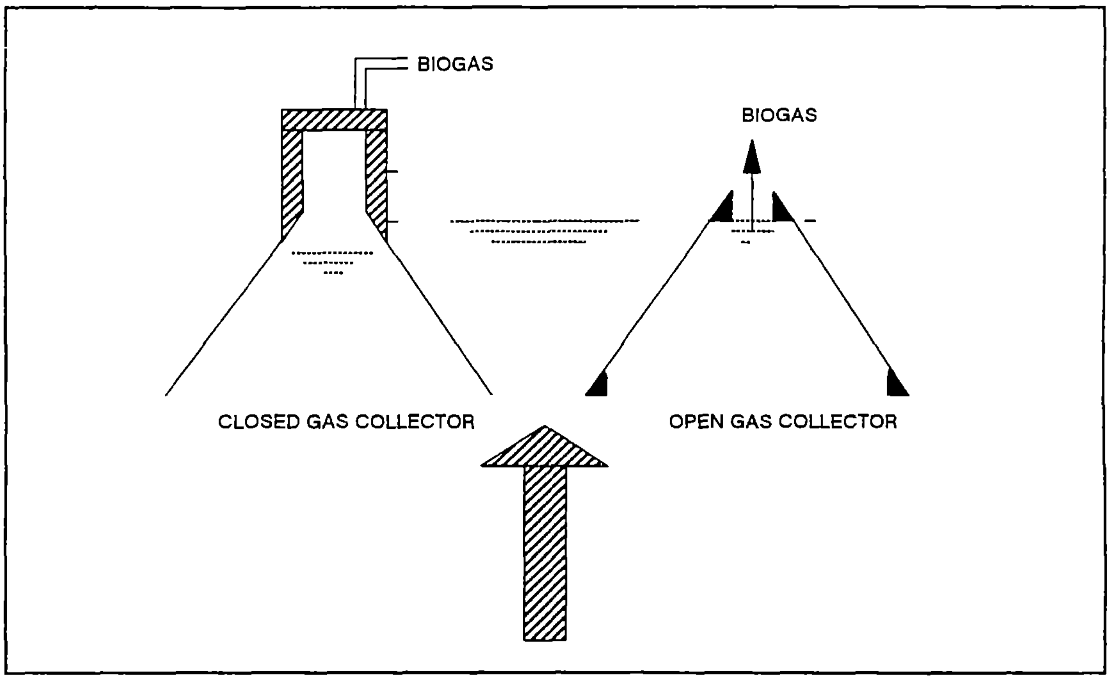

Figure 13. Schematic representation of closed and open gas collectors.

At larger plants utilization of the biogas becomes feasible. Latter will depend on the local situation. Biogas can be used for heating or for the generation of electricity, thus making the plant independent of external energy supply. The energetic value of biogas containing 75 % methane can be illustrated by the following comparison. Theoretically, 1 m^3 biogas is energetically equivalent to: 0.8 l petrol, 1.3 l alcohol, 1.4 kg charcoal, 2.7 kg fire wood, or 1.4 kWh electricity.

6.2.8 Post-treatment

The effluent quality of a UASB treatment plant has been discussed in Part 1, § 4.4. Situations exist in which a further polishing of the effluent is required, which can concern: increase of the O_2 concentration, solids removal, nitrification, nutrient removal, or pathogen removal.

Oxygenation is a simple way to upgrade the effluent. As the effluent leaves the reactor under anaerobic conditions, a direct oxygen demand exists, rising from components that oxidize in contact with the atmosphere, such as hydrogen sulphide and ammonium. This oxygen demand will be satisfied at contact with the air. In order to avoid discharge of an anaerobic effluent to the receiving water body a simple cascade system is sufficient.

Addition of Fe^{2+} can be applied to decrease the concentration of H_2S in the water, and therefore reduce both the odour nuisance as the immediate oxygen demand of the effluent.

Solids removal can be accomplished by a secondary settling tank. It will be necessary to maintain aerobic conditions in the settling tank in order to avoid floating of the settled sludge due to the production of methane. Due to the high settling velocities of UASB sludge the design of such a settling tanks is not critical. The same criteria as used for secondary clarification of aerobic treatment plants can be used.

Nitrification is the oxidation of ammonium to nitrate. Ammonium is formed in the biological reduction of organic nitrogen. Ammonium has a direct oxygen demand and is toxic to water organisms. The nitrification of ammonium takes place under aerobic conditions, i.e. in the receiving water or in an aerobic post-treatment. Many aerobic post-treatment methods are in principle suitable for nitrification, but only facultative and maturation ponds and trickling filters are fitting into the general concept of UASB treatment plants. With both systems exists some practical experience. At this stage design criteria cannot be presented and will have to be assessed in pilot scale studies at the treatment site.

Nutrient removal may be considered from two different viewpoints:
- reduction of eutrophication of the receiving water body.
- reuse of nutrients.

Chemical P-removal is a well-accepted method for eutrophication control and is very effective. Nitrogen removal is less effective as nitrogen can be taken up from the atmosphere by blue-green algae. At present systems for reuse of nutrients are still in the development phase, such as hydroponic growth of crops and algae, duckweed and water hyacinth ponds. The widely employed system of sewage farming can be considered as a form of nutrient removal and reuse method.
Anaerobic treatment appears to be particularly interesting as pre-treatment in wastewater reuse schemes, as it reduces the major part of the organic contamination, while nutrients are hardly removed and remain in a form that is favourable for uptake by plants.

Pathogen removal is of special interest in wastewater treatment as it constitutes the sanitation impact of the treatment scheme. The UASB reactor does not give a significant pathogen removal. A complementary treatment will be necessary if a high hygienic quality is desired. A generally accepted method for pathogen reduction is pounding in facultative or maturation ponds, where the residence time is the key criterium. As the land requirement of pond systems is large, disinfection may be an alternative.

6.2.9 Disinfection

Disinfection is not the same as pathogen removal. It means a total elimination of microbial germs, while pathogen removal only aims at eliminating pathogenic micro-organisms. For disinfection strong chemical agents as hypochlorite or ozone, heat shocks (pasteurizing, sterilizing) or radiation are employed to achieve the desired effect. In practice only chemical methods are used.

Disinfection can be necessary when the link between sewage discharge and water use is short, and the water is used for preparation of drinking water, recreation or agriculture.

6.2.10 Treatment of off-gases

Air treatment may be incorporated in the complete treatment scheme to reduce odour nuisance. Units that may be covered and ventilated include the grit chambers, and the open surfaces on top of the UASB reactor.

Basically, there are two options for the treatment of the ventilated air to be treated: addition of the ventilated air to the flare in which the biogas is burnt and treatment of the ventilated air in biological filters of some kind. In the treatment of domestic wastewater, the amount of methane formed generally is insufficient for the dilution of the ventilated air before flaring. The methane concentration in the gas to be flared would become too low.
Ventilated air should thus preferably be treated in compost filters. Compost filters for the treatment of ventilated air should have a maximum surface loading of approximately 50 $m^3.m^{-2}.h^{-1}$, and the H_2S loading should be maximally 5 $g.m^{-3}.^{-1}$. The ventilation rate to be applied is in the range of 1 to 3 $volumes.volume^{-1}.h^{-1}$. Depending on the amount of air to be treated, the filters should be designed on either the surface or the H_2S loading.

6.3 Literature for further reading

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7. DESIGN OF A UASB REACTOR

7.1 Introduction

In the design of a UASB reactor, as with any other wastewater treatment system, it is the wastewater characteristics that will determine the design of the reactor. In this chapter the wastewater characteristics are assumed to be available. Without any knowledge of the wastewater characteristics, especially the solids and BOD concentrations and the flow patterns, it is impossible to design a UASB reactor.

The design of a UASB reactor follows a strict pattern. This pattern is also followed in this chapter: first the number of reactions should be chosen, then the reactor shape. Next comes the calculation of the reactor volume, and the approximate dimensions. From there, the UASB reactor is designed from bottom to top, so first the wastewater distribution system has to be designed, and thereafter the definitive dimensions are fixed. The next step is the calculation of the gas collectors. Effluent and sludge discharge follow, and the final step is the gas collection system. For smooth operation, facilities for the monitoring of the sludge content of the reactor and for the removal of scum layers should be included.

7.2 Number of reactors

The number of reactors depends on the wastewater flow to be handled. With small wastewater flows, small reactors can be anticipated. In case the wastewater flow is below 500 m^3/d, a single reactor may suffice. However, if continuous operation is a necessity, the minimum number of reactors should be two. For reasons of flexibility of operation it is recommended to construct two UASB units at each plant site at the minimum, because:

- The start-up will be easier as one module can be started up with sufficient seed sludge. This module on its turn will provide seed sludge for the other module(s).
- Maintenance will be more flexible as one reactor can be taken out of operation and even emptied, while the other remains in operation. Afterwards, the working module will provide seed for the new start-up.
- The construction can be phased according to the required treatment capacity. This may be important in housing areas under development.

7.3 Reactor shape

Reactor shape can be circular or rectangular. With small reactors of up to 200 to 300 m^3, reactor shape can be circular. With reactor volumes exceeding this value, circular reactors become economically less favourable, depending on local factors. Building of rectangular reactor requires more construction materials, but is less labour intensive. Also, the construction of the gas collectors is more complex in circular reactors. With eactor volumes exceeding 200 to 300 m^3, rectangular reactors are more often used.

7.4 Critical design parameters

The critical general design parameters for a UASB reactor, either for domestic or for industrial wastewater treatment, are

- the solids retention time in the reactor;

- the liquid upflow velocity of the wastewater;
- the surface loading of the biogas.

All other design parameters are more or less related to these central parameters. The minimum hydraulic retention time, for instance, is inversely related with the maximum liquid upflow velocity. The maximum volumetric loading rate is related to the minimum solids retention time *SRT*.

The solids retention time *SRT* in a UASB reactor will depend on the wastewater characteristics. For industrial wastewater, a high conversion rate is aimed at. The desired *SRT* can be close to the minimum (with inclusion of a safety factor) allowed by the anaerobic bacteria, especially the acetate forming and methanogenic bacteria. With domestic wastewater the desired *SRT* does not depend on the growth rate of the bacteria, but on the degree of stabilization that the wastewater solids have to achieve. In both cases the desired *SRT* is strongly depending on the temperature.

The applicable liquid upflow velocity is mainly determined by the settleability of the sludge. In the treatment of industrial wastewater with low contents of suspended solids, the sludge may have very good settling properties allowing liquid upflow velocities of over 4 m/h. In the treatment of domestic wastewater, however, the liquid upflow velocities should be much lower. The applicable liquid upflow velocity in domestic wastewater treatment largely depends on the degree of solids removal that is aimed at in the treatment.

The surface loading of the biogas gives an indication of the turbulence in the reactor. This maximum surface loading is not significantly changing with temperature. Once the *SRT*, the liquid upflow velocity and the biogas loading rates are set, the data for the design are there.

7.5 Outline of design procedure

A general design procedure for the design of a UASB reactor is as follows.

1 First a tentative reactor height and gas collector height as chosen.

2 Thereafter one has to calculate the three average liquid upflow velocities corresponding with the minimum *SRT*, with the demands on the upflow velocity itself (determined by either average or maximum flow), and with the biogas loading rate. The lowest of these upflow velocities will determine the actual average upflow velocity to be used in further calculations.

3 If this liquid upflow velocity is determined by the *SRT*, increasing reactor height may result in a reduction of the total reactor volume.

4 After these calculations the ultimate reactor height and the average liquid upflow velocity are known. From the average liquid upflow velocity, the approximate reactor length and width can be calculated.

5 On the basis of the liquid upflow velocity, the HRT in the settling zone, and the gas collector design criteria the minimum gas collector width and height are calculated. If necessary, the preset height of the gas collector (set in 1) should be adjusted.

6 The feed inlet distribution will determine the total width of the gas collector system (including aperture width). The gas collector system should have a width of 1.0, 1.5, 2.0, 2.5 etcetera times the distance between two feed inlet points. The lowest total width of the gas collector system to satisfy these

demands will result in the definitive gas collector dimensions.

7 After completion of the calculations on the gas collectors, the feed inlet distribution and the effluent gutters can be calculated.

This general outline of the design procedure for a UASB reactor is illustrated in Figure 14.

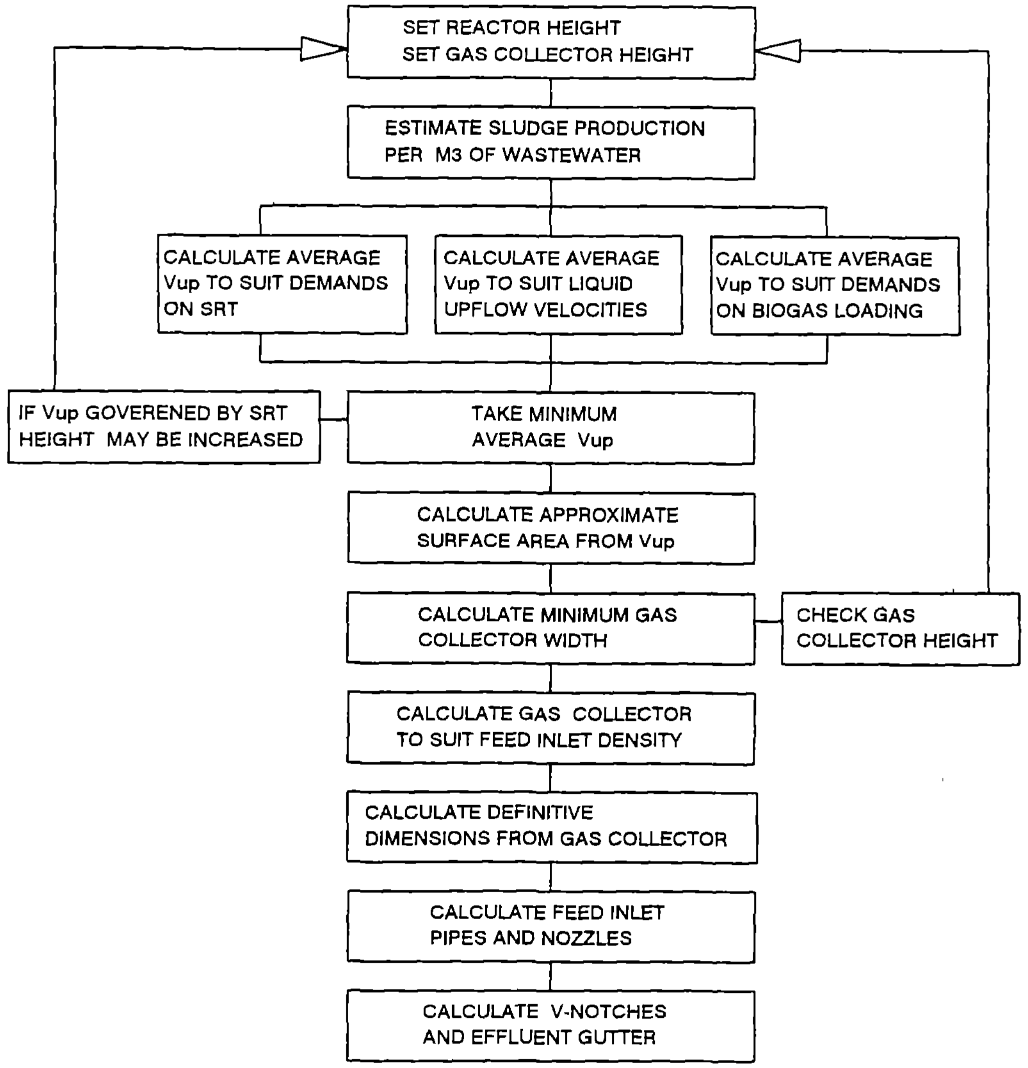

Figure 14. General outline of the procedure to be followed in the design of a UASB reactor.

7.6 Design criteria

The values of the design parameters to be used are presented in Table 11.

Table 11. Design values for UASB reactors for the treatment of domestic wastewater.

PARAMETER	VALUE	UNIT
REACTOR COMPARTMENT		
height separation zone[1]	15 % of height to gas collector	%
sludge bed height[1]	85 % of heigth to gas collector	%
average liquid upflow velocity	maximally 0.5	$m^3.m^{-2}.h^{-1}$
maximum liquid upflow velocity	maximally 0.8	$m^3.m^{-2}.h^{-1}$
peak liquid upflow velocity	maximally 1.5	$m^3.m^{-2}.h^{-1}$
biogas loading[2]	maximally 1.0	$m^3.m^{-2}.h^{-1}$
solids retention time	see Table 13	
GAS COLLECTORS		
gas collector gas loading[2]	maximally 3.0	$m^3.m^{-2}.h^{-1}$
average aperture velocity	maximally 2.0	$m^3.m^{-2}.h^{-1}$
maximum aperture velocity	maximally 5.0	$m^3.m^{-2}.h^{-1}$
peak aperture velocity	maximally 8.0	$m^3.m^{-2}.h^{-1}$
weir overflow loading	maximally 5.0	$m^3.m^{-1}.h^{-1}$
overlap	minimally 0.15	m
FEED INLET		
distribution density	minimally 0.25	m^2
disribution over bottom:		
pipe velocity	minimally 1.0	m/s
pipe velocity	maximally 5.0	m/s
nozzle velocity	minimally 0.5	m/s
nozzle velocity	maximally 4	m/s
distribution over top:		
inlet box servicing area	maximally 70	m^2
feed inlet pipes	minimally 0.30	m/s

1 : Relating to the height of the sludge bed under average flow conditions, for instance, early in the morning.
2: Not important in the treatment of domestic wastewater.

7.7 Assumptions for calculation of *SRT* and biogas production

A few further assumptions have to ne made, before the calculations can be performed. They are presented in Table 12.

Table 12. Assumptions necessary for further calculations.

parameter	value	unit
sludge bed solids concentration	90	kg TSS/m^3
minimum sludge bed height	2	m
COD efficiency of treatment	80	% (on total in)
COD conversion to methane	40	% (on total in)
degradation of solids in the reactor	40	% (on VSS basis)

7.8 Start of design procedure: initial settings

As a first approach, the reactor height and the gas collector height should be set at 4.0 m and 1.4 m, respectively.

7.9 Calculation of liquid upflow velocities

The design procedure is followed by the calculation of three liquid upflow velocities, the lowest of which may be determining the ultimate liquid upflow velocity to be applied in the design.

7.9.1 Liquid upflow velocity to fulfil demand on *SRT*

The minimum design *SRT* for a UASB reactor for domestic wastewater treatment is dependent on the temperature and is given in Table 13. In Table 11 the design criteria for UASB reactors for domestic wastewater are summarized.

Table 13. Minimum solids retention time *SRT* as a function of temperature.

temperature	solids retention time
°C	days
20	38
22	35
24	31
26	28
28	26
30	24

The maximum average liquid upflow velocity to fulfil the demands on the *SRT* is calculated as

$$V_{UP} = H / HRT_{MIN},$$

in which H is the reactor height, set at 4.0 m, and HRT_{MIN} is calculated as follows (see § 5.5.2 (Part 1) of this manual).

With

$$HRT_{MIN} = P_{TSS} / TSS_{ACC} \text{ (days)}$$

and

$$TSS_{ACC} = TSS_{AVG} / SRT$$

$$V_{UP} = (H * TSS_{AVG}) / (TSS_P * SRT) \text{ (m/d)}$$

The average sludge content TSS_{AVG} over the total reactor volume is a function of the average sludge concentration in the sludge bed, and the height of the reactor and the gas collector.

The *SRT* can be estimated from the sludge production and ther average sludge content of the reactor, see § 5.5.2.

$$SRT = TSS_{AVG} / (P_{TSS} * V_{UP} * H).$$

in which

SRT	is sludge retention time (h or days)
TSS_{AVG}	is average sludge concentration (see below, kg/m^3)
P_{TSS}	is sludge production (see below, mg TSS/l)
V_{UP}	is upflow velocity (m/h)
H	is reactor height (m)

The average sludge concentration can be calculated as follows.

$$TSS_{AVG} = TSS_S * (H - H_G) * (A/100) / H$$

in which

TSS_{AVG}	is the average sludge concentration over the reactor (kg/m^3)
TSS_S	is the average sludge concentration over the sludge bed (kg/m^3)
H	is reactor height (m)
H_G	is height of the gas collector (m)
A	is the sludge bed percentage, the percentage of the height from the bottom of the reactor to the gas collectors, which is occupied by the sludge (%).

Now the average sludge concentration over the reactor can be estimated. The sludge bed concentration may be assumed to be 90 kg TSS/m^3. The height of the gas collector has not been calculated yet, but can be assumed to be 1.2 m. 85% of the height of the reactor to the gas collectors can be assumed to be occupied by the sludge bed. The calculation is illustrated in Figure 15.

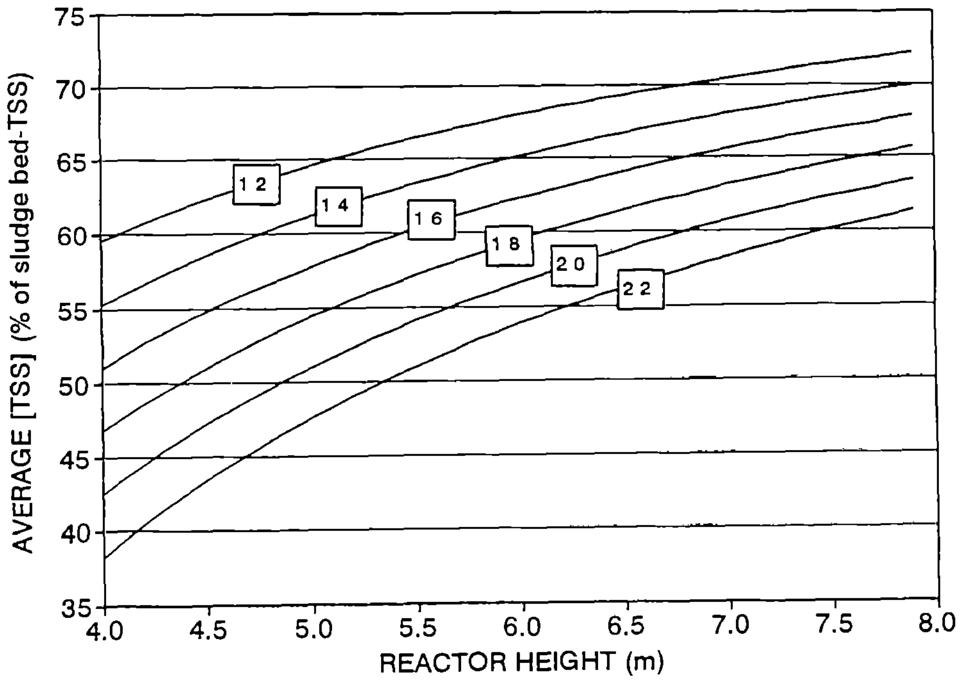

Figure 15. Average sludge concentration over the total reactor as a function of reactor height (X-axis) and gas collector height (indexed in the Figure). The average sludge concentration is expressed as the percentage of the sludge bed concentration. 85 % of the volume to the gas collectors is assumed to be occupied by the sludge bed.

The sludge production per m^3 of wastewater can be calculated as follows (see also part 1, § 5.5.2):

$$P_{VSS} = TSS_{IN} * (1 - (A_{IN} / 100)) * (1 - (Z / 100)) + Y_{TOT} * BCOD_{IN}$$

in which

P_{VSS}	is the sludge production per m^3 of wastewater (kg VSS/m^3)
TSS_{IN}	is the total solids content of the wastewater (kg TSS/m^3)
A_{IN}	is the ash percentage of the wastewater solids (%)
$BCOD_{IN}$	is the BCOD (biodegradable COD) of the wastewater (kg/m^3)
Z	is the percentage of the VSS in the wastewater which is degraded during its stay in the UASB reactor
Y_{TOT}	is the conversion coefficient for the conversion of BCOD and into bacteria (kg VSS/kg BCOD)

Now

$$P_{TSS} = P_{VSS} / (1 - (A_{BED} / 100))$$

with P_{TSS} relating to TSS and A_{BED} is the ash percentage of the sludge bed solids.

7.9.2 Average liquid upflow velocity to satisfy demands on upflow velocities

The average liquid upflow velocity to satisfy the demands on the upflow velocities depends on the ratio between maximum and average upflow velocity. If the ratio between maximum and average flow is higher than the ratio between the maximum applicable maximum and average upflow velocities, the average upflow velocity will be determined as follows:

$$V_{UP} = Q_{avg} / Q_{max} * V_{max}$$

in which Q_{avg} is the average wastewater flow, Q_{max} is the maximum wastewater flow, and V_{max} is the liquid upflow velocity allowed during maximum flow.
If on the other hand the ratio between maximum flow and average flow is lower than the ratio between the maximum applicable upflow velocities during maximum and average flow, then of course

$$V_{UP} = V_{avg}.$$

7.9.3 Average liquid upflow velocity to satisfy demands on biogas loading

In the treatment of domestic wastewater the biogas loading will never be important in the design. The biogas loading rate V_B can be estimated optimistically as follows:

$$V_B = COD * E_{COD} * V_{UP} * (T / (T - 273)) * 0.35 / F_{MG}$$

in which

V_B	is the biogas loading rate (m/h)
COD	is the COD of the wastewater (kg/m^3)
E_{COD}	is the efficiency of conversion of COD into methane (-)
V_{UP}	is the liquid upflow velocity (m/h)
T	is the temperature (°C)
F_{MG}	is the fraction of methane in the biogas (-).

It can be calculated that in domestic wastewater, for instance with a COD of 500 mg/l, which is converted to methane for 50% and the biogas contains 65 % methane, the biogas loading rate at a maximum wastewater upflow velocity of 1.0 m/h (with 1 kg of CH_4-COD $\equiv$ 0.35 m^3 at 0°C) is still only $0.500 * 0.50 * 1.0 * 0.35 * (303/273) / 0.65 = 0.15$ m/h. Maximum allowable biogas loading rates in the treatment of domestic wastewater will be around 1 m/h. For this reason it will be clear that the biogas surface loading **never** is a critical parameter in the design of UASB reactors for domestic wastewater. This will conveniently reduce the number of truly critical design parameters to only two: *SRT* and liquid upflow velocity.

7.9.4 Comparison of the calculated liquid upflow velocities

The lowest of the three liquid upflow velocities, calculated in the previous paragraphs, should be taken for the further design. However, if the lowest upflow velocity is determined by the demands on the *SRT*, it may be possible to increase the height of the reactor to fulfil the demands on the *SRT*. This will result in a lower total volume of the reactor. The reactor height may be increased up to the level that either the other two liquid upflow velocities become limiting, or the maximum reactor height is reached.

7.10 Reactor height

The height of a UASB reactor is under pressure of two contradictory demands. On one hand, one would like to reactor to contain as much sludge as possible. As there is a certain limit in the distance between the sludge bed and the lower sides of the gas collectors, and the gas collectors themselves have a height of themselves, one would like the reactor to be as high as possible. The maximum height can be set at 8 m.

On the other hand, one would like the wastewater upflow velocity as low as possible. This would imply a very shallow reactor. For reasons of construction, the reactor still should be at least 4 m high (2 to 2.5 m for the sludge bed, 0.5 to 1 m for the minimum distance between sludge bed and gas collector, and approximately 1.4 m for the gas collectors).
If the liquid upflow velocity is determined by the *SRT* (at initial reactor height setting of 4.0 m), reactor height may become higher than 4.0 m, otherwise 4.0 m will be the definitive reactor height.

7.11 Reactor surface area

Once the definitive average upflow velocity is calculated, the surface area of he reactor will follow logically from the wastewater data. The approximate surface area *AA* is simply calculated as:

$$AA = Q_{avg} / V_{UP,avg}$$

in which

Q_{avg} is average wastewater flow (m^3/h)
$V_{UP,avg}$ is average upflow velocity (m/h).

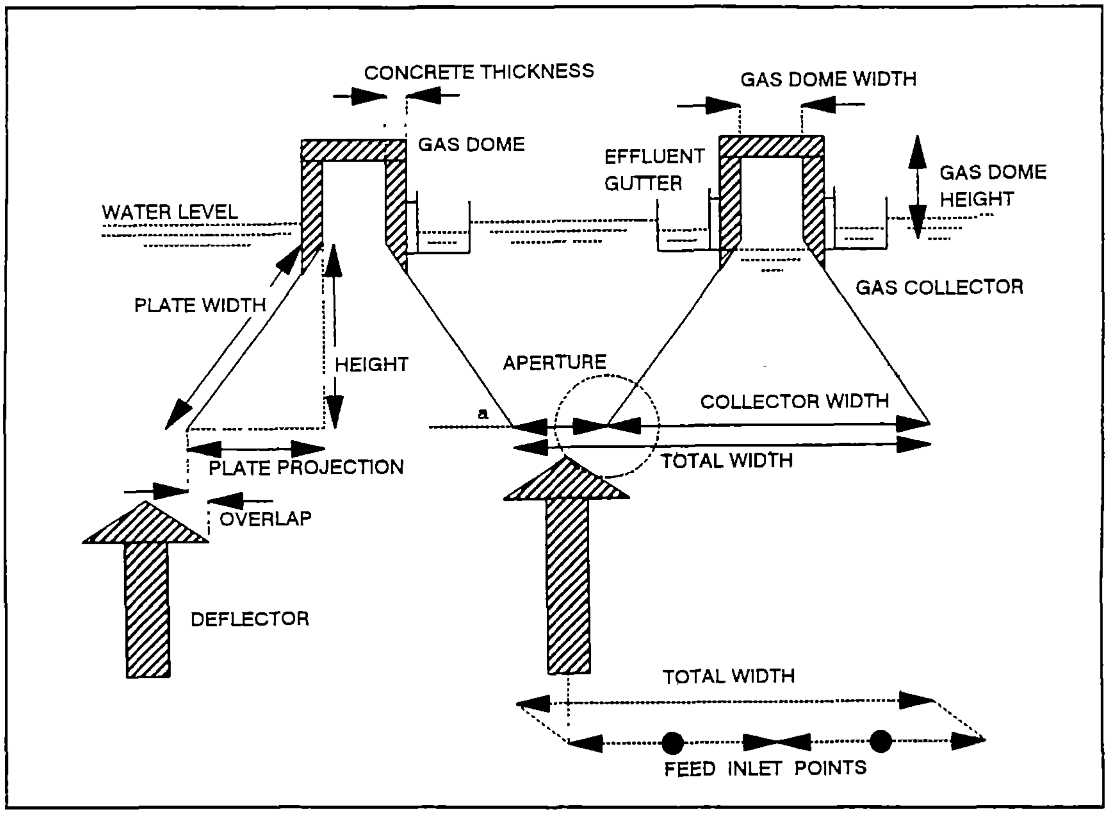

Figure 16. Schematic representation of the gas collector system

From the surface area of the reactor, the choice of the reactor length and width is not quite simple. It should be based on considerations on

- how to place the influent distribution system;
- the dimensions of the gas collectors.

The influent distribution system should be placed in a fashion that allows even distribution of the wastewater over the bottom of the reactor. As the feed inlet system will be placed evenly over the bottom of the reactor, and the gas collectors have to be placed evenly over the top of the reactor, the design of feed inlet system and gas collectors is interrelated.

7.12 Gas collectors

The design of the gas collectors for UASB reactors treating domestic sewage, and with feed inlet over the top of the reactor, is strongly influenced by the feed inlet system. The design is illustrated in Figure 16. In this figure the following parameters are used:

- The *gas dome width* is the internal width of the gas dome. For the calculation of the total width of the gas dome, it is also necessary to know the *dome thickness*, which is the width of the material forming the gas domes.
- The *height of the gas dome* is the height above the sides of the gas collector.
- The *collector width* is the total width of the gas collector. The total width is determined by the total gas dome width and the *plate projections*.

- The plate projection and the *angle a* together determine the *height* of the gas collector, and the *plate width* of the plates forming the sides of the gas collectors.
- The *aperture width* is the distance between two gas collectors. Aperture width and collector width together form the *total width* of the collector system. This total width is determined by the density of the feed inlet points.
- The *deflector* beams are necessary to lead all thew biogas into the gas collectors. They should have an *overlap* with the sides of the gas collector, to collect all the biogas onto the gas collectors.
- The advised location of the *effluent gutters* is indicated in Figure 16. The design of the effluent gutters is dealt with in the next paragraph.

The aperture width is one of the most important aspects for the design of the gas collectors. The aperture width is calculated by first calculating the percentage of the reactor surface area that should be occupied by the apertures. This percentage can be calculated from the upflow liquid velocities allowed for in the reactor, and the upflow velocity allowed in the aperture. If the allowed upflow liquid velocity over the reactor is V_{UP}, and the aperture velocity is allowed to be V_A, the aperture width of the total of the apertures should be V_A / V_{UP}. (This is also referred to as the aperture percentage *AP* (in %). If the total width of gas collector plus aperture (which is determined by the feed inlet density) is *TW*, then the aperture width is

$$AW = V_A * TW / V_{UP}$$

With the aperture width, also the collector width is determined. The collector width is

$$CW = (1 - V_A / V_{UP}) * TW$$

Depending on the placing of the sides of the gas collectors, the calculation of the dimensions of the plates should either include or exclude the concrete thickness. It is strongly advised to construct a gas collector as in Figure 16, with the plates forming the sides of the gas collectors mounted to the insides of the gas dome. In this case the plate projection *PP* (the projection of the sides of the gas collectors onto the horizontal plane) is calculated as

$$PP = (CW - HW) / 2$$

in which *HW* is gas hood width.

The angle at with the sides of the gas collectors should be placed is *a*. This angle should be between 50 and 60°; in most cases 50° is considered sufficient. Once the plate projection is known and the angle *a* is set, the height of the gas collectors and the width of the plates forming the sides of the gas collectors can be calculated.

The plates of the gas collectors should preferably be placed in such a way, that if for some reason a pressure build-up occurs in the biogas collection system, the gas is allowed to leave the gas collectors. This can be done by attaching the plates to the gas dome with a few millimetres space to allow for gas escape.

The height *PH* of the plates will be

$$PH = PP * tg\ a$$

and the plate width *PW* will be

$$PW = PP * cos\ a$$

The *height of the gas dome* is not subject to any calculation. Normally a height of 50 cm is used.

The *deflector width* is determined by the aperture width and the *overlap* between the deflector and the gas collector. The deflector width DW is

$$DW = AW + 2 * OV$$

in which OV is the overlap, which is normally set at 10 to 15 cm.

The deflectors should have a distance to the gas collectors which is equal to the aperture width (indicated by the circle in Figure 16). The values of the design criteria used for the design of gas collectors have been summarized in Table 11.

7.12.1 Calculation of minimum gas collector width

It is the *hydraulic residence time* in the settling zone which ultimately determines the minimum size of the gas collectors. The minimum size of the gas collectors is calculated as follows:

With HRT_{SZ} is the hydraulic residence time in the settling zone, the average cross-sectional height CH of the settling zone becomes

$$CH = V_{UP} * HRT_{SZ} \text{ (m)},$$

with V_{UP} is the definitive average upflow velocity.

The ratio between the cross-sectional surface of the settling zone to the total width of the gas collector system is

$$R = (TW - (HW + PP)) / TW \text{ (-)}$$

in which

R is the ratio (-)
TW is the total width of the gas collector system (inclusing aperture) (m)
PP is the plate projection (m)

Note that TW is not known yet, so that a tentative value of 4.00 m should be used.

Now the collector plate height PH is

$$PH = CH / R \text{ (m)}$$

so the collector width CW is

$$CW = 1 / (tg\ a * PH * 2 + HW)$$

and the total width (including aperture) is

$$TW = CW / (1 - AP / 100)$$

in which AP is the aperture percentage.

This calculation is most conveniently carried out in an iterative fashion, as outlined in Figure 17.

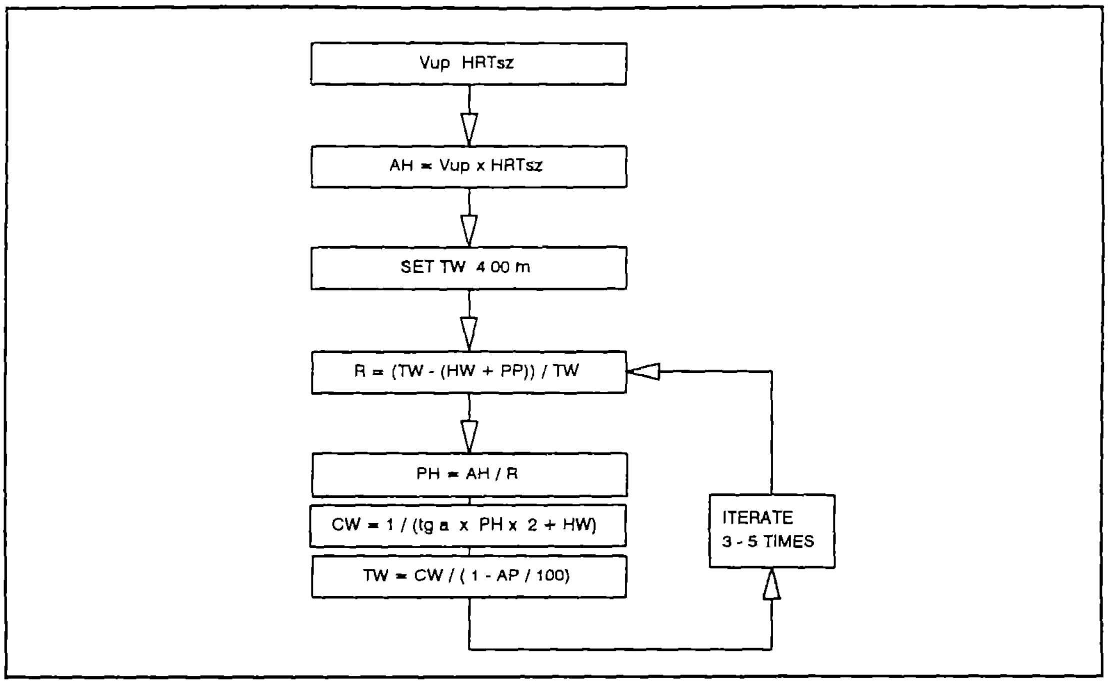

Figure 17. Iterative calculation of minimum gas collector dimensions.

7.12.2 Calculation of definitive gas collector dimensions

If the feed inlet point density is one point per D m^2, the width of the area serviced by one gas collector is

$$W = D^{1/2} * N_W/2,$$

in which N_W is a whole number, (1 to approximately 7), depending on the total width of the gas collector. N_W should be the lowest number to result in a width larger than the minimum total width (including the aperture width) of the gas collector.

If a feed inlet density of one per 4 m^2 (or more correctly: a density of 0.25 m^{-2}) is chosen, the width of the area serviced by one distribution box is 4.00 m. This is the value most commonly used for the design of UASB reactors for domestic wastewater treatment.

7.13 Definitive reactor dimensions

The definitive reactor dimensions are now determined by the total width of the gas collector system. As the calculation of the gas collector accounted for the feed inlet density, the width of an even number of gas collectors will also result in a whole number of feed inlet points.

So, one *unit width* of a UASB reactor will be the width of two gas collectors. In formula:

$$UW = 2 * TW \text{ (m)}$$

The length of the reactor can now be calculated as a function of the number of width units.

$$L_N = ROUND\ (AA / (UW * N_U)) * UW * N_U$$

in which

L_N is the length belonging to the number of width units (m);
AA is the approximate surface area as calculated in § 7.11 (m^2);
UW is unit width (m)
N_U is the number of width units
ROUND denotes rounding off to the nearest integer (whole number) value;

This calculation can be carried out for $N_U = 1$ to 6. The *definitive* number will be the N_U for which the difference between L_N and $UW * N_U$ (reactor width) is smallest. This will result in the definitive length L_D and width $UW * D$ of the UASB reactor.

This definitive length and width of the reactor will lead to dimensions which may not fit the calculated approxinate surface area completely, but may differ by a few percent. If the difference is consered too large, the feed inlet density can be changed by a few percent to result in more appropriate surface area.

The definitive number of feed inlet points is

$$N_F = L_D * UW * D / (A_F),$$

in which A_F is the area for one feed inlet point (1 per A_F m^2).

7.14 Wastewater distribution system

7.14.1 Distribution boxes

The wastewater inlet system is determined by the area serviced by one single feed inlet point. A distribution box for the feed inlet system may most suitably contain piping to 6, 8, 10 or 12 or even more feed inlet points. The distribution boxes are placed at the sides of the top of the UASB reactor in smaller reactors, and between the gas collectors (with the piping via the aperture) in larger reactors. A feed inlet box located in between two gas collectors will always serve an even number of gas collectors. If the feed inlet of the UASB reactor is over the top of the reactor, the dimensions of the reactor will be determined by the placing of the wastewater distribution boxes. This is illustrated in Figure 18.

The number of distribution boxes depends on the admissible length of the inlet tubes and thus on the size of the reactor. Two factors are important in the deciding on the number of distribution boxes to be constructed:

1) At longer lengths of the inlet tubes the danger of obstruction increases and tubes will be more difficult to clean.
2) A lower number of distribution boxes means that the boxes are larger and more difficult to maintain.

No exact criteria can be given for the length of the inlet tubes and the number of distribution boxes. Distribution boxes should preferably serve an area of maximally approximately 40 to 70 m^2.

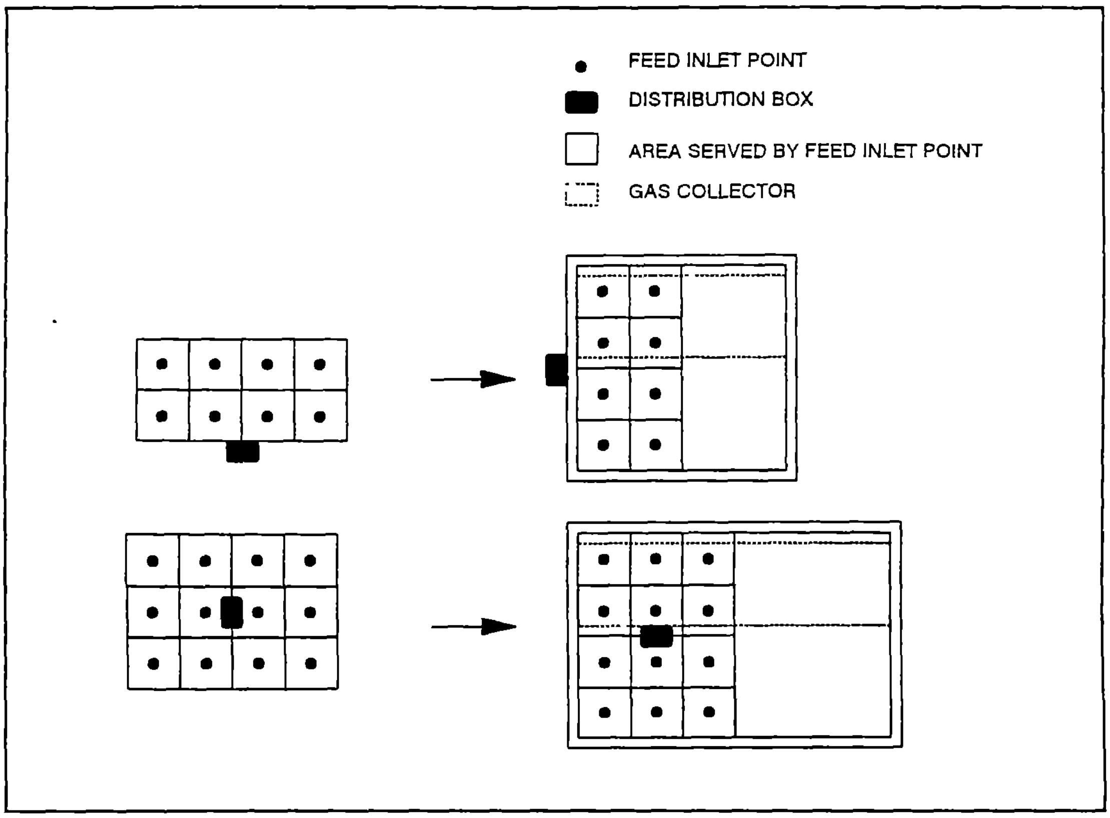

Figure 18. Schematic representation of the feed inlet system of a UASB reactor. Two possible configurations of feed inlet boxes each servicing 8 or 6 feed inlet points in a reactor containing 24 feed inlet points is also shown.

If all calculations are carried out correctly, the number of feed inlet points calculated for the definitive reactor dimensions will lead logically to a suitable number of distribution boxes.

$$N_{DB} \quad = \quad A_D / A_B \quad = A_D / (N_F * A_F)$$

in which

N_{DB}	is the number of feed inlet boxes
A_D	is the definitive surface area of the UASB reactor
A_B	is the servicing area of one disrtibution box
N_F	is the number of feed inlets per distribution box
A_F	is the area per feed inlet point (1 inlet per A_F m^2)

N_F should be chosen such that

- N_F = 2, 4, 6, 8, 9, 10, 12, 14, 15, 18, 20, 24 *etcetera;*
- N_F should be equal or smaller than the maximum number N_{MAX} to result in the maximum servicing area for one distribution box;
- N_F should be such that N_{DB} is a whole (integer) number

7.14.2 Piping

The *diameter* for the piping for a feed inlet system over the top of the reactor should provide for easy cleaning. The diameter of the piping should be such, that the liquid velocity in the pipes exceeds a minimum value. The diameter D of the pipes should be at least:

$$D_{MIN} \quad = \quad 2 * \{(Q_{min} / N_F) / (V * \pi)\}^{½} \text{ (m)}$$

in which
Q_{min} is the minimum wastewater flow (m^3/s)
N_F is the number of feed inlet pipes (-)
V is the minimum wastewater velocity through the pipes (m/s)

Design criteria for the water velocities in the feed inlet piping have been presented in Table 11.

For a feed inlet system over the bottom of the reactor, the piping should be such, that the flow velocity the length is approximately constant. This implies a decrease in diameter over the length of the pipe. For the nozzle diameter, an calculation, identical to that for the pipe diameter can be carried out. The nozzle diameter should be between D_{MIN} and D_{MAX}, to be calculated for Q_{min} and V_{max} and Q_{max} and V_{min}, respectively.

The *static hydraulic head* of the distribution box above the water level in the UASB should be 0.3 - 0.5 m at the minimum. The theoretical head losses over the inlet tubes will be small (some 7 - 15 cm). However, in practice higher losses will occur due to partial clogging of the tubes and additional pressure losses at the bottom caused by highly concentrated sludge. The spare static head will enable some self-unplugging at a sudden clogging of a tube.

It is advised to construct the *outlet* of a feed inlet tube at ± 10 cm from the bottom in order to allow some accumulation of sand at the bottom before it starts to obstruct the inlet tubes.

7.15 Effluent collection system

The effluent has to leave the UASB reactor via effluent gutters, which are located at the top of the gas collectors. The aspects of the effluent gutters aspects are illustrated in Figure 19. The effluent gutters have to be designed in such a way that

- the weir overflow rate (in $m^3.m^{-1}.h^{-1}$) does not exceed a maximum value;
- the effluent leaves the reactor with a weir overflow which is as even as possible;
- the effluent gutters are able to contain the maximum flows allowed into the reactors, which implies that the water level in the gutter should always be below the V-notches.

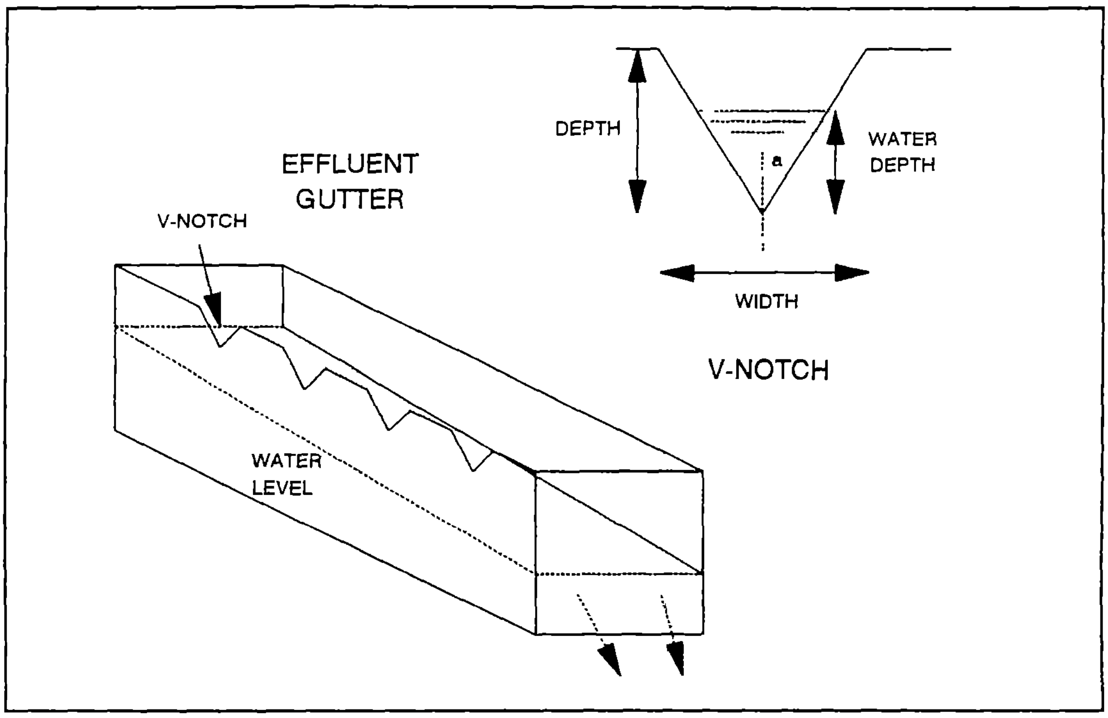

Figure 19. Schematic representation of the effluent gutter.

Completely level weirs are very difficult to construct. Therefore, V-notches are used to allow for an even overflow if the gutters are not completely level. The V-notches have to be such that

- their density is high enough to allow for an even overflow;
- the dimensions of the notches are suited to receive peak flows.

It is recommended to apply a minimum of 4 notches per meter.
The flow-rate Q_V per V-notch is:

$$Q_V = 5040 * tg\ v * h^{5/2} \qquad (m^3/h)$$

in which h is the height of the V-notch in m. The angle v usually is set at 45°.

The water depth in the V-notch will be

$$h = (Q_V / (5040 * tg\ v))^{2/5}\ (\mathrm{m})$$

so the height of the V-notch is determined by the maximum flow, the total length of the gutters, and the number of V-notches per unit length of the gutters.

If N_V is the number of V-notches per m, and L is the total length of the gutters, the height of the water in the V-notches can be calculated as:

$$h = \{[Q / (N_V * L)] / [5040 * tg\ v]\}^{2/5}\ (\mathrm{m})$$

The water height should be 3 cm in the V-notches at maximum flow. To the calculated height, some 5 cm may be added for safety reasons.

The dimensions of the gutters are calculated as to allow the flow to be contained by the gutters. The water height at the outflow will be:

$$h_1 = \{Q^2 / (B^2 * 9.81)\}^{1/3}$$

whereas the water height before falling of the water out of the gutter is

$$h_2 = h_1 * \sqrt{3}.$$

To this the pressure drop in the gutter should be added, which for gutter with a length less than 20 m can be taken as 10 % of h_2. So the height of the effluent gutter should be

$$H_E = 1.1 * \sqrt{3} * \{Q^2 / (B^2 * 9.81)\}^{1/3} + H_V$$

in which

H_E = the height of the effluent gutter (m)
H_V = the depth of the V-notch (m)
B = effluent gutter width

Effluent gutter width should be 15 cm as a minimum, as otherwise the maintenance of the gutters becomes difficult. The effluent gutters should be provided with scum baffles or have a free overflow. When the effluent gutters are provided with scum baffles, the V-notches in the gutters will be protected from clogging as the floating material is retained by the baffle. This will reduce operator attendance. A scum layer will be formed at the top of the reactor. Periodically a visual check-up has to be carried out and the scum layer removed.
If the effluent gutters are not provided with scum baffles, the floating substances will leave the reactor via the flow weirs. The incidence of clogged V-notches will be higher and will require regular cleaning.

The position of the effluent gutters should be along the sides of the gas collector. A position along the sides of the gas collector will provide for easy fixation of the gutters, the easy access for cleaning and maintenance over the top of the reactor, and a good hydraulic distribution of the wastewater as the flow is divided over both sides of the settler compartment. It is also it is easy to construct scum baffles when desired.

7.16 Sludge discharge system

With a *SRT* of 20 - 30 days, each day 3 to 5 % of the reactor contents are removed from the reactor. This removal takes place either by washout of solids in the effluent, or by sludge removal. In order to minimize sludge washout, sludge should be removed from the rector on a regular basis. Sludge removal should be possible at different locations from the reactor, and at different heights. Different heights are needed to prevent vortexes in the sludge due to which sludge removal will be less efficient. Sometimes debris is accumulating in the lower parts of the reactor, which may be removed, or low-quality sludge is accumulating in the higher parts of the sludge bed.

With only one sludge removal point, during sludge removal so much sludge may be removed that only water from above the sludge bed is removed. It is advised to have one sludge removal pipe (with outlets at different heights) per 200 m^2.

The amount of sludge to be removed can be calculated:

$$TSS_{rem} = TSS_R \, / \, SRT_D \; - Q * TSS_{eff}$$

in which

TSS_{rem}	is the amount of TSS to be removed (kg)
TSS_R	is the amount of sludge TSS in the reactor (kg)
SRT_D	is the desired SRT (d)
Q	is the average wastewater flow (m^3/d)
TSS_{eff}	is the average TSS concentration in the effluent (kg/m^3)

Sludge removal facilities should consist of three outlets per sludge discharge pipe, one at the lower parts of the sludge bed, one at the higher parts (at 1.0 - 1.5 m from the reactor bottom), and one outlet above the gas collectors. The last outlet is used for flushing of the piping.

The sludge removal should preferably have a provision to prevent too much sludge to be removed.

There are various methods for sludge discharging.

1. Principal of the telescopic pipe (Figure 20A). Gravitational evacuation of sludge using the static head between the water surface and the level of the sludge discharge point. In this manner static head may be gained, which in some cases may save the application of sludge pumps. The disadvantage is that a separate provision has to be made for complete emptying of the reactor.
2. Valves at different heights in the wall of the reactor, leading to a sludge pit. In the sludge pit pumps are installed for the evacuation of the sludge (Figure 20B).
3. A variation of 2). Here the sludge valves are connected directly to a pump. The sludge pit can be omitted (Figure 20C).

7.17 Facilities for sludge monitoring

The *SRT* of the sludge is important in the evaluation of the functioning of a UASB reactor, and the *SRT* can only be estimated by measurements of the total amount of sludge in the reactor. Therefore it is advised to construct facilities for the monitoring of the sludge content in a UASB reactor.

A quite exact assessment of the sludge quantity and level in the reactor can be made by means of a sludge sampling device that is lowered through an orifice at the top of the gas collector to various levels in the reactor. An example of such a design is given in Figure 21.

7.18 Gas collection system

The biogas should be led from the top of the gas collectors to the biogas utilization system, or to the flare. The piping should be laid out in such a way, that condens water in the piping does not have the opportunity to accumulate in the piping system. If accumulation does occur, the pressure drop may become too high, and the biogas will leave the system via the gas domes.

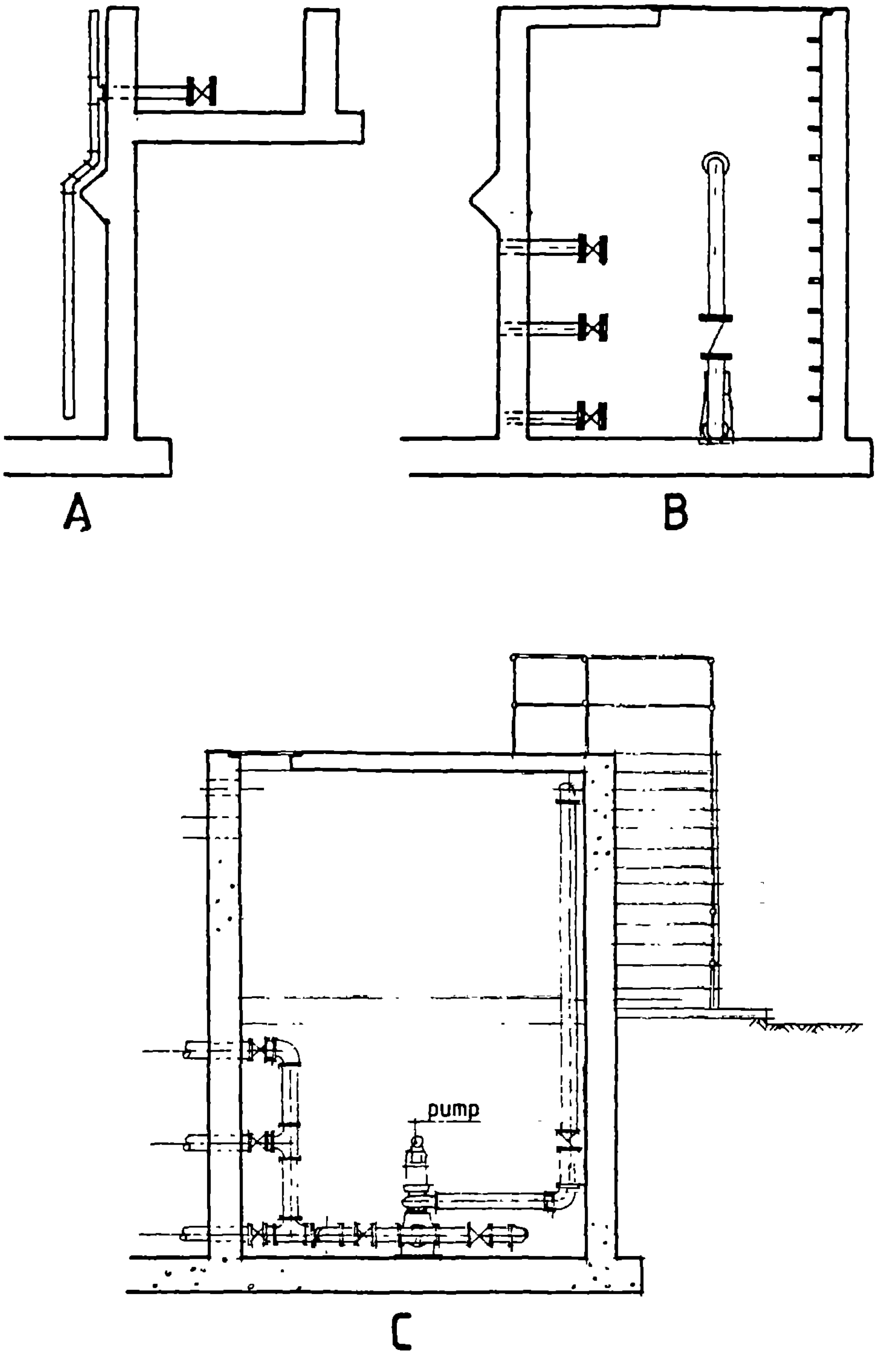

Figure 20. Different examples of sludge discharge facilities. A: Telescopic sludge pipes; B: sludge collection pit with pumping; C: direct pumping of excess sludge.

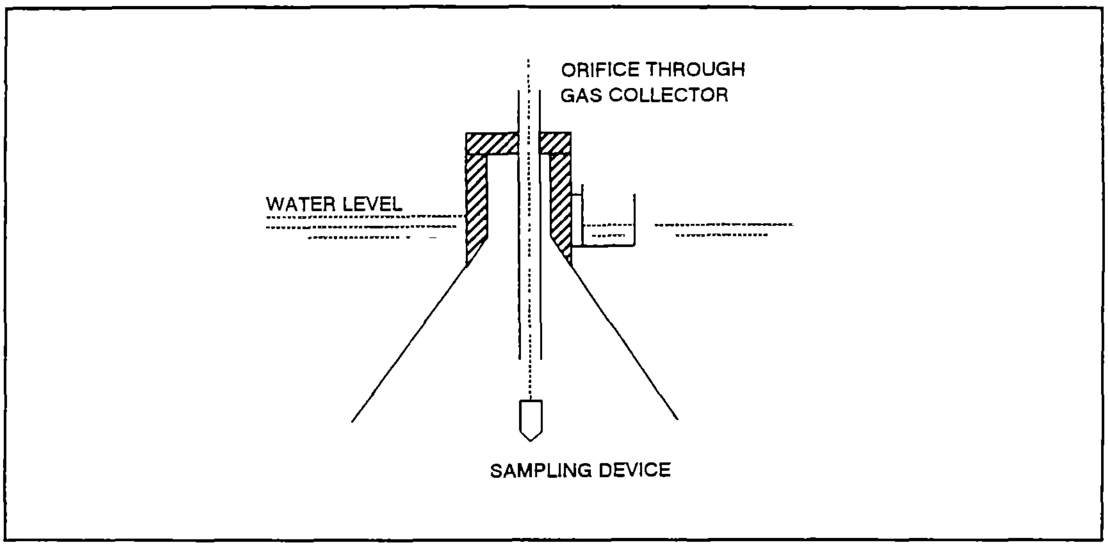

Figure 21. Sampling device entered into the reactor through orifice in the gas collector.

The gas that is formed in the reactor is saturated with water. At cooling, the water tends to condensate in the tubes. The tubes should be constructed under a small angle directed to a water trap. The water trap always should be located at the lowest point in the gas piping.

A gas meter always should be located at a high point in the gas piping as to avoid as much as possible the accumulation of condense water. In any case the gas meter should be located after the water - trap or pressure vessel.

8. CONSTRUCTION OF UASB-PLANTS AND CONSTRUCTION MATERIALS

The UASB-reactor for domestic wastewater is a relatively plain and low-technological treatment system: expensive high-technology devices are absent. Whenever possible, the advantages of the plainness should be used in the design and construction of the entire treatment plant. Treatment plants, especially those in developing countries, must have a high cost-effectiveness, which means a high benefit at minimum cost-input. For this, treatment plants have to be reliable, easy to operate, have a long lifetime and require low inputs for operation and maintenance. To meet these requirements, the following considerations are of importance:

- The choice of construction materials for the plant should be in accordance with the local construction practice and experience.
- Care should be taken in the selection of materials with a sufficiently long lifetime without excessive maintenance. In Chapter 7.2 some criteria on this matter will be given.
- The use of mechanical equipment should be minimized. Often a choice can be made between manual cleaning and mechanical cleaning equipment. If possible, operation should be carried out manually, because mechanical equipment is often costly and requires a more specialized operation and maintenance.
  For large-size plants mechanical equipment will often be necessary in order to reduce the manpower input.
- The type of mechanical and control-equipment should be within local competence of operation and maintenance. It should be taken into mind that the operation and maintenance has to be carried out by local operators and technicians. Therefore, equipment should be used of which spare parts are locally available or can be locally constructed.

8.1 Construction materials

The environment in and around an anaerobic wastewater treatment plants is quite corrosive. The impact of the corrosive environment on the construction materials depends of their application. In the following, suggestions will be given for possible applications of various construction materials, taking into account the economy of the construction.
The following materials can be considered for application in an anaerobic treatment plant:

Concrete

Concrete is widely available in most developing countries and generally a lot of experience exists in working with concrete. It is known that concrete is corroded in sewer systems due to the formation of H_2SO_4. In anaerobic reactors it was found that the concrete below the water surface is attached by CO_2 that is formed in the biological process. Above the water surface concrete is not attacked. It is quite possible, that the quality of the concrete strongly influences the susceptibility to CO_2-corrosion. Therefore, high quality concrete should be used and casting should be executed with much care, such as extra cover or PVC lining. Additionally, the wet surfaces of the plant can be lined with a protective coating, if available.

Stainless steel.

Some types of stainless steel are resistant to the environment at the treatment plant, whereas others are not. Corrosion-resistant types are recommended for all parts of the plant, but it is expensive and often not available. For this reason corrosion-resistant stainless steel should be used only for those parts that are critical to a proper functioning of the plant and that are very susceptible to corrosion. These applications are the overflow weirs of distribution boxes and effluent gutters and the bolts and nuts necessary for adjustments. If stainless steel is readily available, the construction of the entire distribution boxes and effluent gutters can be considered. Cost-evaluation and design aspects will be decisive in this respect.

Galvanized iron

Normal galvanized iron is not suitable for corrosive environments. Hot-dipped galvanized iron is found to be resistant to the corrosive environment at the plant site. In wet applications, however, it has been found that the medium is aggressive to the coating and once the coating is "eaten" the iron corrodes rapidly. It may therefore be used in dry applications, such as railings and grids and bolts and nuts that are not into contact with water.

Cast-iron

Cast-iron is generally applied for tubings, valves and wall-passings and pump-casings in wastewater treatment plants. Cast-iron also has to be provided with a suitable coating.

Steel

Steel is heavily attacked both by the wastewater as in the environment around the plant. In wet applications it has been found that carefully applied anti-corrosive paintings are not sufficiently protective. Unless special, very expensive epoxy-coatings are available, the use of steel in wet applications is not recommended.

Aluminium

Aluminium can be used as a replacement for stainless steel. It is reasonable suited for wet applications. An aluminium alloy containing 3 % magnesium and 0.5 % manganese should be used.

Brass

Brass is in use for valves and electrical cabling. The corrosive environment around the plant can attack the surface of brass objects in a matter of hours. Electrical connections are found to suffer from this corrosion due to reduced conductibility. Switch boards etc. should be properly isolated.

PVC

PVC is very suitable for tubings in and on the reactor, such as the inlet- and distribution tubes, because it is light, easy to handle and resistant. It can also be considered to use PVC-sheets for the construction of distribution boxes and the sides of the gas collectors, although its cost may be too high. Note that PVC

should not be used if it is in contact with light, because it is susceptible to UV-irradiation.

Polyethylene (PE)

PE-tubing can be used for the inlet tubes. Through its flexibility it is easy to install. Special care should be taken to the fixation of the pipes.

Polyester-glass fibre.

Polyester-glass fibre, when well-elaborated, is very resistant to the aggressive medium of an anaerobic reactor. It can be used for the construction of distribution boxes and effluent gutters. It should be taken into account that glass fibre is very rigid and that it should be mounted in such a way that shocks or vibrations are avoided. Its high costs and fragility may be prohibitive for general use.
The polyester cannot be processed (sawing or cutting or connecting by srews), as the glass-fibre will absorp water, resulting in destruction of the plate.

8.2 Treatment plant

8.2.1 Fencing

A treatment plant is a potentially dangerous structure, because it constitutes a health risk and a danger for drowning or physical harm by moving parts or differences in level. This danger increases at increasing size of the plant and the introduction of mechanical equipment. Furthermore, the presence of water makes a treatment plant an attractive playground for children and a potential drinking place for animals.
Apart from the problems in operation that may arise, for social and sanitary reasons it is recommendable not to allow the access of non-authorized persons to the plant. Therefore, whatever the size of the treatment plant is, it should be fenced.

8.2.2 Screening

The advantage of the relative simplicity of a UASB treatment system should preferably not be lost by the installation of sophisticated and expensive automatically cleaned screens, which also need higher level skills for operation and maintenance. Occasionally, for instance at large plants and at locations where a mechanical/ electrical engineering staff is present, mechanical cleaning systems can be preferred.

At small plants, manually cleaned screens have to be made of high quality steel, if possible hot-dipped galvanized. If hot-dipped galvanizing is not available, thermical galvanization is no good alternative, as the coating will be scraped of by the rake. When inferior materials have to be used, a frequent replacement of the screen should be accounted for.

8.2.3 Pumping

Pumping of sewage or sludge is almost always necessary. Pumps are critical parts in the plant operation and much care has be taken in the selection of the type and the brand of pumps. Preferably, pumps of local make should be used as an

adequate maintenance by skilled personnel can be guaranteed and spare parts are available.

Concerning influent pumps the following remarks can be made:

- Submersible pumps generally are used for small capacities up to 150 m^3/h. At larger capacities these pumps are too heavy for easy handling and a dry-pit mounting is preferred. Submersible pumps are sensitive to leakage, because the mechanical seals become dirty by solids. Pumps of a good quality should be used and a very strict maintenance scheme has to be adopted.
- Above the pumps there should always possibility to lift the pumps out.
- The minimum free passage should be 100 mm, if possible.
- If more than one pump is used, always non-return valves should be installed, except for sludge pumps.
- Butterfly valves should not be used for closing.
- Unless more than two pumps are used, always a sparepump has to be installed.
- As an alternative, screw pumps can be considered (Figure 22), although this type of pumps require a careful construction of the pump housing. The economical feasibility of the application of screw pumps is restricted to pumping of large quantities of water low pumping heads. In hot countries screw pumps have to be covered in order to avoid damage by buckling of the screw.

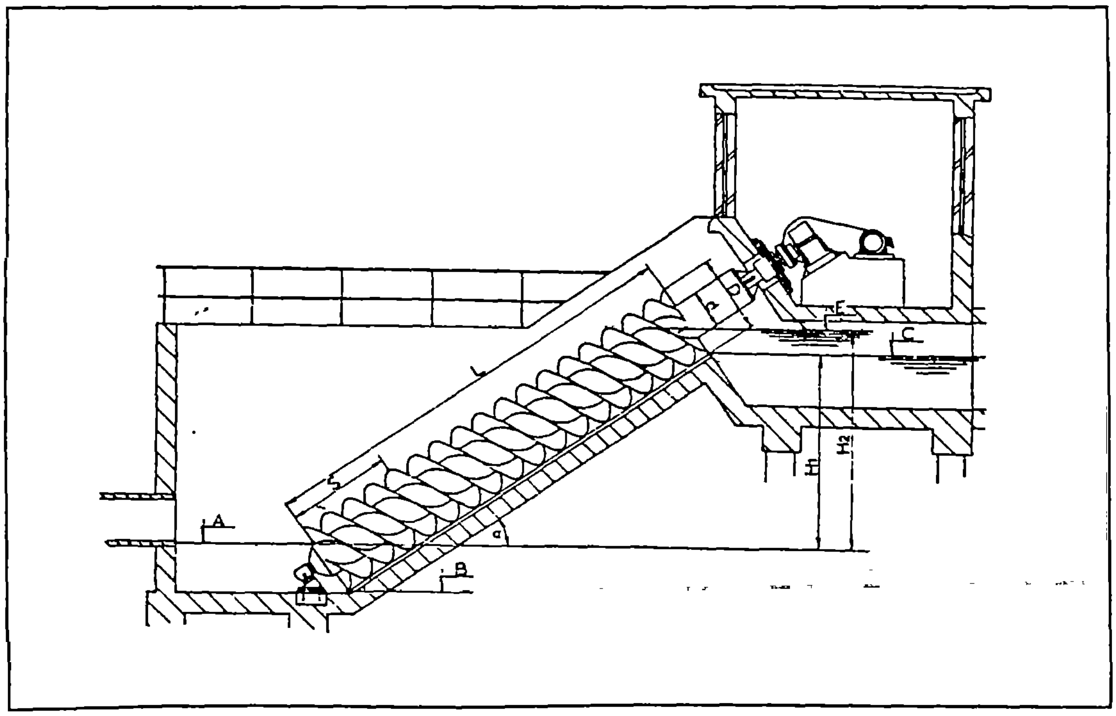

Figure 22. Mounting of screw pump

For sludge pumping the same remarks can be made. Due to the relatively small pump capacity required, submersible pumps are generally used. At selection of sludge pumps it has to be taken into consideration that sludge is not a homogeneous material.

8.2.4 Grit removal

During the design it has to be considered that easy operation (dewatering and grit removal) will be the best guarantee for smooth operation and maintenance of the grit chambers.Installation of mechanical scrapers or airlift sand pumps will increase the investment costs and require more maintenance. For the ease of operation and for adequate access, the bottom of the grit chambers should preferably be above ground level. Provisions have to be made to drain the water before cleaning.

8.3 UASB reactor

8.3.1 Reactor

Alternatives for the construction of the reactor are:

- In many cases reinforced concrete constructions will be used as ample experience exists with these type of constructions in most tropical countries. It has been found that the medium in the reactor is aggressive to concrete. If available, high quality sulphide-resistant concrete should be used.

- It is possible to make a combination of concrete and brick construction, where concrete is difficult to obtain or just for reasons of saving costs. Then, the upper part of the walls of the reactor can be constructed in brick. This is however, not advised, as there may occur problems with shrinking of the materials. So, whenever possible complete construction in reinforced concrete is preferable.
  Brick construction is suitable for the construction of small circular tanks below ground level.

- The use of ferro-cement is attractive for the construction of small circular tanks and is economical in use of materials. High demands are put on workmanship as the aggressive makes the structure sensitive to rupture.

It has to be taken into consideration that the environment around the plant is aggressive. In the choice of materials this has to be taken into account. Bolts and nuts are critical parts with respect to corrosion, especially those that are used for adjustment. Here preferably stainless steel should be used. Components such as grids, railings, stairs and fencing, if not to be constructed in concrete or brick should be made in aluminium or hot-dipped galvanized steel.

8.3.2 Feed distribution system

The function of the inlet structures is to spread the influent equally over the bottom of the reactor. There are several alternatives for locating the distribution boxes. One is to build separate boxes on top of the wall with tubes that lead along the wall via to build them in between the gas collectors.

The boxes can be made of concrete (combined with stainless steel V-notches), of stainless steel, of glass fibre reinforced polyester, but not of PVC-sheets as PVC is not resistant to UV-irradiation. For tubing PE can be used. PVC has the advantage that it is rigid and therefore easy to install. It should only be used below ground or in the water. Adapters are necessary to make curves and bends. Adapters tend to be the places where obstructions occur and special care should be taken at mounting the tubes as to assure a smooth inner surface.
PE is flexible and can be directed in one piece in gentle curves and bends to the outlet point. Particular attention has to be paid that no doubling of the tubes will occur.

8.3.3 Gas collectors

For small plants removable gas collector can be considered. This facilitates the maintenance of the reactor and the gas collector without major problems. The gas collector can be supported on the concrete beams.

Removable gas collectors can be constructed in stainless steel, aluminium, glassfibre reinforced polyester or similar synthetic material. In this set-up it is most practical to place the distribution boxes on top of the walls of the reactor. This set-up can only be used with very small reactors.
If some gas pressure is required for the utilization of the biogas, the gas collector should be fixed or provided with ballast.

A second possibility is a combination of a concrete frame with sheets of aluminium, plastic or glass fibre enforced polyester. The sheets are the sides of the gas collector.
In open gas collectors the plates can be fixed on concrete or steel beams, as shown in Figure 13. PVC is an appropriate material for the plates.

8.3.4 Effluent gutters

Effluent gutters have to be placed rigidly at the top of the reactor in such a way that the water flow is levelled out over the total length of the gutters. For this reason the gutters should have a mechanism to adjust their height. For an equal outflow, they always should be provided with V-notches.

For the construction of effluent gutters at the side of the gas collectors various designs are possible, e.g.

- an integrated (pre-fab)gas collector/effluent gutter. The effluent weirs are made of stainless steel and are fixed to the gutter with nuts.

- concrete or stainless steel consoles integrated in the construction of the gas collectors provided with adjustable stainless steel effluent gutters.

The baffles of the effluent gutters can be made of stainless steel.

9. EXAMPLE OF DESIGN CALCULATIONS FOR A UASB REACTOR

In the following, the calculations on the various units of a UASB reactor will be illustrated with an example. The calculations will follow the sequence as in the previous paragraphs. It is assumed that screening and grit removal have been taken place before the wastewaters enters the UASB units.

9.1 Wastewater characteristics

The data on the wastewater characteristics are given in Table 14. In practice, measurements are necessary to determine the actual wastewater parameters, before such a Table can be prepared. Especially flow variations should be registered carefully.

Table 14. Summary of waste water characteristics, used as a basis for design calculations.

parameter	value	unit
wastewater flow	6000	m^3/d
maximum flow	450	m^3/h
peak factor	1.8	Q_{max}/Q_{avg}
COD	450	mg/l
BCOD	300	mg/l
BOD	200	mg/l
TSS	250	mg/l
temperature	24	°C

9.2 Design criteria and assumptions

The design criteria and assumption needed for further calculations are those presented in Table 11, 12 and 13 in § 7.6, § 7.7 and § 7.9.

9.3 Calculations

The procedure as outlined in § 7.5 and followed in § 7.7 to § 7.15 is used here. See also Figure 14.

9.3.1 Setting of reactor height and gas collector height

Height of the reactor is set at 4.0 m and height of the gas collector is set at 1.4 m.

9.3.2 Calculation of the upflow velocities

First, the sludge production has to be estimated. The sludge production is estimated from the *BCOD*, the *TSS* and its ash content, the degradation that the TSS will undergo during its stay in the reactor, and the yield coefficient of the bacteria.

The biological sludge production will be $Y_{TOT} * BCOD$ = 0.10 * 300 = 30 mg VSS/l.
The non-biological sludge production (in mg VSS/l) will be TSS * ash content * (1-degradation percentage) = 250 * (65/100) * (1- 40/100) = 98 mg VSS/l.
The ash content of the sludge may be assumed to be 40 %, so the total sludge production is (30 + 98) / (1-40/100) = 213 mg TSS/l.
The *SRT* may be set at 31 days, at a temperature of 24 °C.
The minimum average *HRT* to fulfil the demands on this *SRT* is the sludge production, divided by the average sludge content.

$$HRTMIN = \frac{(sludge\ production\ /\ 1000)}{(SS_{BED} * \%\text{-}age\ occupied\ by\ bed * ((H_R - H_G)/H_R)}$$

$$= 213/1000\ /\ (80 * 0.85 * (4.00 - 1.40)/4.00) * 24$$
$$= 3.7\ \text{h}$$

(remember that *HRT* is expressed in hours, and *SRT* in days).

The corresponding upflow velocity is reactor height divided by *HRT* = 4.00 / 3.7 = 1.08 m/h

The maximum admissible average liquid upflow velocity according to the design criteria for the upflow velocities is determined by the criteria for maximum flow, because the ration between the maximum and average flow (the peak factor) is higher than the ratio between the design criteria for maximum and average upflow velocities. If a maximum flow of 450 m^3/h would yield an upflow velocity of 0.8 m/h, then the average flow would result in an upflow velocity of 250/450 * 0.8 = 0.44 m/h.

For completeness sake, here the liquid upflow velocity for the maximum biogas loading will also be calculated. The COD conversion efficiency can be estimated at 60 %, and the percentage CH_4 in the biogas may be assumed to be around 80 %. At 24 °C, 74 mg/l of CH_4-COD will remain dissolved in the water. So, per m^3 of wastewater, 0.09 m^3 of CH_4 may be expected, of which some 0.03 m^3 will remain in the water. There will escape some 0.06 m^3/m^3 of wastewater, equivalent with 0.08 m^3/m^3 of biogas. To satisfy the design criteria on the biogas loading (of 1.0 m/h), an liquid upflow velocity of 1.0 / 0.08 = 12.5 m/h would be allowed.

Comparison of the calculated upflow velocities shows, that the maximum flow conditions will determine the average liquid upflow velocity. It results in the lowest of the calculated upflow velocities. The design upflow velocity is 0.44 m/h.

9.3.3 Dimensions

Because the upflow velocity is determined by the flows, and not by the SRT, there is no gain in increasing the reactor height: the upflow velocity would remain the same. The definitive reactor height is 4.0 m.

The number of reactors is chosen to be 2. A higher number is not justified, as the flow is not quite high.

The approximate surface area calculated from average flow (per reactor) and upflow velocity:
it is (250/2) / 0.44 = 281.3 m^2

(So the reactor volume is 1125 m^3 and the loading is 1.2 kg $COD.m^{-3}.d^{-1}$).

The minimum collector width to achieve a HRT_{SZ} of 1.5 h is calculated as follows: with assumed total width of 4.00 m, and aperture percentage of 16 %, and an angle of 50°, the gas collector width is 3.36 m, the collector plate projection is 1.43 m, and the collector plate height is 1.70 m.
This initial plate projection and plate height can be used for the following calculation, as outlined in Figure 17. With a HRT_{SZ} of 1.5 h in the settling zone, the average height becomes $AH = HRT_{SZ} * V_{UP} = 1.5 * 0.44 = 0.72$ m/h. Then the ratio between the cross-sectional surface of the settling zone to the total width of the gas collector system is

$$
\begin{aligned}
R &= (TW - (HW + PP)) / TW \text{ (-)} = (4.00 - (0.50 + 1.43)) / 4.00 \\
&= 0.52
\end{aligned}
$$

Now the plate height will be $CH / R = 0.72 / 0.52 = 1.29$ m, and accordingly, the gas collector width will be 2.66 m and the total width will be 3.17 m. With this total width, the complete calculation can be re-entered again. After three to five circulations, the dimensions of the gas collectors will not change anymore. The outcome of the calculations is 3.24 m for the total width of the gas collector system, with 2.72 for the gas collector itself, and 1.33 m for the plate height.

With a minimum gas collector width of 3.24 m, and a feed inlet density of 1 per 4 m^2, corresponding to 1 feed inlet point per 2 m, the definitive total width of the gas collector should be 2 feed inlet points wide = 2* 2.00 = 4.00 m.

This will result in the following gas collector dimensions:

total width	4.00	m
aperture	16	%
collector width	3.36	m
plate projection	1.43	m
plate height	1.70	m

The collector height is now somewhat larger than assumed in the initial settings. Therefore, the sludge content of the reactor will be some 12 % lower than initially estimated (see Figure 15), this will have no consequences. The maximum liquid upflow velocity is still the velocity determining the reactor dimensions.

The definitive dimensions are calculated as in Table 15.

Table 15. Tabulated calculation of the definitive reactor dimensions. The results of the calculation are printed in boldface. At a unit width of 2 * 8.00 m, the reactor length is 18 m. The resulting length and width are those with the minimum difference between length and width. The definitive surface area of 288 m^2 is 2.4 % more than actually needed. This will represent no problem.

number	length	definitive length	width	surface area	difference L and W	difference with AA
-	m	m	m	m^2	m	%
1	35	36	8	288	28	2.4
2	**18**	**18**	**16**	**288**	**2**	**2.4**
3	12	12	24	288	12	2.4
4	9	8	32	256	24	-9.0
5	7	8	40	320	32	13.8
6	6	6	48	288	42	2.4
7	5	6	56	336	50	19.5
8	4	4	64	256	60	-9.0

If the difference between the definitive surface area and the approximate area is quite large, it is most convenient to decrease the feed inlet density somewhat, to arrive at more suitable dimensions.

9.3.4 Feed inlet boxes

The number of feed inlet boxes is calculated quite simply. The calculation is presented in Table 16.

Table 16. Tabulated calculation of the number of feed inlet boxes. The calculation leading to the definitive number is printed in boldface. The number of feed inlet points to satisfy the demand on the servicing area being lower than 50 m^2 is 12, yielding 48 m^2. This results in 6.0 feed inlet boxes, which is a whole number and which is also the lowest possible number. Therefore it is the definitive number.

number	area	area	approx. no. boxes	definitive no. boxes
-	m^2	m^2	-	-
2	8	8	36.0	36
4	16	16	18.0	18
6	24	24	12.0	12
8	32	32	9.0	9
9	36	36	8.0	8
10	40	40	7.2	not OK[2]
12	**48**	**48**	**6.0**	**6**
14	56	not OK[1]	5.1	not OK[1]
15	60	not OK[1]	4.8	not OK[1]

1: larger than maximum area for feed inlet box
2: not leading to a whole (integer) number of boxes

9.3.5 Effluent gutters

The calculations regarding the effluent gutters are as follows.
The number of V-notches per meter is set at 4. There will be effluent gutters on both sides of the gas collectors. The angle of the V-notches can be set at 45°. The total length of the effluent gutters is 8 (number of gas collector * 2) * length = 8 * 18 = 144 m. The water height in the V-notches is 3.0 cm at maximum flow, and 2.4 cm at average flow. So, with an extra depth of 5 cm, the V-notches will be 8 cm deep.
The length of an individual gutter is 18 m. The flow per gutter will be 56.3 m^3/h at maximum flow. During peak flow the flow may be 1.5 timewes as high, so the gutter should be able to contain this flow. The the calculated water depth, 1 cm may be added for safety purposes. With a tabulated calculation as in Table 17, the optimum effluent gutter dimensions can be calculated. Please note that an effluent gutter always should be at least 15 cm wide, to facilitate maintenance.

Table 17. Tabulated calculation of the dimensions of the effluent gutters. The calculation leading to the definitive number is printed in boldface. The definitive dimensions are those with the largest width of the ones with the lowest perimeter.

gutter width	water depth	total depth	gutter perimeter
cm	cm	cm	cm
15	20.9	30	75
20	17.2	30	80
25	**14.8**	**25**	**75**
30	13.1	25	80
35	11.9	25	85
40	10.8	20	80
45	10.0	20	85

9.3.6 Sludge drying beds

For the design of the sludge drying beds, the sludge production has to be estimated. From the effluent estimates, the amount of sludge to be removed can be calculated. If the sludge drying bed capacity is known (which depends very strongly on regional conditions), the sludge bed surface area can be calculated.

The sludge production has been calculated as 283 mg/l, equalling 1275 kg/day. When the effluent TSS is estimated at some 100 mg/l, the amount of sludge to be removed will be 1275 - (250 * 0.100 * 24) = 675 kg/day. At the sludge bed solids concentration of 80 kg TSS/m^3, this will equal 8.4 m^3 of sludge per day.

With a sludge bed loading of 1.43 kg $TSS.m^{-2}.day^{-1}$, which has been applied in Cali, Colombia, the drying bed surface area would amount to 473 m^2. In India, sludge drying bed loading can be applied that are around twice as high as the values found in Columbia.

Sludge bed loadings are strongly dependent on climatological conditions. Therefore, it is necessary to have an indication of the amount of rainfall, and solar irradiation. If these are not readily available, 0.7 kg $TSS.m^{-2}.d^{-1}$ is advised to use as a design figure.

PART 3

OPERATION AND MAINTENANCE

CONTENTS page

10. MANAGEMENT OF PLANT OPERATION AND MAINTENANCE

10.1 Introduction

The objectives of a wastewater treatment plant are to reduce the pollution load of wastewater and to dispose the plant effluent and any by-products such as separated solids, excess sludge and gas. These objectives have to be gained within the restraints imposed by the administrator of the plant.
Governmental legislation puts demands on the quality of the effluent, the handling and disposal of side-products and further environmental impact of the treatment works. The administrator in its turn faces budget limitations and will allocate a budget for investments and operational costs. The administrator is responsible for the safety and well-being of employees at the treatment site.
A wastewater treatment facility can be effectively run only within a well-managed, smoothly operating entity.

The three main activities in plant control are operation, maintenance and data collection.

- Operation concerns the day to day activities required to maintain the quality of the treatment process.
- Maintenance concern the activities to keep the plant facilities in good shape. In this sense, maintenance refer to preventive maintenance.
- The data collection concerns the collection of data on the treatment performance of the plant.

The management of these three functions is only possible with an adequate flow of information on all relevant aspects of plant control. Therefore, a proper and simple reporting system is essential for an effective organization and a proper operation of the plant. It is the plant managers responsibility to set up, claim, process and translate this information into adjustments in operation and maintenance schemes, immediate maintenance actions and process modifications. It is of great importance that plant personnel is well-trained in collecting and reporting information and it is the task of the plant manager to organize this training. It may be clear that a motivating attitude of the plant manager towards his personnel is essential to obtain a maximum effectiveness of his management and information transfer.

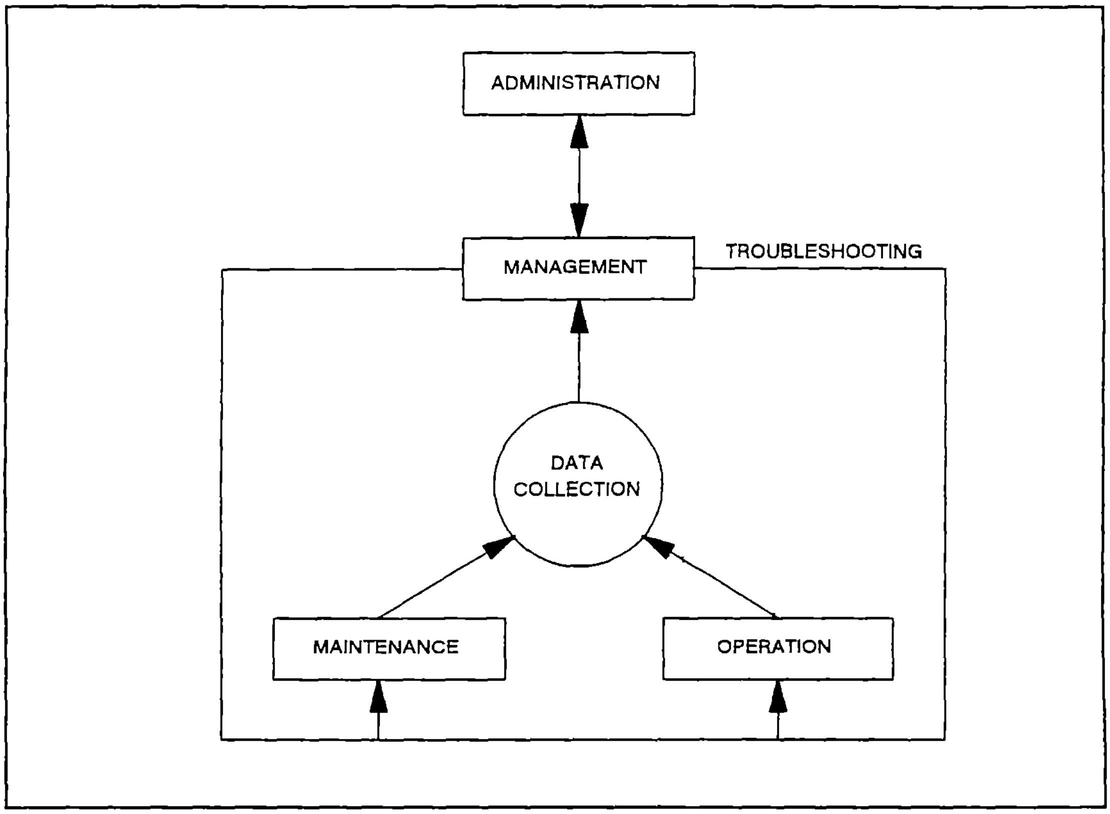

Figure 23. Diagram of the interrelations between the different activities in a wastewater treatment plant.

The degree of assigning the distinguished activities to specific task-forces largely depends on the size and complexity of the plant. In small plants most tasks will be performed by one or several workers and a direct relation will exist between the plant manager and the operator(s); either the plant manager and the operator are one person or a single plant manager will be in charge of several small plants with their own operators. In these plants a single operator will be working at the plant, leaving the plant unattended during the night and weekends.
The larger the plant, the more personnel will be required for its operation. At large plants operators, maintenance staff and laboratory personnel will be required and the communication between the labourers and the plant management will be more indirect. The plant manager is responsible for the overall operation of the treatment plant. The operator is responsible for the day-to-day operation and can implement changes in process conditions. Operators, furthermore, indicate the need for specific maintenance operations. In large plants operators will work in shifts, while the operators will be assigned to specific tasks.
In a small plant maintenance staff consists of personnel that carries out regular maintenance activities. To carry out specialized maintenance on pumps and other equipment external personnel has to be hired. The larger the plant, the more maintenance activities will be carried out by plant personnel, for which a higher degree of specialization is required.

The decisions on operation and maintenance activities are based on data collected at the plant site. These data will vary between information on pumping hours to

physico-chemical analyses on influent, effluent and sludge. For small plants, an expensive and extensive data-collection scheme cannot be justified on grounds of costs per treatment unit. For larger plants more data can be made available for adequate control of the processes. A schematic arrangement of the interrelations between the various activities in a wastewater treatment plant are given in Figure 23.

10.2 Plant management

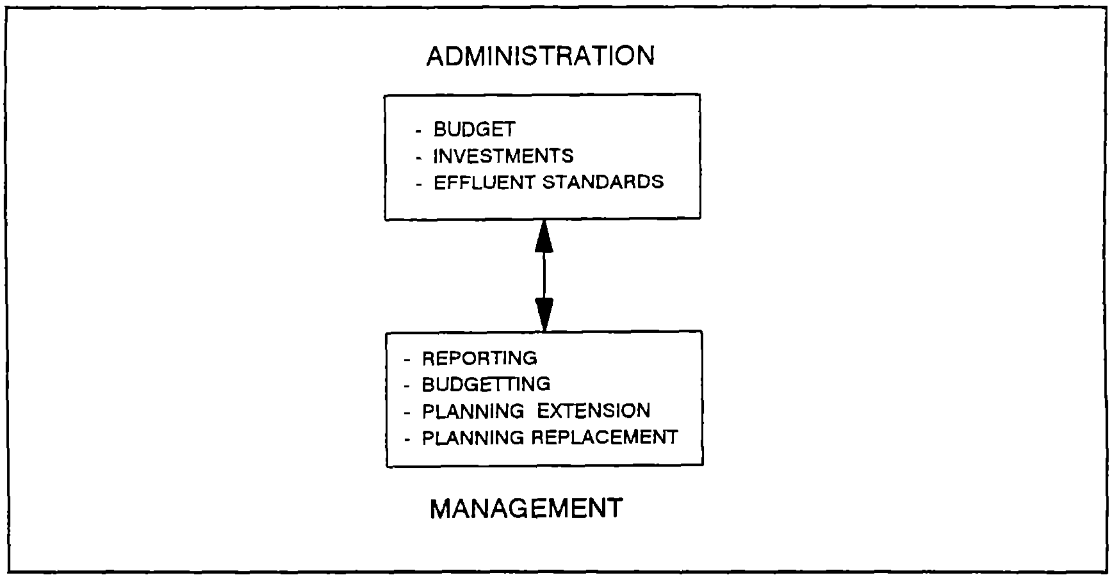

Figure 24. Activities and relations of the plant management with the administration.

In Figure 24 the activities and relations of the plant management with the administration are illustrated.The basic functions of plant-management are identical for all wastewater treatment systems but vary in scope depending on the systems' complexity, its condition, its size and its location. The management functions include the evaluation of plant performance, the planning, organizing, staffing, training control, budgeting and reporting to the administration. The effectiveness of plant management relies on the information received from the personnel with respect to plant-performance and to the executed labour. The basic information-flow can be directed through standard reports, in the design of which the plant manager plays an important role. It has been found that operation and maintenance-staff consider reporting a difficult task and easy-to-handle standard forms can be of use to guarantee an adequate transfer of information.

The reporting on plant performance includes:
- treatment parameters (influent, effluent), flow-rates etc.,
- utilities, such as energy-consumption and hours of operation of electro/mechanical equipment,
- reports of operation and maintenance activities, both planned and occasional,
- records of production of screening material, grit, sludge and on their discharge,
- compilation of spare-parts, supplies etc.,
- time-spending records of staff personnel.

An often underestimated source of information is the experience of plant personnel. Through regular staff-meeting, additional information can be obtained on performance of equipment, friction points in operation and maintenance etc. An effective and intensive relation between the plant manager and the personnel is indispensable to collect and utilize the information adequately.

The plant manager translates the information into working-plans for the plant personnel. His main tool is the planning-scheme of operation and maintenance activities which he can adapt according to the actual state of the plant. In this respect a clear distinction has to be made between normal operation and maintenance activities and trouble-shooting.

a. Normal operation and maintenance activities are planned. The planning is adapted to the experiences. This implicates that every plant, regardless its size, must have an operation and maintenance program.
b. Trouble-shooting refers to activities that have to be carried out in addition to the planned program to react on calamities or plant failure. Whereas normal operation and maintenance mainly requires technical and management skills, for trouble-shooting creativity and basic technical and process knowledge is necessary.

A second task of the plant manager is to process the information on treatment performance, energy-consumption, production of side-products and operation and maintenance efforts. The processed data are used to report to the responsible authorities and to forecast life-time of equipment, future maintenance activities and tendencies in treatment performance.

10.3 Staffing

The time-spending of a plant manager depends on the size and complexity of the plant. In small plants the function of plant operator and manager will be concentrated in one person, or one plant manager supervises more than one treatment plant. In larger plants more separate tasks will be distinguished and the input of the plant manager will be more specific. As a general indication it is estimated that the manpower input for the plant manager will be as in Table 18.

The staffing of operators not only depends of the size of the plant, but also on its technical complexity. Consequently, the technical level of the plant operators depends on the complexity of the plant as well. A small plant with little mechanical equipment can be operated by one operator who takes decision on the basis of fixed criteria for plant operation. Such a plant will not require 24-hour attention. The operator will be present at normal working hours during the week and leave the plant unattended during the night and in weekend.
In larger treatment plants the technical level of the operators has to be higher, so that they can take decisions autonomously in the absence of the plant manager. Such plants require 24-hour attention. In large plants operators will have to be specialized in different aspects of the treatment process, for instance water treatment, sludge handling and gas handling. The personnel requirement for plant operation is roughly indicated in Table 18.

Table 18. Manpower input for management, operators and maintenance staff in UASB treatment plants as related to plant size

Plant size (P.E.)	Management (man/wk)	Operation (hr/day)		Maintenance (hr/day)	
	man/wk	manual	mechanized	manual	mechanized
< 10,000	0.2	1 x 8	1 x 8	1 x 8	1 x 8
10,000 - 30,000	0.5	1 x 8	1 x 24	4 x 8	2 x 8
30,000 - 50,000	0.5	1 x 24	2 x 24	7 x 8	3 x 8
> 50,000	1.0	> 2 x 24	> 3 x 24	> 10 x 8	> 4 x 8

Maintenance staff can be subdivided in personnel for daily maintenance activities and more specialized personnel such as electricians and mechanics. Depending on the size of the plant the specialized personnel are contracted or incorporated into the regular staff. Also specialized personnel can be recruited to combine operation and maintenance in one post. The input of maintenance personnel largely depends on the degree of automatization of the plant.

10.4 Maintenance

Starting-point in plant management is that an adequate maintenance program is a condition for a proper plant operation. Maintenance in this manual refers to preventive maintenance: a scheduled maintenance to preserve the plant components and to avoid plant failures or deficient functioning. The maintenance activities vary from regular cleaning of screens, grit chambers, inlet structures etc., to lubrication of electro-mechanical equipment and replacement of defective or worn-out parts.
A maintenance scheme has to be made for each plant, taking into account the complexity and amount of equipment. The maintenance scheme has to be adapted to experiences during operation of the plant.

A maintenance scheme indicates the need for the execution of specific tasks at specific times. A maintenance scheme includes the following items:

1. Planning and scheduling of activities;
2. Planning and scheduling of personnel;
3. Maintenance instructions and guidelines;
4. Maintenance records;
5. Stock control;
6. Budget control.

The relation between these items has been visualized in Figure 25.

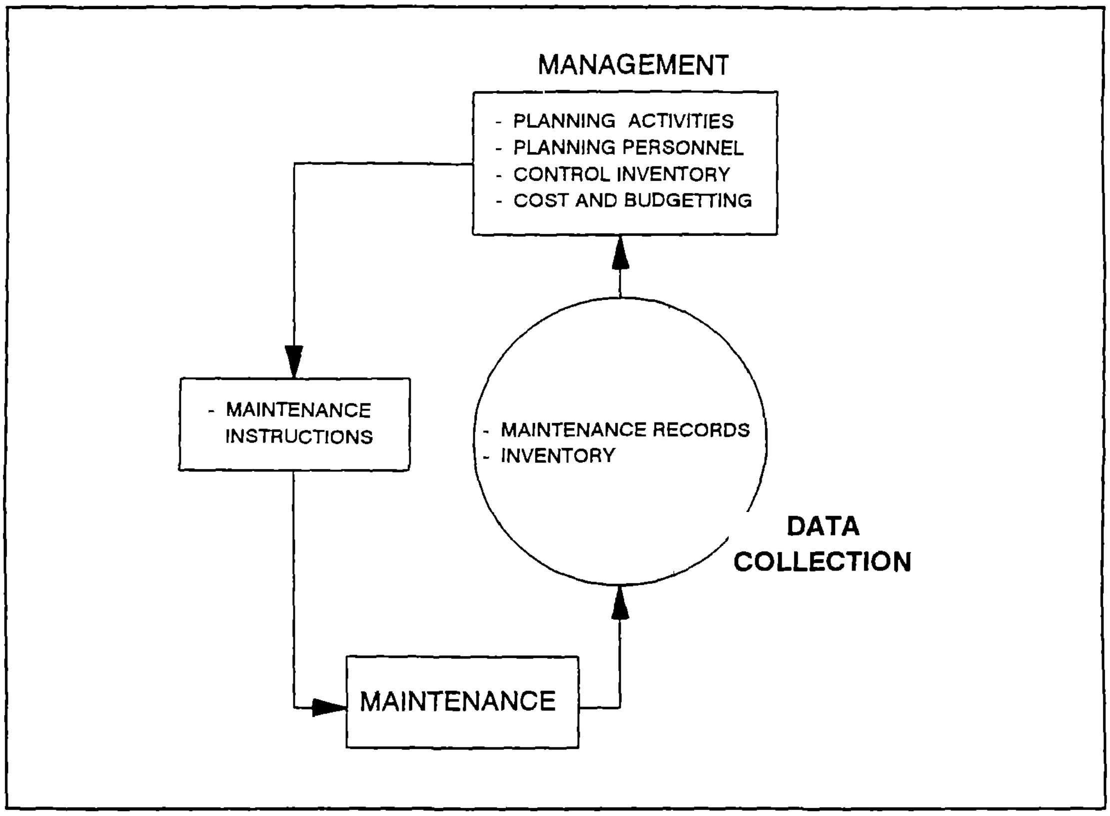

Figure 25. Relations in maintenance activities.

Planning and scheduling of activities

Maintenance schedules has to be tailor-made to the specific situation of a treatment plant. The maintenance requirements of each part of equipment and of all components of the treatment plant are included. The maintenance manuals provided by the manufacturers of plant equipment serve as a basis for the elaboration of a preventive maintenance schedule.

The scheduling chart is divided in suitable time-periods: day, week, month, etc., as directed by the workload. A scheduling-chart can be subdivided into more detailed charts, for instance by time or by day, as the complexity of the plant requires.

Planning and scheduling of maintenance personnel

The planning of personnel is closely related to the maintenance schedule. In this respect the plant size is important, because the larger the plant the more maintenance activities will be carried out by own staff personnel. Very specialized tasks on mechanical or electrical parts, however, may have to be performed by contractors. These activities have to be included in the planning scheme and should be contracted for prolonged periods, to enable the contractor to contribute in the feed-back of his experiences to the maintenance program.

The maintenance of treatment plants generally is a specific work. Much attention should be paid to on-the-job training of personnel to guarantee an optimal plant performance. Formal training courses, should be included in the activities of the maintenance staff.

Maintenance instructions

For each treatment plant an operation and maintenance manual has to be elaborated. In this manual all information is compiled on the design-principles of the plant, the technical description of mechanical equipment, piping diagrams, maintenance requirements of the plant and detailed descriptions of each operation and maintenance activity.

The plant operators receive their maintenance instructions from the plant manager, who is responsible for updating of the and maintenance manual. Based on the experiences of the plant personnel, the procedures or frequency of the maintenance activities have to be modified.

Maintenance records

A suitable way to regulate the information on maintenance activities is the use of maintenance records, in which the plant personnel describes their activities in routine lists. The maintenance records should contain information on the date, the time-spending and the nature of the maintenance activities as well as the quantity of supplies (oil, grease, bolts, nuts, paint etc.) and spare parts that were used for the execution of the job. The records can be used for tracing the cause of equipment failures and provide information for the updating of maintenance schedules. Furthermore, the records are the basis for the stock control.

Stock control

The plant should always be provided with a sufficient stock of spare parts and supplies. The stock level should be established according to the recommendations of equipment manufacturers and on the basis of experience. Furthermore the stock level should be accommodated to the time to order and deliver spare parts. The stock should be controlled, e.g. by means of a stock card system.

Budgeting

One of the key-activities of a plant manager is to control the plant budget. This is essential for an effective and efficient operation of a plant.

10.5 Operation

Operation refers to the activities that concern a proper physical, chemical and biological performance of a treatment plant. Operation is carried out in a programmed way. An important task of plant operators is to collect data on plant performance and comparison of the data with reference data. The operation is carried out on the basis of the manual. The operation- and maintenance manual has to be tailor-made.

The plant operators have to communicate with the plant manager and with the maintenance staff. Their findings form the basis for decisions on maintenance activities or modifications in plant operation. It is evident, that data collection and transfer is a vital element in managing plant operation.

The operation staff has to collect data on energy consumption, hours of operation of equipment, treated wastewater volume, production of side-products, such as screening material, grit, sludge and gas, and has to take samples to be analyzed in the laboratory.

The main task of the operation staff is to check the functioning of each component of the plant and to check the process performance. The operation staff is

responsible for the removal of screening material, grit, sludge etc. The technical and process knowledge of the operation staff should be sufficient to take corrective measures. For this it is advised to provide training courses and on-the-job training for plant operation.

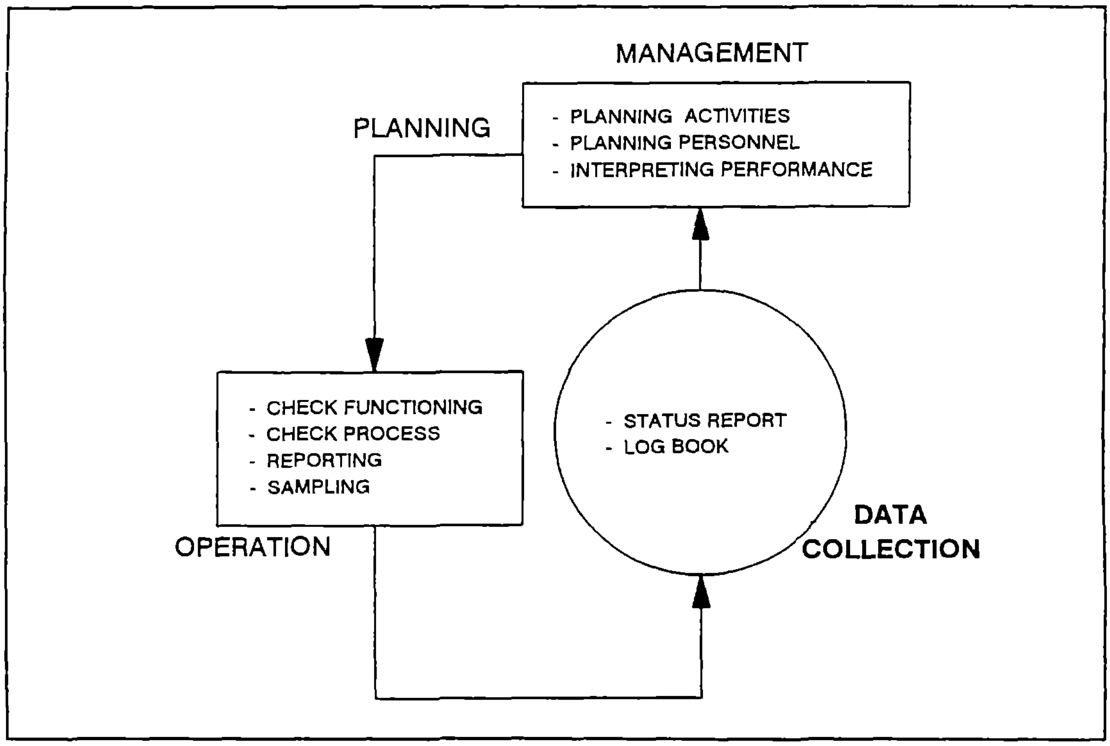

Figure 26. Relations in operation activities

10.6 Data collection

Data collection and data management are the key-elements in an effective and efficient plant management. Data collection concerns all information obtained on operation and maintenance activities, manpower input, process performance, equipment performance, consumption of energy, spare parts and supplies and production and disposal of side-products. It is essential that the flow of information is canalized as much as possible through standard forms, to be filled in on a routine basis by the plant personnel. The forms that can be used are a plant log book, status report, maintenance sheet, operation and performance sheet and inventory control.

The task of the plant manager is to evaluate the information and to use it for modifications in operation and maintenance procedures or to anticipate to changes in external conditions, such as increases in the wastewater supply.

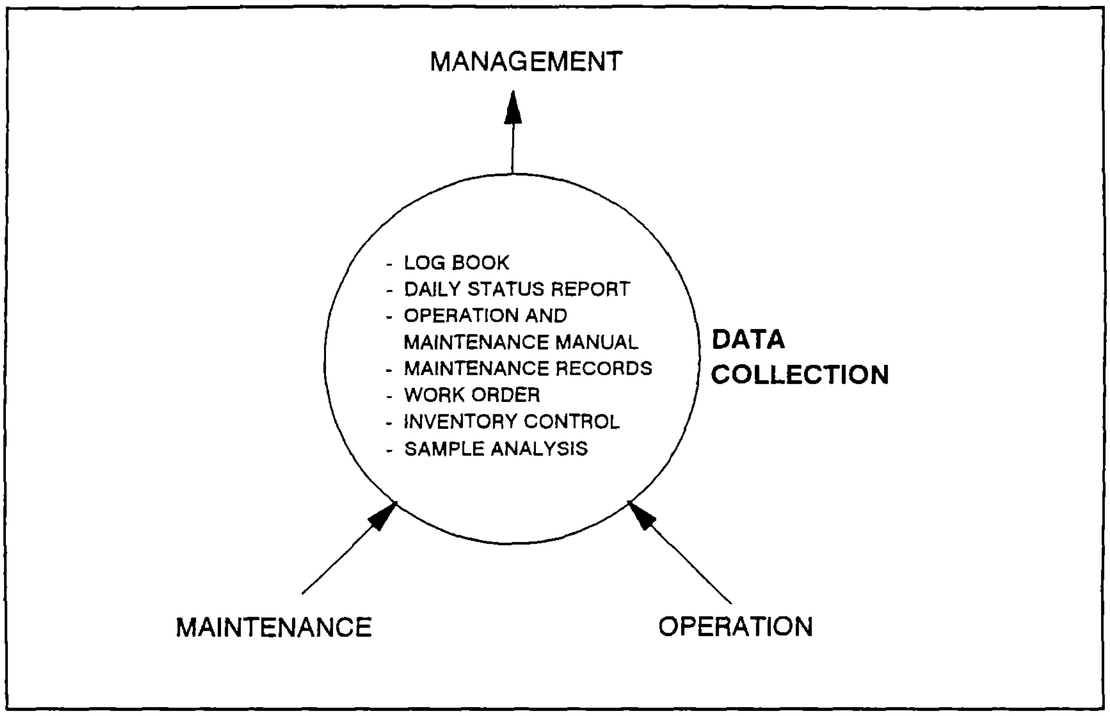

Figure 27. Relations in data collection activities

11. MAINTENANCE ACTIVITIES

11.1 Introduction

Maintenance is carried out to protect an investment, and to keep the plant in a proper condition. It concerns both maintenance of equipment and structures and the quality of the treatment process. This chapter intends to be a practical guide for the maintenance of a UASB-treatment plant. Each part of mechanical equipment has its own maintenance requirements which are generally described in a maintenance manual. The construction materials used in a plant require maintenance, that largely depend on local practice and use of materials. It is beyond the scope of this manual to give an extensive description on these details.

In this chapter the maintenance activities of a UASB-treatment plant are described in a general way. The maintenance of each key-component of a UASB-plant will be presented. A subdivision will be made between daily maintenance and preventive maintenance. Daily maintenance concerns the indispensable activities for a continuous and trouble-free performance of the plant and includes cleaning, removal of waste-products etc. Preventive maintenance includes activities to avoid plant or equipment failure by replacing worn parts in time, prolonging the life-time of components by proper preservation and lubrication etc.

11.2 Flow control structures

11.2.1 Daily maintenance

The regular maintenance of this device consists of cleaning the overflow weir and checking for obstructions in the by-pass, which might cause inundation of the plant during a storm-event. If the plant is provided with a buffer basin, the basin must be cleaned after use in order to avoid odour nuisance through rotting of accumulated solids.

11.2.2 Preventive maintenance

Adjustable weirs in the overflow-device require periodic greasing of the bolts and nuts and depending on the material, protection against corrosion. The valves to regulate the flow to the plant should be periodically greased and should be protected against corrosion.

11.3 Screening

11.3.1 Daily maintenance

Both course and fine screens have to be cleaned at least once a day. In the start-up phase of the plant particular attention should be paid to the accumulation of debris at the screens and the maintenance scheme should be elaborated accordingly. During rainfall sewage generally contains larger amounts of screening material and the frequency of cleaning should be increased accordingly.

The removed debris has to be collected in closed containers in order to prevent odours and flies. The screening material consists of poorly stabilized organic material and should be disposed regularly. The debris separated by mechanically raked screens has to be removed from the site and collected in a closed container

or disposed daily.

11.3.2 Preventive maintenance

For manually-operated screens the only type of preventive maintenance consists of the timely replacement of worn or corroded screen bars. For mechanically raked screens the lubrication of moving parts is the most important activity. Bearings of electric motors and sprockets have to be lubricated according to the manufacturers specifications. Chains will need monthly or even weekly greasing when they operate submerged.

To assure minimum break-down time, badly worn parts have to be replaced. Typical parts to be replaced in screens are chains and sprockets. A sufficient stock of these parts should be available.

11.4 Grit removal

11.4.1 Daily maintenance

Grit chambers require a regular removal of the accumulated material, firstly to assure proper hydraulic functioning and secondly, to avoid odour nuisance due to putrefaction of organic material in the grit. Slides used for flow-control or shutting-off of grit channels need regular cleaning in order to avoid damaging of the lining. Mechanical grit removal equipment does not require daily maintenance, apart from the removal and disposal of the grit, and of course, checking of proper functioning.

11.4.2 Preventive maintenance

Valves and slides have to be lubricated regularly. Mechanical grit removal equipment has to be checked on a regular basis on wear of bearings, chains, sprockets and alike and their replacement has to be carried out according to the maintenance schedule.
In large grit chambers the even distribution of the flow has to be checked and adjusted.

11.5 Wastewater pumping

11.5.1 Daily maintenance

All operable equipment is to be inspected for visible and audible indications of possible malfunctions as often as recommended by the preventive maintenance procedures in the operation and maintenance instructions for the various pumps. Typical for the things to look for and listen to are:

1 Observe operation of all moving mechanisms to determine if they are aligned properly., moving at constant speeds, and producing no unusual vibrations. Feel bearings and motor to detect overheating.

2 Listen to all moving mechanisms for normal operational sounds(screeches should indicate lack of lubrication; thumps should indicate broken or loose components).

3 Look for leaking or dripping water to determine of cracks or other openings have developed.

11.5.2 Preventive maintenance

Lubrication

Pumps and their associated motors and drives are to be lubricated in accordance with the manufacturer's recommendations. This means that specific lubricants are to be applied to specific points at specific time intervals. The pumping units should be lubricated during shutdown, not while in operation, unless otherwise specified by the manufacturer. If oil is injected into the housing while the pump shaft is rotating, the rotary motion of the ball bearings will pick up and retain a considerable amount of the oil. When the unit comes to rest, the oil will drain down, resulting in an overflow around the shaft or from the oil cup. When oil is being changed, the bearings should be cleaned and examined for possible wear.

Packing

Packing is to be removed at the recommended intervals of operations time to prevent scoring of the shaft or shaft sleeve. To renew the packing, the packing nuts, clamps, and glands are removed in accordance with the manufacturer's instructions (use of split glands will facilitate removal). Before the packing is removed, the number of packing rings in front and in back of the lantern ring are to be noted. After removal of the packing and the water seal lantern ring, the packing box and the shaft are cleaned thoroughly. The new packing must be of the same size provided by the manufacturer and must be installed properly, with correct gland alignment.

Each packing ring is cut to the proper length (ends must meet around the shaft, but not overlap). Each ring is dipped in oil or otherwise lubricated, as specified by the manufacturer, before it is placed in the packing box. Only one ring is to be inserted at a time. Hand pressure should be sufficient to push the layers of packing into place. Succeeding rings of packing are placed in the stuffing box so that the joints are staggered.

The reinstalled glands then may be taken up lightly by a slight tightening of the adjustment nut to form the packing in the packing box. The gland followers should enter the packing box at least 0.13 in. (3 mm) to prevent blocking of the glands, but they should not touch the shaft.

In water seal units, leakage from the packing box is necessary to keep the packing cool and in good condition. The packing boxes are inspected for leakage of sealing water while the pump is running. If leaking is found to be excessive or insufficient, the glands are to be tightened or loosened as required. After adjustment of the packing glands, the shaft should rotate freely when turned by hand.

Liquid level controls

Systematic inspections are to be made of all liquid level controls, which include the float, pressure and electrode level sensors, and the switches actuated by them. Routine checks are to be made of the actual water levels at which the level controls cut in and cut out.

Much of the level control pumping problems encountered will be caused by a loss of signal or inaccurate signals. This may be traced to a variety of reasons such as coating on probes, float hang-ups, leaks in bladders, and fouling in bubblers.

11.6 UASB reactor

11.6.1 Daily maintenance

Hardware

The daily maintenance of the hardware of the UASB-reactor consists mainly of cleaning operations. The influent distribution system consists of a series of flow divisions over V-notches. These notches can easily obstruct, which cause an unequal flow distribution. The influent distribution system, therefore, has to be cleaned daily.
The effluent gutters are provided with V-notches, which have to be cleaned daily to avoid growth of algae and to avoid obstruction of the V-notches.
Occasionally the floating layer that is normally present at the water surface of reactors provided with side baffles can show an excessive growth. When the floating layer exceeds a thickness of around 5 cm, it should be removed. The material cannot be re-introduced into the reactor as it will flotate again.

Feed inlet
The feed inlet system is prone to clogging. This can be seen quite easily by watching the flow n the distribution boxes. If the flow in the distribution boxes in not even over the outlets it is quite likely that one of the feed inlet pipes is clogged. Clogging will yield an uneven distribution of the wastewater over the bottom of the reactor, and will lead to an inefficient use of the sludge, because part of the sludge is bypassed. Therefore, check of the distribution boxes should be made daily.

Effluent gutters
The effluent gutters are essential for the removal of the effluent of the reactors. If the gutters are not level, and the water in the V-notches is not at the same level in all of the notches in one gutter, or in different gutters, then the flow will be uneven. This will lead to more solids washout then necessary. Similarly, blocking of the V-notches of the effluent gutters will lead to an uneven flow over the effluent gutters. The effluent gutters have to be inspected on a regular basis (once per two days), to remove any material blocking an even outflow over the V-notches in the gutters. The level of the gutters has to be inspected on a regular basis also, and if uneven flow is seen, adjustment of the level of the gutters should be made.

Regular maintenance of the effluent gutter consists of the following activities. Cleaning is done from the top of the reactor, during which the V-notches are cleaned with a broom, and sludge from the effluent gutters is removed with a brush or with a water jet. Also a floating layer on top of the water surface of the reactors should be removed.

Gas collectors
The gas collectors should be checked for leakage. As leakage is easily seen, this can be done on a regular basis, while checking the effluent gutters. If the gas collectors are leaking, they should be repaired as soon as possible.
Regular maintenance will include:

1 Open hatch boxes and remove floating layer inside the gas collectors.
2 Check gas collectors for gas leaking and repair when necessary.

Biological process
Daily maintenance of the biological processes in the UASB reactors follows logically from the preceding paragraphs. Effluent data should be observed, and the solids retention time should be under close control. Data should be obtained on the

functioning of the plant, and checked. If the wastewater flow, the biogas production, and the effluent concentrations are normal, no actions should be taken. The reader is referred to § 8.6.1. and § 13.1 if this is not the case.

11.6.2 Preventive maintenance

A carefully elaborated and executed maintenance scheme has to be maintained for the UASB-reactor. The influent distribution boxes and the effluent gutters are components that require special care. The constantly changing contact with water and air results in a highly corrosive environment. Only very resistant materials that are carefully maintained and protected will have a sufficient life-time.

Valves of the influent distribution system and the sludge discharge pipes have to be checked regularly on correct functioning and have to be greased according to the specifications.

The floating material inside the gas chambers has to be removed at least every two years. After the cleaning operation attention should be paid to a gaslight closing of the manholes.

At least every year the correct levelling of effluent gutters has to be checked. The effluent gutters should be placed horizontally and all separate gutters should be at the same level. During this check the adjustment screws have to be lubricated.

The reactor has to be emptied completely every 5 years, or more frequently when obstructions of the feed inlet tubes often occur. In the maintenance period the accumulated inert material at the bottom of the reactor should be removed. After a complete cleaning an intensive general inspection should be carried out.

- The correct fixation and the quality of each feed inlet tube should be checked. If necessary deteriorated parts should be replaced.
- The quality of the parts of the GLS-separator and the correct position of the plates should be checked with emphasis on a sufficient overlap and aperture to the settling compartment. If necessary, deteriorated parts should be replaced or repaired adequately.
- The inside of concrete gas chambers should be checked for cracks. In that case a protective lining should be applied.
- The walls of concrete tanks should be checked for concrete corrosion. When a protective coating had been applied, it should be checked for its quality and when necessary it should be repaired. When corrosion of concrete walls is observed, the walls should be cleaned and provided with a coating, for instance epoxy-coating.

11.7 Gas collection

11.7.1 Daily maintenance

None.

11.7.2 Preventive maintenance

It has to be reminded that the biogas constitutes a potential hazard due to

- explosion risk when a gas-air mixture is formed;
- fire risk, as it is highly combustible;
- odour nuisance, due to the presence of H_2S.

The escape of gas at unintended places should be avoided as much as possible and for this reason a strict execution of the maintenance program is necessary.

It is of extreme importance for the proper functioning of the gas collection system that the condense trap and the pressure regulating system are kept in perfect working conditions. The accumulation of condensate in the trap will cause excessive pressure on the system, so that gas can escape into the atmosphere through the pressure relief valve. This will result in odour nuisance.

A malfunctioning pressure relief valve may cause structural damage to the UASB-reactor, as the gas chamber has not been designed for high internal pressures. Gas chambers may start to float or the plates of the gas chamber may be blown up. The occurrence of under-pressure in the system during the emptying of the reactor may cause the collapse of the gas chambers when the vacuum-relief valve is not properly operating. Both the pressure relief valve and the vacuum relief valve have to be checked for correct functioning every 6 months.

Gasmeters are almost free of maintenance, but condensate can accumulate. The condensate should be removed every 6 months, during which exposure of the inside of the meter to the air should be avoided. Severe corrosion will not take place as long as the environment remains anaerobic.

Inside the gas chambers a floating layer will accumulate. This material has to be removed every 2 years in order to avoid problems with the gas release and the consequent build-up of pressure inside the system. This, inevitably, will cause damage to the gas chambers. During the cleaning operation it has to be reminded that methane is being formed continuously in the reactor and that in the gas chambers and around the manholes a serious explosion risk exists. Plant personnel in charge for the removal of the floating layer should be equipped with respiration equipment and an explosion-risk meter should be used at the site.
Gas leakages can be formed in concrete gas domes due to cracking of the concrete. In this event a proper lining has to be applied inside the gas chamber.

11.8 Sludge dewatering

11.8.1 Daily maintenance

In general excess sludge from UASB-reactor will be conducted to sludge dewatering facilities by pumping. After sludge discharge from the reactor the pumping pit should be thoroughly cleaned in order to avoid odour problems, problems with fly breeding and formation of sludge cakes in the pit. The sludge tubing should be washed through, for instance with effluent, to avoid clogging of pumps and tubes.

The daily maintenance of sludge dewatering facilities largely depends on the method that is employed. When mechanical dewatering equipment is used, the equipment has been provided with an extensive operation and maintenance manual that should be followed to assure proper functioning of the equipment.

Sludge drying beds are very useful to dewater sludge from UASB-reactors. Drying beds can be emptied by hand or mechanically. In either case attention should be paid to the correct cleaning of the sand bed in order to avoid clogging problems of the filter medium or stagnant zones in the filter.

11.8.2 Preventive maintenance

For maintenance on sludge pumps the reader is referred to Chapter , and to the manufacturer's instructions on the pumps. When clogging of the filter medium occurs, periodic replacement of the top layer of the sand bed should be included in the maintenance scheme. In case of clogged underdrains, flushing of the drains has to be programmed. Mechanical dewatering equipment should be maintained according to the instructions provided by the manufacturer.

12. OPERATION ACTIVITIES

12.1 Introduction

The operation of a sewage treatment plant consists of activities necessary for a correct performance of the treatment plant. Activities concerning plant operation are:
- monitoring of the process performance,
- collection of data on hardware performance, etc.,
- collection of influent, effluent and sludge samples,
- control of correct functioning of the treatment plant and its components.

An important task of the operator is to signalize malfunctioning of equipment and process units and execute corrective measures, when possible, or inform the plant manager, who will take the necessary steps to solve the problem. In this sense the plant operator is responsible for the proper functioning of the plant and forms a direct link between the plant and the plant manager. The plant manager schedules maintenance activities and executes process modifications on the basis of the information he receives from the plant operator.

The assignment of specific tasks to different persons strongly depends on the size of the treatment plant. At small plants it is likely that the plant manager and plant operator are the same person. At large plants the plant manager will manage a crew of plant operators and maintenance staff.

Plant operation not only consists of standard operation activities, but also concerns special actions, such as process start-up, shut-down of the plant or part of the plant and operation during plant stand-still.

12.2 Flow control structures

12.2.1 Start-up

The task of the operator is to adjust the flow to the plant according to the required loading rates and to check this daily. The operator should check the correct functioning of the by-pass during maximum- and minimum flow-rates and during peak flow conditions.

The principal operation parameters in the wastewater supply system are the flow-rate and the wastewater quality. It is assumed that the operation and maintenance of wastewater collection systems is not the competence of the treatment plant manager.

12.2.2 Normal operation

The flow-rate should preferentially be recorded continuously. In this manner peak-flows to the plant can be detected and the normal variations in the sewage flow can be monitored. This offers the opportunity of optimum adjustment of the pumping regime and plant operation schemes. Furthermore trends in sewage flow become manifest and plant extension measures can be prepared.

At small plants a continuous flow measurement and registration would lead to unacceptably high costs. At these plants the sewage flow can be estimated roughly from the working hours of the pumps and the pump flow-rates. Anyhow, flow measurements should be carried out with regular intervals, using the flow

measuring device (parshall-flume, overflow-weirs) that are installed in every treatment plant. These measurements have to be executed at least every 6 months and over a period of at least 24 hours.
The influent and the effluent have to be sampled and analyzed regularly on relevant plant performance parameters. In plants with more treatment steps, for instance with post-treatment, it is desirable to sample and analyze the effluent of each treatment step.
The sampling and the operation of sampling equipment is the responsibility of the plant operator. The plant operator is familiar with the method used for sample collection and the factors influencing in the representativity of the samples. In this respect a good communication between the operators and the laboratory personnel is essential.
The frequency of sampling depends on the size of the plant. At small plants it is sufficient to take one 24-hours composed sample every month. At a large plant composed samples have to be taken daily and analyzed on relevant parameters.

12.2.3 Operational problems

At shut-down of the plant the operator has to check whether the by-pass is functioning correctly. Otherwise, sewage accumulates in the sewer system and may cause flooding in the streets.

12.3 Wastewater pumping

12.3.1 Start-up

Before starting a "new" centrifugal pump, inspection of the bearings for proper lubrication is made. If necessary. the mechanical seals are greased. When possible, the shaft is turned initially by hand to assure that it will rotate freely. The alignment of coupling shafts should be assured. [If the unit is belt driven] sheave alignment and belt tension are checked to assure conformance to the manufacturer's specifications.

Thermal overload elements in the motor starters are to be checked and reset if necessary. The motor is started momentarily to check that it turns the pump in the direction indicated by the directional arrow on the pump.

12.3.2 Pump shutdown

If a centrifugal pump is to be shut down for an extended period of time, the valves on the suction, discharge, ring flushing water, and water seal lines should be shut tightly. The pump then is drained by removing the drain plug and opening the air vent valve. Draining the pump to remove sludge and other debris eliminates the possibility of gas building up to pressures high enough to rupture the pump casing.

In pumping systems incorporating automatic discharge valve opening and closing, the proper operation of limit switches, vacuum system, seal water system, and wearing ring flushing water system should be checked during the pump shutdown period.

12.3.3 Pump control

The control equipment of the pumps consists of water level sensors. The water level sensors are used to respond to a changing water level or pressure in the pump suction to turn pumps on or off as required by the control program. The program is adjustable so that the on-off sequence may be modified based on experience.

12.3.4 Pump protection

wastewater pumping units require protection from abrasive materials and objects that may cause damage internally or obstruct the flow of the suction lines. For this reason, screening and grit removal facilities usually are used ahead of the pumps when they are used for raw wastewater.

If sand accumulates in the wet well, it should be removed to prevent it from entering the pumps. If sand is allowed to enter the pumps, maintenance problems will follow. Pumped sand may also enter the stuffing box packing, damaging the packing and pump shaft sleeve, unless effective water seals are provided. On submerged pumps, the lower sleeve bearings may wear out within a few weeks. Because most damage to pumping units is caused by abrasive and stringy material in the wastewater

12.3.5 Grease control

If grease is allowed to accumulate on the walls of the wet well, lange chunks of grease eventually break loose and disrupt operations by clogging the pump suction line or the pump itself. Suspended grease concentration may also prevent the pump liquid level controls from operating properly within the float guide chamber or cage. Grease accumulations on the walls may be controlled by frequent cleaning of the wet well with a high-pressure water hose or by scraping. If necessary, removal of grease from the water surface may be accomplished by dewatering the wet well, then scraping the grease from the floor. Dewatering should be done slowly, however, to prevent the grease from entering and clogging the pump.

12.4 Operational problems

Operational problems can be divided into two categories: pumping equipment failure and control system failure. To achieve maximum operation of the equipment used, the manufacturer's operation and maintenance manuals for each specific pump type should be read and understood.

Typical of equipment and control problems occurring in pumping are those shown in the list below. Not included are basic faults as tripped circuit breakers and plant power failures. Also not included are those items normally checked and corrected during the performance of preventive maintenance tasks, such as loose wires and dirty or corroded contacts.

There are a number of miscellaneous items that were considered at the time the pumps were selected and specified that are to be continuously reconsidered as the pump is operated. Among them are:

1 *Vibration.* A measurable limit on vibration may have been specified. This should be checked periodically.

2 *Noise.* Pumps ordinarily are specified to operate quietly without excessive noise. Some consideration should be given to developing a workable means of identifying excessive noise during operation.

3 *Bearings.* The type, design, and lubrication of all bearings should be known and receive the required attention.

4 *Wearing ring.* Generally, wearing ring clearance should be sufficient to permit operation without rubbing and to avoid a rapid drop in efficiency after a short period of operation.

5 *Seals and packings.* Operation personnel should be familiar with and suggest modifications required in accessibility and in the materials used for packings and seals.

6 *Assembling and dismantling.* All facets of the design and arrangement of pumping units should be understood so that required dismantling and reassembly for inspection and maintenance operations may be performed with a minimum of inconvenience.

7 *Replacement parts.* A reasonably adequate supply of replacement pars should have been furnished with the pumping equipment. These are also to be maintained in good condition and available when needed.

In Table 19 a number of problems are presented, with their possible causes and appropriate remedies.

Table 19. Pumping problems, causes and remedies.

SYMPTOM	CAUSE AND REMEDY
Pump inoperative, no motor current drawn	Defective control circuit. Using meter, check starting, stopping, and switching circuits and replace as necessary.
	If bubbler type controls are used and the switching circuit is normal, check air compressor; if defective, switch to standby unit.
	Defective motor. Turn motor control to OFF-LOCK-OUT and replace motor.
Pump inoperative. Motor runs at no-load current.	Broken coupling. Turn motor to OFF and replace coupling.
Pump operative, but at reduced discharge.	Pump air-bound. Prime according to instructions. In pumps with submerged suctions, check air-bleed pipe from high point of pump volute to wet well to make sure the bleed pipe is not clogged
	Partially clogged impeller. Turn motor control to OFF-LOCK-OUT, and isolate pump by closing suction and discharge line valves, remove inspection hand hole, and clear obstruction.
	Air leaks in suction line or packing box. Tighten seals or replace packing as required.
	Pump drawing air from wet well through suction line Set low level cut-off point of pump higher by readjusting float switches.
	Discharge check calve stuck partially open. Turn motor control to OFF-LOCK-OUT, isolate discharge line, and clean, repair, or replace check valve.
	Damaged impeller. Turn motor control to OFF-LOCK-OUT, isolate pump by closing suction line valve, remove suction line, disassemble pump as required to replace impeller.
	Water seal plugged. Turn motor control to OFF-LOCK-OUT, and disassemble pump as required to replace clear obstruction.
	Wearing rings. Check to determine whether clearance is excessive.
Excessive power consumption	Pump is short-cycling (discharge valve stuck open, draining force main back into wet well). Turn motor control to OFF-LOCK-OUT, isolate discharge line, and clean or replace check valve.
	Partially clogged pump. Turn motor control to OFF-LOCK-OUT, and isolate pump by closing suction line valve, remove suction line, and clear obstruction.
	Improper or worn impeller. Replace impeller.
	Pump running at higher than proper speed. If belt driven, check pulleys and change if necessary. If the motor is new, check proper speed.
	Operating at lower head than designed.
Noisy pump.	Incomplete priming. Prime according to instructions.
	Inlet clogged. Turn motor control to OFF-LOCK-OUT, and clear as required.
	Worn impeller. Turn motor control to OFF-LOCK-OUT, isolate pump by inlet and discharge lines, and disassemble as required to replace impeller.
	Pump drawing air from wet well through suction line. Set low level cut-off point of pump higher by readjusting float switch.
	Cavitation occurring at eye of pump impeller because suction lift is too high. Reset low-level pump cutoff by readjusting float switch.
	Extension shafting for vertical pumps with ground-level-mounted motors is out of alignment. Check shafting and repair as required.

12.5 Screens

12.5.1 Start-up

At the actual start-up of the plant the production-rate of screening material has to be determined. Based on the production the maintenance-schedule of manual raking as well as the frequency and speed of mechanical raking has to be established. During start-up the plant operator has to check the accumulation of screening material several times a day and adjust the raking frequency.

12.5.2 Normal operation

During normal operation the operator has to check the accumulation of debris and be aware of visual and audible signs, indicating malfunctioning of the rakes and damages of the screens. When mechanical rakes are not in operation upon checking, they should be started manually in order to check their performance. The operator has to estimate the daily production of debris.

12.5.3 Shut-down and standstill

At shut-down of the plant all accumulated debris in the screens section have to be removed in order to avoid odours and fly-breeding. The debris should be disposed of immediately.
During prolonged periods of standstill the submerged parts have to be protected against corrosion by painting or greasing. Moving parts have to be greased and to be moved weekly to avoid sticking.

12.5.4 Operational problems

Problems may occur with unusual operating conditions (sudden loads of debris that clog or physically jam the screening equipment), equipment breakdown and control failure.

Sudden large loads of debris may jam the raking equipment. If the automatic rake is not operative the mechanism probably is jammed. Then operation should be switched over to the manually operated screen. If the motor is running, but the rake is inoperative, some mechanical part is broken. Turn off the motor, and check the equipment.

12.6 Grit chambers

12.6.1 Start-up

At start-up the equal flow-division over the area of the grit chambers has to be adjusted. In channel-type chambers this is not necessary. The cleaning cycle of manually operated grit chambers has to be determined by regular checking. The procedures have to be described in the operation and maintenance manual.
The operation of mechanically operated grit chambers has to be adjusted to the actual production of grit.

12.6.2 Normal operation

The operation of grit chambers consists of checking the normal functioning of mechanical cleaning devices. For manually cleaned grit chambers the quantity of sludge accumulated in the chambers has to be checked and the regular maintenance schedule has to be adapted to changes in the sludge accumulation.
The operator has to measure and record or estimate the quantity of grit that is produced. The operator has to check the flow velocity in the channels to avoid excessive sedimentation of organic material. For this reason he has to inspect the quality of the grit.
Gas production in the grit chambers has to be looked at and the frequency of cleaning has to be changed when this occurs. To avoid odour nuisance, the grit chambers have be cleaned at least every 2 - 3 days.

12.6.3 Shut-down and standstill

At shut-down of the plant the grit chambers have to be emptied and the removed grit should be disposed of. Afterwards the grit chambers are cleaned. Mechanical equipment has to be cleaned, lubricated, greased and painted where necessary. Moving parts, especially chains, have to be greased and moved regularly to avoid corrosion.

12.6.4 Operational problems

There are no real operational problems to be expected from grit chambers. When the grit chamber is not cleaned frequently enough, the grit chamber may fill up, thereby allowing too much passage of grit. This will result in damage to downstream pumps, tanks and reactors.

12.7 UASB reactor

12.7.1 Commissioning

Before start-up the reactor has to be checked on its correct hydraulic functioning. This concerns the equal distribution of the influent in the flow-distribution boxes and the correct levelling of the effluent gutters. Not only each effluent gutter has to be levelled, also all gutters have to be at the same level. The necessary adjustments have to be carried out before the reactor is put into operation.

The gas collection system has to be checked for gas tightness. Hereto the system can be brought under pressure during filling-up. All critical joints have to be checked on gas tightness with a soap solution.

The sludge discharge system should be tested with water on its correct functioning.

12.7.2 Start-up

Generally domestic sewage contains methanogenic bacteria and has a relatively low strength as compared to industrial wastewaters. Therefore, the start-up of a UASB-reactor for domestic wastewater can be rather straightforward. The plant can be put into operation without seeding and at the design flow-rate. If the

accumulation of solids in the reactor does not proceed very well, it is advised to bypass peak flows during the start-up procedure.
If the domestic wastewater contains a high proportion of industrial effluent, wastewater BOD and COD concentrations may be very high. If the COD concentration is higher than 1000 mg/l, the loading should be stepped from initial very low loading rates, in order to prevent low pH in the UASB reactor.

At start-up the development of the sludge bed, the quality of the sludge and the gas production have to be monitored. The development of the sludge bed indicates the quantity of sludge in the reactor. The quality of the sludge can be assessed with parameters such as settling velocity, methanogenic activity and stability. The start-up of the reactor should take no longer than 3 months. Start-up is completed is sludge stability is low, and the effluent parameters VFA, BOD, COD and TSS are low. Sludge parameters as sludge stability and methanogenic activity will be indicative for process performance, but the results are very hard to interpret. In general sludge stability should be as low as 20 - 40 ml CH_4/g VSS, and the methanogenic activity should be in the range of 0.1 - 0.3 g COD/g VSS.d^{-1}.
When start-up proceeds slowly, it is advised to stop the feeding of the plant for a period of 2 - 4 weeks. In this period of time the sludge is able to digest the accumulated organic material. The methanogenic population can grow now and the settling properties of the sludge generally improve. During standstill the gas production has to be recorded daily or twice daily. It should show an ever decreasing rate of biogas production (as in Figure 34).

12.7.3 Normal operation

Normal operation of a UASB requires little effort. Process control should be based on the quality of influent, effluent, and sludge. Samples are taken and analyzed in the laboratory. These results and their interpretation define the operation of the reactor. The operation of the biological process should be controlled by the biogas production and the effluent measurements. Adequate measurements for the biological functioning of the plant are the soluble COD of the effluent, and incidental soluble BOD measurements for control purposes.
The operation of the UASB-reactor can be adjusted through modifications in the hydraulic retention time (HRT) and the sludge quantity.

Flow rates

The operator has to record the total daily flow to the plant and check whether its values are in accordance to the design parameters. He also has to check the correct hydraulic functioning of the plant, especially of influent distribution and effluent recollection. In case of malfunctioning he has to inform the plant manager and/or the maintenance personnel.

Effluent

The greatest concern of the plant operator is to achieve the best effluent quality. Visual inspection can already give basic information. A transparent, clear effluent without sludge particles indicates a proper functioning of the plant. A turbid effluent indicates a poor removal of colloidal, dissolved matter. This can be caused by too high flow-rates or by a poor quality of the sludge. A large fraction of solids in the effluent can result from too high sewage flows (sludge wash-out) or from a high sludge level in the reactor. Visual observations always have to be complemented with laboratory-analyses of influent and effluent. All data have to

be interpreted, compared with average data and plotted to identify changes in course of time.

Floating layers on the settling compartment have to be checked weekly and have to be removed when they become too thick. A fast growing floating layer is a sign of overloading of the reactor. In reactors without effluent baffles the presence of sludge and course particles in the effluent indicates the same problem.

Sludge management

The main tool of a plant operator to control the performance of a UASB-reactor is the management of the sludge in the reactor. When the sludge level in the reactor is too high, sludge is washed out, resulting in poor treatment efficiencies. On the other hand, when the sludge level in the reactor is very low, removal efficiencies will be low as well. A proper management of the sludge in the reactor, therefore, is very important. The sludge amount in the reactor is managed through the regular discharge of sludge. The amount of sludge and the height of the sludge bed should be more or less constant and therefore a regular determination of the height and shape of the sludge bed is required. A sludge profile is determined by sampling the sludge at different heights through the sampling points at the top of the reactor.

The sludge discharge is carried out through the valves in the sludge pit. The sludge is pumped to the sludge drying beds. Sludge discharge is carried out as a routine activity by the process engineers. The operator has to check the sludge level at least every week. These checks have to be carried out at a fixed hour, preferably in the afternoon, when expansion of the sludge bed is at the maximum. When the top of the sludge blanket is close to the entrance to the settling compartment, sludge has to be discharged. These discharges should be frequent and in small portions, to maintain the quantity of sludge in the reactor as constant as possible. The quantity of sludge discharges has to be determined empirically, but in practice standard routines can be developed.

A sludge profile should be made every month. The sludge profile has to be determined at a fixed time of the day, preferably in the afternoon. The sludge profiles make it possible to calculate the amount of sludge in the reactor and give an indication of the sludge quality. When the sludge bed and the sludge blanket cannot be clearly distinguished, the sludge is of a poor quality: the settling properties are poor and probably the stability is low as well.

The operator has to take sludge samples for assessing the settling velocity, the methanogenic activity and the stability.

Sludge is routinely is discharged every day in large reactors, but less often in smaller ones. The volume of sludge to be discharged should be known before discharge is made. If there are a lower and a higher outlet for the sludge, the sludge concentration from the higher valve should be checked. If the sludge concentration is too low, only the lower valve should be used for sludge removal.

Biogas production

The total gas production of the plant has to be recorded daily. The gas production has to be compared with the values expected from the COD-load of the reactor. Drops in the specific gas production (m^3 biogas per kg COD removed) point at a possible intoxication of the sludge.

12.7.4 Shut-down and standstill

At shut-down of the plant the sludge will settle to the bottom of the reactor. The biological activity of the sludge decreases only slowly during standstill. Care should be taken that the sludge is not exposed to aerobic conditions. This might occur, for instance, when the reactor is flushed with clean water for prolonged periods of time.

When the reactor is partially or completely emptied, it is essential to make an open connection between the gas collectors and the open air, e.g. by opening manholes, in order to avoid implosion of the gas collectors. At refilling the reactor, the manholes should be placed and sealed only then when the reactor is completely filled up. When it is necessary to enter the reactor, while sludge is present it has to be realized that methane is being formed continuously. A proper ventilation of the reactor is absolutely necessary. The workers should wear respiration equipment to be protected against suffocation. Furthermore, precautions have to be taken to prevent explosions in the system: mixtures of biogas and air can be explosive.

12.7.5 Operational problems in the biological process

If there are problems in the biological process there is a well-defined way to go to try and solve these problems. Checking of the effluent parameters, namely the soluble COD, and the figures on the gas production will reveal whether the sludge is functioning well. Checking of the TSS content in effluent and reactor and the sludge removal figures can give an insight in the SRT of the reactor contents.

Soluble COD

If the *soluble COD in the effluent* is normal, the breakdown of soluble organic material is good and that part of the reactor is functioning well. If the soluble COD in the effluent is too high, the *specific gas production* should be calculated. If this value is too low, preferably the *methanogenic activity* should be tested. This is a laborious test, of which the results are not very accurate. A low specific gas production or methanogenic activity may indicate too high concentrations of toxic compounds in the wastewater.

If the specific gas production is normal, the *influent COD* should be checked. If its concentration is high, this may be the reason for the effluent COD being too high. The *HRT* should be checked too. If it is too low, then overloading may cause high soluble COD in the effluent. With a normal influent COD and HRT, and still too high effluent concentrations, possibly the *amount of sludge* in the reactor is not sufficient. With a high solids loading, the SRT may decrease wen the *sludge stability* is less then normal. This parameter, however, takes much time to measure.

TSS

If the *TSS in the effluent* is rather high, sludge washout may be the result. I that case the sludge removal regime has to be changed. Otherwise the SRT may drop below the minimum value of 12.5 days. If TSS in the effluent behaves normal, then the *influent TSS* should be checked. High TSS in the effluent may be caused by hydraulic overloading, or by solids overloading. The result is the same: a decrease in SRT, eventually below the minimum level. If the *ash content* of the

sludge is either very high or very low, this may have negative effects on the sludge. An exceedingly high ash content will mean there is less space in the reactor for the bacteria, and a low ash content is often associated with poor settling characteristics.

Gas production

The gas production can be calculated as the *daily gas production*, and as the *specific gas production* (related to the amount of sludge in the reactor). If both parameters behave normal, there should be no problem. If both are low, this is caused by either problems with degradation of organic material or problems with gas collection. If no cause can be detected a check should be made for gas leakage. If the daily gas production is low whereas the specific gas production is normal, there is organic underloading. If it is the other way around, the reactor is overloaded.

Sludge production

The *sludge production* also is a very important control parameter for the biological process. If it is lower than expected, the proportion of soluble components in the wastewater might be higher than anticipated. If it is too high, the SRT may become too low. A high sludge production can be caused by accumulation of organic material with possibly low biodegradability in the sludge, or by solids overloading (either by concentration of hydraulically).

In § 5.1 a step-by-step sequence is given for the solution of biological process malfunctioning.

12.7.6 Operational problems with UASB hardware

The main opperational problem to be expected in plugging of the feed inlet pipes. Unplugging of feed inlet pipes is done by introducing the special orifice of the pressure water hose in the obstructed inlet pipe. The orifice should close the pipe hermetically, so that pressure can be built up. The pipe is flushed with water until it is fully open. If inlet pipe cannot be unplugged in this manner a flexible rod should be inserted to remove the obstruction.

In chapter 5, an extensive survey is given on operational problems with UASB hardware, and how to solve them.

12.8 **Gas collection**

12.8.1 Start-up

At process start-up the gas production is low and not constant. Furthermore, the combustion value is only low and it will be difficult to use the gas for a combustion process. It can even occur that the gas consists of an explosive mixture of biogas and air.In the start-up phase it is necessary to control the gas pressure and to adjust the switch values of the pressure- and vacuum release valves.

12.8.2 Normal operation

During normal operation the gas production has to be recorded daily and checked with expectable values. Unexpected values have to be related to changes in

process conditions. When the deviation of gas production cannot be explained from this, physical defects of the gas collection system have to be traced.

The normal operation of gas flares has to be checked daily. When the flares are not in operation, the functioning of the flare has to be tested through a manual start at least every week.

The operation of gas motors has to be carried out according to the manufacturers instructions.

Occasionally samples on the gas composition have to be taken.

12.8.3 Shut-down and standstill

At shut-down of the plant the gas production will decrease. At a prolonged period of plant standstill, the pressure in the gas collection system can drop and air may enter into the system. In this situation internal parts of the gas flare, the gas meter and the pressure/vacuum release valves that normally are not in contact with the atmospheric air start to corrode. These parts have to be protected, for instance by greasing.

When during plant shut-down the water level in the tank is lowered, it should be taken into account that the capacity of the vacuum release valves is limited and that imploding of the gas collectors may occur at fast withdrawal of the reactor contents. At lowering of the water level in the reactor it is advised to open the manholes on top of the gas collectors. Only after re-establishing the maximum water level the manholes can be closed and sealed.

When the manholes are opened and in general with every type of work on the gas collectors it should be taken into account that an explosive mixture of air and methane can develop in or around the gas collectors. Very strict rules concerning open fire, spark emission etc. should be used. When entering the reactor plant personnel should wear respiration equipment. Measurements of explosion risk and the H_2S concentration have to be taken frequently when repair works are carried out.

12.8.4 Operational problems

12.9 Sludge dewatering

12.9.1 Start-up

The first activity at start-up of drying beds is to determine the sludge drying-time. The average sludge drying-time depends on weather conditions and process conditions, such as the sludge characteristics and the height of the sludge layer.
One of the most important decisions to be taken concerns the depth of the sludge-layer. Sludge applied at shallow depths dewaters rapidly, but requires more frequent sludge discharges than greater depths, which on their turn increases sand loss. The most favourable depth has to be determined empirically for each individual plant. During start-up the operator has to apply increasing depths of sludge and monitor regularly the moisture content and the consistency. The optimum sludge depth is reached when the yearly sludge loading capacity is at the maximum. The sludge loading is calculated by:

sludge loading = dry matter applied / drying time

dry matter applied = height x area x solids fraction

It has be taken into consideration that the sludge drying time may vary throughout the year due to climatological conditions.

12.9.2 Normal operation

Before each sludge application to a drying bed the operator has to check the correct preparation of the sand bed. The sand bed has to be levelled and raked and should not contain weeds in order to guarantee a proper dewatering of the sludge.

After application the sludge piping has to be washed with water to avoid clogging with dried sludge and to avoid pressure build-up in the piping system.

The plant operator has to monitor the drying process by determining the sludge consistency. Sludge discharge can be considered when the sludge is liftable. When the sludge bed is larger than strictly necessary the sludge can be left until the drying bed area is required again. When the capacity of the sludge beds is small, the sludge should be left to dry until it is considered liftable. The operator has to record dates and volumes of sludge applications. At removal, the volume of the sludge and its water content has to be assessed and recorded. Lost sand should be replaced when 50 % of the original depth has been lost.

After reaching the target consistency the dried sludge can be removed and the beds have to be prepared for receiving fresh sludge. The sludge pipes have to be flushed thoroughly and the sludge pumps prepared as described in chapter 10.3.3. The valves in the sludge lines should be opened and greased.

12.9.3 Operational problems

Odours escaping when sludge is applied to sludge drying beds may indicate inadequate digestion of sludge. The reactor loading rates should be checked, and if possible adjusted. In extreme cases the feeding of the UASB reactors can be stopped until sludge has stabilized.

Excessive dewatering times may be caused by application of too high layers of sludge in the sludge beds, by application of sludge to drying beds which have not been cleaned sufficiently, by clogging of the drainage pipes and by rainy weather. If malfunctioning of the sludge beds is suspected, the decrease of the water depth in the sludge bed after application of a new sludge layer to a cleaned sludge bed should be noted. This drawdown should typically be over 3 cm/day. If the drawdown is less, it is advised to use a sludge depth of twice the drawdown over the first 3 days of application of the sludge drying bed. Addition of polymer to the sludge before drying can be considered.

Clogged sludge feed pipes may be attributed to accumulation of grit and solids in the pipes. By opening the valves fully at the start of sludge application the pipes may be cleaned; if necessary the pipes can be flushed with water.

Very thin sludge drawn from the digester may be attributed to "cone forming" occurring in the UASB reactors, with water being pulled out and sludge left behind. Sludge should then be removed from a lower height in the reactor.

Breeding of flies in the sludge beds, can be combatted by breaking of the sludge crust and use of a larvicide such as borax, or calcium borate to kill the larvae. Adult flies can be killed with a suitable insecticide.

13. DATA COLLECTION ACTIVITIES

13.1 Introduction

Regular records and reports of wastewater treatment plant operations can be used for many purposes. The collected data serve the plant manager to judge on the performance of the plant and to justify decisions concerning operation and maintenance activities, budget allocations and proposals for plant expansion. The plant operator should use the data as a guide for regulating, adjusting and modifying the plant facilities and treatment processes. For the plant operator the collected data will serve as a check of his visual observations and will provide a continuous record of performance. The records also serve for external consultants and regulatory agencies to judge the plant performance, to justify modifications and to trace the cause of failures.

The records that should be maintained at a sewage treatment plant can be separated into the following classifications:
- Status reports,
- Hardware performance,
- Process performance.

13.2 Status reports

These records contain the basic readings and calculations on the overall plant status, the log book and the operation and maintenance manuals.

13.2.1 Daily status report

The daily status report should contain information about the weather conditions, the sewage flow, the working hours of electro-mechanical equipment, the power consumption and amperages of the plant and estimates of the production of screening material, grit and amount of disposed dried sludge. An example of a daily status report is given in Figure 28.

The operator can read part of the information from the control panels of the plant. The other information will be collected during his rounds over the plant.

13.2.2 Plant log book

The plant log book should be used as a plant diary, that describes and interrelates all movements to and from the plant. It should describe the receipts of supplies and spare parts, the disposal of waste products and its quantities, the entrance and departure of external maintenance personnel and information or reports received on discharges of hazardous components to the sewer system.

13.2.3 Operation and maintenance manual

The operation and maintenance manual of a sewage treatment plant should contain at least the following items:

1 Description of the plant. This part contains the design criteria and parameters, the service area, the capacities of each of the treatment units, copies of manufacturers specifications of each piece of equipment with its operation and

maintenance instructions.

2 Copies of the legal approval of plant operation and the effluent quality standards.
3 Operation manual for the entire treatment plant.
4 Maintenance manual for the entire treatment plant.
5 Sampling procedures and handling of samples.
6 Safety regulations at the plant site.

The operation and maintenance manual should be updated regularly by the plant manager on the basis of new experiences. The operation and maintenance manual should be accessible for each member of the staff and should be well indexed.

13.3 Hardware performance

Records on hardware performance contain all information on operation and maintenance activities. The records consist of the maintenance records, the work orders for maintenance personnel and the stock control.

13.3.1 Maintenance records

The maintenance records describe when and which type of maintenance has to be carried out. The maintenance records are based on the preventive maintenance schedules of the manual and are complemented, if necessary, with orders from the plant manager, who responds to new situations at the plant.

The maintenance records should be complemented with the information filled in by the maintenance staff on the work orders, and so provide a complete view on the activities.

For small treatment plants the maintenance records can consists of a chronological list of activities. In larger plants it is advisable to use a card system or a computer management system. The card system should contain each serviceable part of the treatment plant and should list the dates of next maintenance activity.

13.3.2 Work order

The maintenance staff receives its orders on a work order form. The work order describes the activity and leaves room to fill in data such as time spent on the activity, materials used (spare parts, lubricants etc.), observations on the job and problems. The information provided by the maintenance staff is transferred to the maintenance records.

13.3.3 Stock control

Stock control is necessary to maintain the stocks of supplies and spare parts at the desired level and to monitor the use of materials at the plant site. Furthermore, it provides a means to determine points of care in the maintenance scheme and trends in the consumption of supplies. Depending on the size of the plant the stock control system can be manual or computerized.
A card system is very useful for this purpose. It should be noted that the effective use of the stock control system depends on a strict and consequent registration

of all incoming and outgoing parts.

13.4 Process performance

Process performance is evaluated at two sites, viz. directly at the plant-site by the operator and in the laboratory through the analyses of influent, effluent, sludge and gas. The information will be recorded on two forms: the daily status report and the laboratory sheet.

13.4.1 Daily status report

The daily status report is filled in on a daily basis by the operation staff. This report has been mentioned in Chapter 11.2 and is used by the operator to fill in all the information collected at the plant site. The most important data with respect to plant performance are the sewage flow, the debris, grit and sludge production, the gas production and the visual impression of the effluent quality, and state of the various process steps. It is important that the operator gets accustomed to register every observation on his activities, including deviating conditions in the functioning of the plant. The status report also should include registration of samples that were sent to the laboratory, to be able to check afterwards whether all data have been collected and elaborated. (See Example form Figure 28).
A daily status report has to be filled in once a day, for small plants and during each shift at large treatment plants.

13.4.2 Laboratory sheet

The laboratory sheet(s) are used to transcribe all laboratory data in such a form that the data can be used for further processing. The sheets should leave room for relevant calculations, such as efficiencies, loads etc. It is practical to pile up the laboratory sheets in a computer, where the relevant calculations can be carried out automatically.

The frequency of the analyses depends on the size of the plant and on the demands of controlling authorities. Effluent quality standards and regulation vary from one country to the other. The standards and regulations concern either the effluent quality in terms of maximum-concentrations or the removal efficiencies. Important parameters in many standards are COD, BOD, Solids and nitrogen (N-kj or Nitrate).
For process control the same parameters are important, together with general parameters as temperature, pH and alkalinity. The analytical schemes for treatment plants have been summarized in Table 20. A division has been made between small plants (< 10,000 p.e.), middle-size plants (10,000 - 50,000 p.e.) and large plants (> 50,000 p.e.).

DAILY STATUS RECORD			
DAY :	**MONTH :**	**YEAR :**	**OPERATOR 1 :** **OPERATOR 2 :**

	POWER SUPPLY		**SCREENS**	**GRIT CHAMBERS**						**TANNERY FLOW**	
	TIME		ESTIMATE	IN OPERATION			IN OPERATION				
	STARTED	CLOSED	(L/DAY)	1	2	no barrows	1	2	no barrows	TIME	READING
SHIFT 1											
SHIFT 2											

	BIOGAS PRODUCTION			**EFFLUENT**				**SLUDGE DISCHARGE**			
	TIME	READING		TIME	READING		TEMP	DISCHARGE VOLUME		SAMPLES TAKEN	
		1	2		1	2		1	2	1	2
SHIFT 1											
SHIFT 2											

	DRYING BEDS				**SAMPLES TAKEN**						
	LOADING		DISPOSAL								
	BED NO	DEPTH	BED NO	DEPHT							
SHIFT 1											
SHIFT 2											

REMARKS

Figure 28. Example of daily status record for a UASB plant.

Table 20. Frequency of measurements for different plant sizes.

	PLANT SIZE		
	small < 10,000 P.E.	middle 10,000 - 50,000 P.E.	large > 50,000 P.E.
BIOGAS			
gas production	daily	daily	daily
gas composition	incidentally	incidentally	monthly
INFLUENT / EFFLUENT			
pH	daily	daily	daily
Temperature	daily	daily	daily
COD total	weekly	daily	daily
COD filtered	monthly	weekly	daily
BOD total	monthly	monthly	weekly
BOD filtered	incidentally	incidentally	incidentally
TSS	weekly	weekly	daily
VSS	monthly	weekly	daily
N_{kj}-N	bi-monthly	monthly	weekly
Ammonium	bi-monthly	bi-monthly	weekly
Total phosphorus	bi-monthly	monthly	weekly
Alkalinity	bi-monthly	monthly	weekly
SLUDGE			
methanogenic activity	incidentally	bi-monthly	bi-monthly
stability	incidentally	incidentally	incidentally
sludge profile	incidentally	bi-monthly	monthly
settleability	incidentally	monthly	monthly

13.4.3 Monthly sheets for process evaluation

The monthly evaluation report consists of a data sheet containing all essential information on the plant performance of the past month and a report, in which the principle findings are described and wherein an interpretation of the performance is given. The evaluation sheet is filled in by the process engineers. In this sheet the information from the daily status record and the laboratory record is compiled. It comprises of calculations of treatment efficiencies, loading rates and other relevant parameters for the evaluation of the plant performance. The plant report is filled in for each reactor separately.

The monthly evaluation report is finalized by the process manager. The plant report is based on the log book, status record, and laboratory record.

The evaluation sheet is accompanied by graphs that depict the COD of influent and effluent, the BOD of influent and effluent, the gas production, and the removal efficiencies of COD, BOD and TSS.

MONTHLY SHEET UASB WASTEWATER DATA										
MONTH :	**YEAR :**				**OPERATOR :**					
date	**INFLUENT**						**EFFLUENT**			
	flow	CODt	CODs	BOD	VFA	TSS	CODt	CODs	BOD	VFA	TSS
	m^3/d	mg/l	mg/l	mg/l	meq/l	mg/l	mg/l	mg/l	mg/l	meq/l	mg/l
1											
2											
.											
30											
31											

Figure 29. Monthly sheets of laboratory data. A: Above: influent and effluent data. B: Below: biogas data.

MONTHLY SHEET BIOGAS DATA														
MONTH :	**YEAR :**				**OPERATOR :**									
date	**REACTOR 1**							**REACTOR 2**						
	time	meter	biogas	rate	% CO_2	% H_2S	% CH_4	time	meter	biogas	rate	% CO_2	% H_2S	% CH_4
1														
2														
.														
30														
31														

Figure 29C. Monthly sheets of plant efficiency data.

MONTHLY SHEET PLANT EFFICIENCY DATA														
MONTH :		**YEAR :**			**OPERATOR :**									
date	**flow**	**CODt**			**BODt**			**TSS**			**biogas**	**sludge**		
		influent	effluent	removal	influent	effluent	removal	influent	effluent	removal	effic.	content	removal	SRT
	m^3/d	mg/l	mg/l	%	mg/l	mg/l	%	mg/l	mg/l	%	%	kg	kg	days
1														
2														
.														
30														
31														

14. TROUBLESHOOTING

14.1 Troubleshooting for treatment process problems

This paragraph is concerned with the troubleshooting of process parameters. Checking if everything is OK can be performed by checking the parameters of effluent, gas production and sludge production in four steps. These steps are elaborated in the following sequence of Tables, of which each table refers to a consecutive step in the checking procedure.

STEP 1: EFFLUENT QUALITY, SOLUBLE COD REMOVAL

STEP NUMBER	PARAMETER TO BE CHECKED	CHECK RESULT	CONCLUSION	NEXT STEP
1	Effluent concentration COD filtered	OK	No problems with degradation of soluble organic material	Go to 2
		too high		Go to 1.1
1.1	Specific gas production	too low		Go to 1.1.1
		OK	Conversion to methane takes place	Go to 1.2
1.1.1	Methanogenic activity	too low	Sludge quality decreased due to toxic compounds in influent, or organic overloading, or accumulation of material with low biodegradability	Check history of all parameters
		OK		Go to 1.2
1.2	Influent concentration filtered COD	high	Overloading of soluble COD	Cause detected
		normal		Go to 1.3
1.3	HRT	too low	Hydraulic overloading: upflow velocity too high	Cause detected
		normal		Go to 1.4
1.4	Sludge amount in reactor (kg VSS)	too low	Not enough sludge is kept in the reactor	Cause detected
		normal		Go to 2
1.5	Sludge stability	unstable sludge	Accumulation of organic material in sludge	Cause detected
		normal		Go to 2

STEP 2: EFFLUENT QUALITY; SOLIDS REMOVAL

STEP NUMBER	PARAMETER TO BE CHECKED	CHECK RESULT	CONCLUSION	NEXT STEP
2	Effluent concentration TSS	normal	No sludge washout	Go to 3
		too high	Sludge washout	Go to 2.1
2.1	HRT	too low	Hydraulic overloading	Cause detected
		OK		Go to 2.2
2.2	Influent concentration TSS	too low	Solids overloading	Cause detected
		OK		Go to 2.3
2.3	Solids retention time	high	Sludge is not retained properly	Go to 2.3.1
		normal		Go to 3
2.3.1	Sludge profile and settling velocity	too low	Sludge is not retained properly	Go to 2.3.1.1
		normal		Go to 2.3
2.3.1.1	Sludge stability	unstable sludge	Accumulation of organic material in sludge	Cause detected
		normal		Go to 2.3.1.2
2.3.1.2	Ash content	too low	Ash retention is too low, causing poor settling characteristics	Cause detected
		normal		Go to 3

STEP 3: GAS PRODUCTION

STEP NUMBER	PARAMETER TO BE CHECKED	CHECK RESULT	CONCLUSION	NEXT STEP
3	Daily gas production (DGP); Specific gas production (SGP)	DGP normal; SGP normal	Normal gas production	Go to 4
		DGP too low; SGP too low	Either problems with degradation of organic material or problems with gas collection	Go to 1; if no cause can be detected check for gas leakage
		DGP too low; SGP normal		Go to 3.1
		DGP normal; SGP too low		Go to 3.2
3.1	Organic loading rate	lower than usual	Low gas production due to underloading	Cause detected
		normal	Removal rate too low, effluent concentrations must be high	Go back to 1
3.2	Organic loading rate	higher than usual	Organic overloading	Cause detected

STEP 4: SLUDGE PRODUCTION

STEP NUMBER	PARAMETER TO BE CHECKED	CHECK RESULT	CONCLUSION	NEXT STEP
4	Sludge production	normal		End of checks
		too low		Go to 4.1
		too high		Go to 4.3
4.1	TSS influent	too low	Lack of influent solids	Cause detected
		normal	Probably effluent TSS too high	Go to 2
4.2	Sludge stability	unstable sludge	Accumulation of organic material with possibly low biodegradability in the sludge	Cause detected
4.3	Ash content of the sludge	too low	Accumulation in sludge of non-digestible organic material	Cause detected
		too high	Accumulation of ash	Cause detected
		normal		Go to 4.4
4.4	Influent concentration TSS	too high	Solids overloading	Cause detected
		normal		End of checks

14.2 Troubleshooting of equipment functioning

This part of the troubleshooting guide concerns mostly technical problems. The table is self-explanatory.

WASTEWATER SUPPLY			
OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Average flow rate to the plant is higher than designed	Increase of discharge		Plan expansion of the plant
Peak flow rate is higher than designed peak flow rate	Overflow structure not correctly adjusted	Check correct level and functioning of overflow structure	Adjust overflow structure
SCREENS AND SIEVES			
OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Obnoxious odours, flies and other insects	Accumulation of rags and debris	Method and frequency of debris removal	Increase frequency of removal and disposal
Excessive screen clogging	Unusual amount of debris in wastewater	screen size and velocity of wastewater through screen	Use a coarser screen, or identify source of waste causing the problem so that its discharge into the system can be stopped
Mechanical rake inoperative, circuit breaker will not reset	Jammed mechanism	Screen channel	Remove obstruction
Rake inoperative but motor runs	Broken chain or cable	inspect chain	Replace chain of cable
	Broken limit switch	Inspect limit switch	Replace limit switch
Rake inoperative, no visible problem	Defective remote control circuit	Check switching circuits	Replace circuit
	Defective motor.	Check motor operation.	Replace motor.
WASTEWATER PUMPING			
OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Intermittent flow or surging	Improper level switch adjustment	Check sensor and switch adjustments	Adjust switch levels
	Improper wet well sensor adjustment	Check sensor adjustment	Adjust level sensors
	Hydraulic capacity of station is exceeded	Check designed capacity	Install surge tank

WASTEWATER PUMPING (continued)

OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Pump not running	Defective control circuit	Use a meter to check switching circuits	Replace defective part
	Defective motor	Motor operation	Replace motor
Pump not running, circuit breaker will not reset	Clogged pump or closed valve	Inspect pump for obstruction	Remove obstruction
Pump is running, but reduced discharge	Pump air-bound	Air bleed pipe	Remove obstruction
	Clogged impeller	Inspect for obstructions	Remove obstruction
	Wearing rings worn	Check clearance	Replace worn rings
	Damaged impeller	Check impeller	Replace impeller
	Air drawn through suction line, due to leaking seals	Check packings and seals	Replace seals and packings
	Air drawn through suction line due to improper low-level cut-off point	Check pump switch levels	Adjust pump switch levels
Clogged pump or pump suction line	Grease accumulations	Check grease accumulation on walls of wet well	Frequent cleaning of wet well or removal of grease by dewatering the well, and scraping the bottom
Rising power consumption per gallon	Clogged pump	Total daily pumped volume and maximum and minimum flow rates	Remove obstruction in pump
	Misaligned belt drives	Alignment	Realign belt drive
Improper liquid levels	Coating on liquid high probes	Probe	Clean probe
	Hang-ups in float level detectors	Float detector	Remove obstruction, release float
	Leaks in bladders	Bladders	Repair or replace bladder
	Fouling in bubbler	Bubbler	Clean bubbler

WASTEWATER PUMPING (continued)			
OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Excessive wear or damage to pumps	Sand accumulations in wet well	Inspect for eroding action, corrosion, and solids build up	Remove sand from wet well
	Grease accumulations in the wet well	Inspects wet well walls	Clean wet well
Water hammer	High suction head and high discharge pressure	Check pressures	Be sure suction and discharge air chambers are filled with air
	High suction head and high discharge pressure	Check pressures	Change ball checks and seating arrangement
	High suction head and high discharge pressure	Check pressures	Modify pumping rate
Pump inefficiency at high suction	Air leakage through pump seals or valve stem seals	Pour water around seal and visibly inspect sealing check. You may also hear the leak	Check seating and seals on valves, valve covers, valve stems and piston on plunger pump (repair or replace damaged and worn parts)
Excessive leakage around seals on shafts and plungers	Excessive wear on shaft or cylinder	Packing rapidly destroyed	Replace shaft or plunger, replace mechanical seals
Noisy pump	Incomplete priming		Prime according to instructions
	Bad alignment pump and motor	Check alignment shaft or belt	Align pump and carry out necessary repair (bearings)
Pump inoperative, motor runs at no-load current	Broken coupling	Check coupling or belt	Repair coupling or belt

GRIT CHAMBERS			
OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Rotten egg odour in grit chamber	Hydrogen sulphide formation	Sample for total and dissolved sulphides	Wash chamber and dose with hypochlorite
	Submerged debris	Inspect chamber for debris	Wash chamber daily
Corrosion of metal and concrete	Inadequate ventilation	Ventilation	Increase ventilation

GRIT CHAMBERS (continued)

OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Removed grit is grey in colour, smells and feels greasy	Grit removal system velocity too low	Use dye releases to check velocity	Increase velocity in grit chamber
Low recovery rate of grit	Bottom scour	Velocity	Maintain velocity near 1 ft/sec.
	Not enough retention time	Retention period	Increase retention time
Overflowing grit chamber	Pump surge problem	Pumps	Adjust pump controls
Septic waste with grease and gas bubbles rising in grit chamber	Sludge on bottom of chamber	Grit chamber bottom	Wash chamber daily

UASB REACTORS

OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Effluent gutters have more flow on one side than the other	Improper levelling of the effluent gutter	Levelling	Adjust levelling of gutter
Flow of different effluent gutters is not equal	Improper levelling of the effluent gutter	Levelling	Fix every gutter to the same level
Water level of overflow weirs of influent distribution system is not equal	Improper adjustment of the distribution boxes or overflow weirs		Adjust position of distribution box or overflow weirs
Gas production lower than normal	Intoxication of the sludge	Take sample of sludge and determine methanogenic activity	When toxic conditions are still present in sewage, suspend feeding until situation improves. If not, continue feeding and respond as during start-up
	Leak in gas collection system	Check critical points with soap solution	Repair leaks
	Gas meter defect		See "Observations gas collection": gas meter failure

UASB REACTORS (continued)			
OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
During start-up at short HRT the sludge does not improve	Solids loading rate is too high to allow growth of the methanogenic population		Stop feeding of the reactor and allow digestion of the solids until gas production is lowered considerably till it is more or less constant
	The sewage contains a large fraction of poorly degradable organic solids	Check biodegradability of the solids	Re-start at HRT = 24 hours and lower step-wise until maximum loading is obtained. Most probably the designed HRT cannot be reached
Effluent turbid	Reactor overloading due to high hydraulic loading-rate	Flow-rate to reactor	If sludge quantity and methanogenic activity of sludge are normal and organic leading rate is normal, then reduce flow-rate
	Reactor overloading due to high organic loading rate	Check organic loading-rate of reactor	When sludge quantity and methanogenic activity are normal, then reduce organic loading rate by increasing HRT
	Reactor overloading due to low biodegradation capacity of the reactor	Check quantity and methanogenic activity of the sludge	Increase sludge quantity in the reactor. Allow for improvement of methanogenic activity, for instance by stopping feeding of the reactor
Large fraction of solids in effluent	High hydraulic loading rate	Check flow-rate to the plant	Reduce flow-rate
	The pump switch levels not properly adjusted	Check switch levels of the pumps	Adjust switch levels
	Sludge level in the reactor is too high	Check sludge profile and the level of the top of the sludge blanket	Discharge sludge
Fast growing floating layer on top of the reactor	High organic loading rates of the reactor	Organic loading-rate and sludge loading rate	Adapt organic loading rate or improve sludge quality
Odours when sludge is applied to sludge drying beds	Inadequate digestion of sludge	Check reactor loading rates	Adjust reactor loading rates to design values In extreme cases stop feeding of reactor until sludge has stabilized

SLUDGE DISPOSAL			
OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Excessive dewatering time in the sludge drying beds	Applied sludge depth is too high	Typically, 8 inches of applied sludge is satisfactory	When bed has dried, remove sludge and clean. Apply a smaller depth of sludge and measure the drawdown over a 3 day period. In next application, apply twice the 3-day drawdown
	Sludge applied to improperly cleaned bed	Note condition of any empty beds	After sludge has dried, remove sludge and dirty sand and replace with 0.5-1 inch of clean sand
	Under drain system is clogged or pipes are broken		Backflush beds slowly by hooking cleaning water source to underdrain piping. Check sand bed and replace media as needed
	Beds undersized	Effects of adding polymer	Normally 5-30 lbs/ton of dry solids of cationic polymer provides improved dewatering rates
	Weather conditions	Temperature, precipitation	Wit until conditions are favourable again
Sludge feed pipes are clogged	Accumulation of grit and solids in pipes		Open valves fully at start of sludge application to clean pipes; flush pipes with water if necessary
Very thin sludge being drawn from digester	"Cone forming" occurring in digester with water being pulled out and sludge left behind		Reduce rate of withdrawal from digester
Flies breeding in sludge beds			Break sludge crust and use larvicide such as borax, or calcium borate or kill adult flues with suitable insecticide
Wrong application of sludge applied	Sludge sometimes contains heavy metals		Explain users that sludge is dangerous, if there are heavy metals present,
Odours from sludge storage lagoons	Improperly digested sludge	Solids retention time, VFA, pH	1. Correct digester operation. 2. Apply lime to lagoon surface. 3. Flood lagoon with heavily chlorinated water.
Mosquitoes breeding on sludge drying beds	Pounding of sludge	Stagnant ponds of sludge	Reduce sludge application rate, improve percolation of water through bed

SLUDGE DISPOSAL (continued)

OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Sludge feed piped are clogged	Accumulation of grit and solids in pipes		Flush pipes after each use
Very thin sludge being drawn from digester	Pumping of sludge at a too high level in the reactor	Check sludge profile in the reactor	Pump from lower level

GAS COLLECTION

OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Gas meter failure (propeller or lobe type)	Debris in line	Condition of gas line	Flush with water, isolating digester and working from digester toward points of usage
	Mechanical failure	Fouled or worn parts	Wash carefully with kerosene or replace worn part
Gas meter failure (bellows type)	Inflexible diaphragm	Isolate valve and open cover	If no leaks are found (using soap solution) diaphragm may be lubricated and softened using neats-foot oil
	Ruptured diaphragm	Visual inspection	1. Replace diaphragm 2. Metal guides may need to be replaced if corroded
Gas is leaking through pressure relief valve (PRV) on roof	Valve not seating properly or is stuck open	Check the manometer to see if digester gas pressure is normal	Remove PRV cover and move weight holder until it seats properly. Install new ring if needed. Rotate a few times for good seating
Manometer shows digester gas pressure is above normal	Obstruction of water in main gas line	If all use points are operating and normal, then check for a waste gas line restriction or a plugged or stuck safety device	Purge with air, drain condensate traps, check for low spots.
	Too fast withdrawal causing a vacuum inside digester	Check vacuum breaker to be sure if it is operating properly	Stop supernatant discharge and close off all gas outlets from digester until pressure returns to normal
Pressure regulating valve not opening as pressure increases	Inflexible diaphragm	Isolate valve and open cover	If no leaks are found (using soap solution) diaphragm may be lubricated and softened using neats-foot oil
	Ruptured diaphragm	Visual inspection	Ruptured diaphragm would require replacement

GAS COLLECTION (continued)

OBSERVATION	PROBABLE CAUSE	CHECK	SOLUTION
Gas pressure lower than normal	pressure relief valve or other pressure control devices stuck open	Pressure relief valve and devices	Manually operate vacuum relief and remove corrosion if present and interfering with operation
	Gas line or hose leaking	Gas line and/or hose	Repair if needed
Leaks around metal covers	Anchor bolts pulled loose and/or sealing material moved or cracking	Concrete broken around anchors, tie-downs bent, sealing materials displaced	Repair concrete with fast sealing concrete repair material. New tie-downs may have to be welded onto old ones and redrilled. Tanks should be drained and well ventilated for this procedure. New sealant material should be applied to leaking area
Suspected gas leaking through concrete cover	Construction cracks	Apply soap solutions to suspected area and check for bubbles	If this is a serious problem, drain tank, clean cracks and repair with concrete sealers. Tanks should be drained and well ventilated for this procedure

15. ANALYSES AND CALCULATIONS

15.1 Volatile fatty acids (VFA) and alkalinity

VFA and Alkalinity are analyzed according to the following procedure:
- Filter Sample
- Pipet **V ml** sample in beaker (V = 100 ml, containing less than 3 meq/l VFA)
- If necessary dilute sample to 100 ml with distilled water
- Titrate with 0.1000 n HCL to **pH = 3.0 (Z ml)**
- Boil under reflux for 3 minutes in 250/500 ml Erlenmeyer flask with condensor
- Allow cooling for 2 minutes
- Pour in beaker and titrate with 0.1000 m NaOH to **pH = 6.5 (B ml)**

Calculations :
If sample volume V = 100 ml

Alkalinity $a = 100 * [B - (1 + 0.9921\, c)]$
a = bicarbonate alkalinity in meq/l

VFA $c = \dfrac{B * 101 - (Z + 100)}{99.23}$

c = Concentration VFA in meq/l

If sample volume V is less than 100 ml

Alkalinity $a' = a * 100 / V$
VFA $c' = c * 100 / V$

15.2 Biogas production

If the biogas production is not read at the exact time the last reading was carried out, calculation of the daily biogas production is carried out as follows:

$$DBP = (R2 - R1) * \frac{(T2_h * 60 + T2_m) + 1440 - (T1_h * 60 + T1_m)}{1440}$$

in which
R1 = biogas reading at first day;
R2 = biogas reading at second day;
$T1_h$ = time in hours at first day;
$T1_m$ = time in minutes at first day;
$T1_h$ = time in hours at second day;
$T1_m$ = time in minutes at second day.

If there are more than one day between two consecutive measurements, the number 1440 has to be multiplied by the number of days between the measurements.

15.3 Loading rate

The loading rate reflects the quantity of COD that enters the reactor during a day and per m^3 reactor volume. To calculate the loading rate the following date are used:
- The daily flow rate (Chapter 4.5.1.1)
- The Total COD concentration of the influent (mg/l * 1000 = kg/m^3) (See Chapter 4.4.4)

$$\text{Loading rate} = \frac{\text{daily flow rate} * \text{total COD infl.}}{\text{volume reactor} * 1000} \quad (\text{kg COD/m3.d})$$

15.4 Biogas production efficiency

The gas production efficiency is an expression of the efficiency of the conversion of COD to biogas and therefore it indicates the performance of the biological processes in the reactor. The gas production efficiency is often expressed as m^3 biogas produced per kg of COD removed.

$$COD_{rem} = \{(\text{Total } COD_{infl} - \text{Total } COD_{effl}) * \text{flow rate}\} / 1000 \quad (\text{kg COD/day})$$

$$\text{Gas prod. efficiency} = \frac{\text{Biogas production}}{COD_{rem} / \text{day}} \quad (m^3/\text{kg } COD_{rem})$$

Alternatively, the biogas efficiency can be expressed as $m^3/kg\ COD_{in}$.

15.5 The amount of sludge in the reactor

The amount of sludge in a compartment is calculated from the sludge profiles. The profiles provided data on the TS- and VS-concentrations of the sludge at different heights in the reactor. The sludge amount is calculated as the sum of the sludge amounts in sections around the height of the individual sludge samples. The course of the sludge concentration over the height of the reactor is shown in Figure 30.

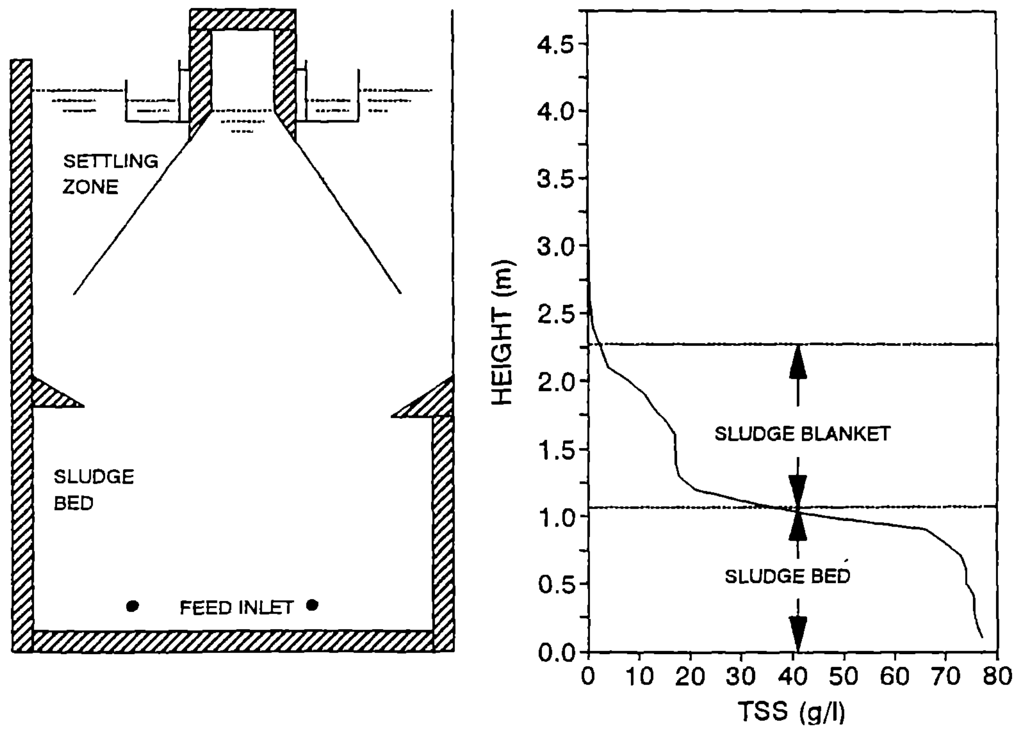

Figure 30. Sludge concentration over the height of the reactor.

The sludge amount in a section is calculated by multiplying the sludge concentration in the sample by the volume of the section:
concentration x height of section x reactor surface = amount (kg TS/m^3).
The total amount of sludge in the reactor is determined by summation of the amounts in each section (See Figure 31) multiplied by the total surface of the reactor.

Sampling for a sludge profile should be performed as follows:

1 Sludge profiles are taken between 12.00 and 14.00 hours.
2 Samples are taken at a level of 20, 40, 80, 120, 160, 200, 260, 320, 380, and 440 cm from the bottom of the reactor.
3 The sludge sampling point is opened.
4 The flexible pipe of the sludge sampling pump is lowered to the desired level.
5 Pump a sufficient quantity of sludge to flush the pipe and the pump.
6 Take a sample of the sludge.
7 Activities 1) to 4) are repeated at different heights.
8 After completing the sampling, the sampling point is covered.
9 After use the pipe and the pump are cleaned with tap water and the pump is stored while completely filled with water.
10 Samples are analyzed on TS and VS.

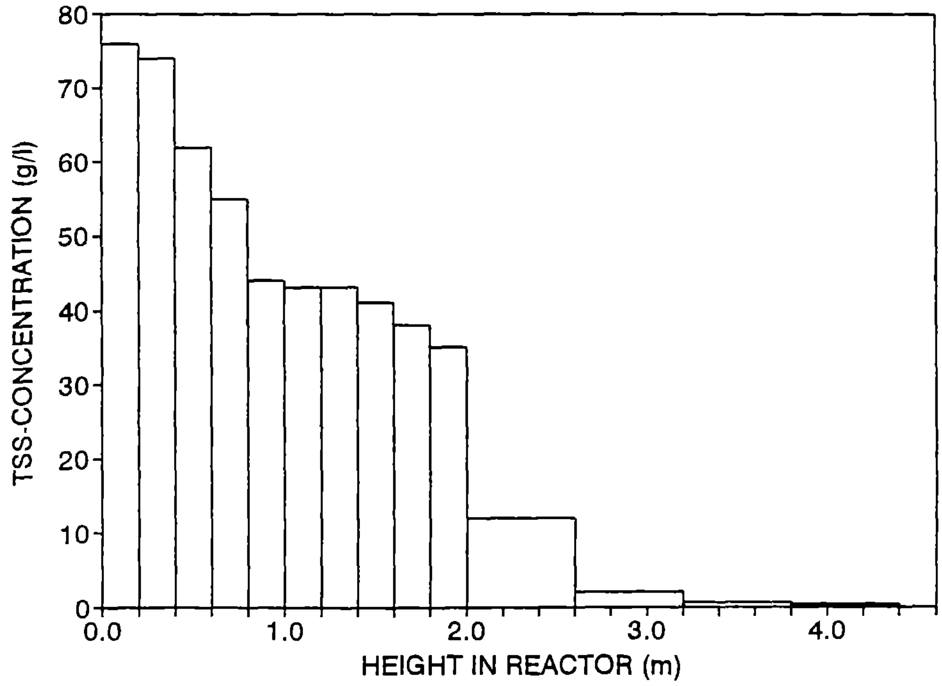

Figure 31. Example of the sludge profile.

15.6 Calculation of the amount of sludge discharged

The dry matter content of the discharged sludge can be calculated when the TS concentration of the sludge is known.
TS concentration is expressed in g/l or kg/m^3. A sludge sample is taken during every discharge.The sludge amount can then be calculated by multiplying the sludge discharge volume and the concentration:
Sludge amount = discharge volume x TS concentr. (kg TS)

15.7 Calculation of solids retention time (SRT)

The solids retention time (*SRT*) of the sludge in the reactor can be calculated from the data from the sludge profile and those from the amount of sludge discharged, and the effluent data. The *SRT* is calculated as:

$$SRT = \frac{\text{amount of TSS in reactor}}{\text{sludge-TSS discharged} + (\text{TSS in effluent} * \text{daily effluent flow})}$$

The determination of the amount of TSS in the reactor, and the sludge discharged has been described in the preceding paragraphs.

15.8 Methanogenic activity

The methanogenic anaerobic sludge is one of the most important process parameters in anaerobic waste water treatment technology. The quality of the sludge determines for the greater part the overall process efficiency, expressed in conversion of the COD of the waste water into methane-COD.

Set-up of equipment

The complete set-up (see Figure 32) for a batch system for the sludge activity test consists of the following equipment:
- 1 serum bottle of 250 ml as reactor vessel with the sludge/model waste water mixture;
- 1 serum bottle of 250 ml, installed upside down and working as a liquid displacement system with a 1.5% NaOh or salt solution;
- a small connection tube between these two bottles with 2 syringe needles;
- a graduated cylinder for collecting the solution, displaced by the biogas, via a discharge needle and a funnel.

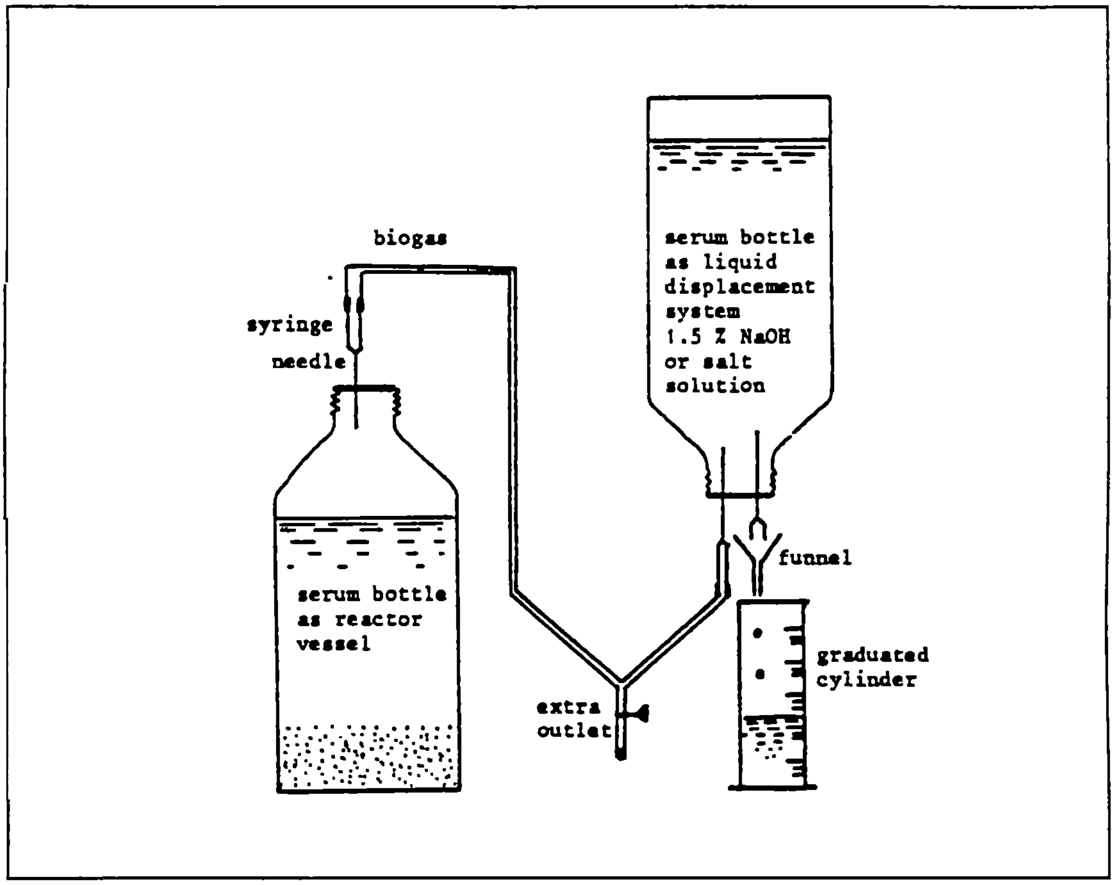

Figure 32. Set-up of batch system for sludge activity test.

The serum bottle serving as the reactor should preferably undergo some mixing. If possible it can be rocked gently in a laboratory stirrer. When applying intermittent mixing a pulse/pause frequency of six seconds stirring every 3 minutes is the absolute minimum. The activity test should preferably be carried out at a constant digestion temperature. So it is advised to heat the reactor vessel one way or the other. Heating systems usually applied are placing the complete set-up in a temperature regulated incubator.

Preparation

Before using the equipment first four stock solutions should be prepared:

- stock solution 1, a macro-nutrient solution: NH_4Cl 170 g/l; KH_2PO_4 37 g/l; $CaCl_2.2H_2$ 8 g/l; $MgSO_4.4H_2O$ 9 g/l;
- stock solution 2, a trace element solution: $FeCl_3.4H_2O$ 2000 mg/l; $CoCl_2.6H_2O$ 2000 mg/l; $MnCl_2.4H_2O$ 500 mg/l; $CuCl_2.2H_2O$ 30 mg/l; $ZnCl_2$ 50 mg/l; H_3BO_3 50 mg/l; $(NH_4)_6Mo_7O_2.4H_2O$ 90 mg/l; $Na_2SeO_3.5H_2O$ 100 mg/l; $NiCl_2.6H_2O$ 50 mg/l; EDTA 1000 mg/l; HCl 36% 1 ml/l; Resazurin 500 mg/l;
- stock solution 3, a VFA solution: acetic acid, neutralized to pH = 7, 100 g COD/l (1 g acetic acid = 1.07 g COD);
- stock solution 4: sulfide solution: $Na_2S.9H_2O$ 100 g/l (This solution has to be prepared (storage in a refrigator in a 40 ml serum bottle for maximum one week)

Procedure

Add to the reactor serum bottle anaerobic sludge at an amount of approximately 0,5 g VSS of sludge and add to this:

- 1,5 ml stock solution 1
- 0,2 ml stock solution 2
- 6 ml stock solution 3
- 2 drops stock solution 4.

Then fill the serum bottle to about 150 ml with oxygen free tap water, water that is flushed with nitrogen gas for at least 15 minutes. Subsequently flush the serum bottle with nitrogen gas, close the bottle gastight and put it in climate room or thermostatic bath on stirrer. Finalize the complete test set-up as indicated in Figure 32.

The liquid in the displacement bottle should contain a concentrated solution of NaOH or KOH ranging from 15-50 g/l in order to rapidly convert CO_2 gas (25 - 75 litre) to carbonate and dissolve it into the solution.
After temperature equilibrium has established (ca. one hour) the graduated cylinder should be emptied (at t = 0, V = 0). At regular intervals the gas production as liquid displacement volume now can be measured and recorded.
After consumption of the substrate (acetate) repeat the experiment by adding another 6 ml of acetate solution.

A blanc experiment should be run simultaneously with water in the experiment bottle in stead of sludge and nutrients, to account for the temperature variations, which will give rise to gas production. This bottle should be filled with the same total volume as the experiment bottle.

Methane production and calculation of methanogenic sludge actiity
When the cumulative gas production is graphically drawn against the time of the test, the methanogenic sludge activity can easily be determined from the slope of the graph, see Figure 33.

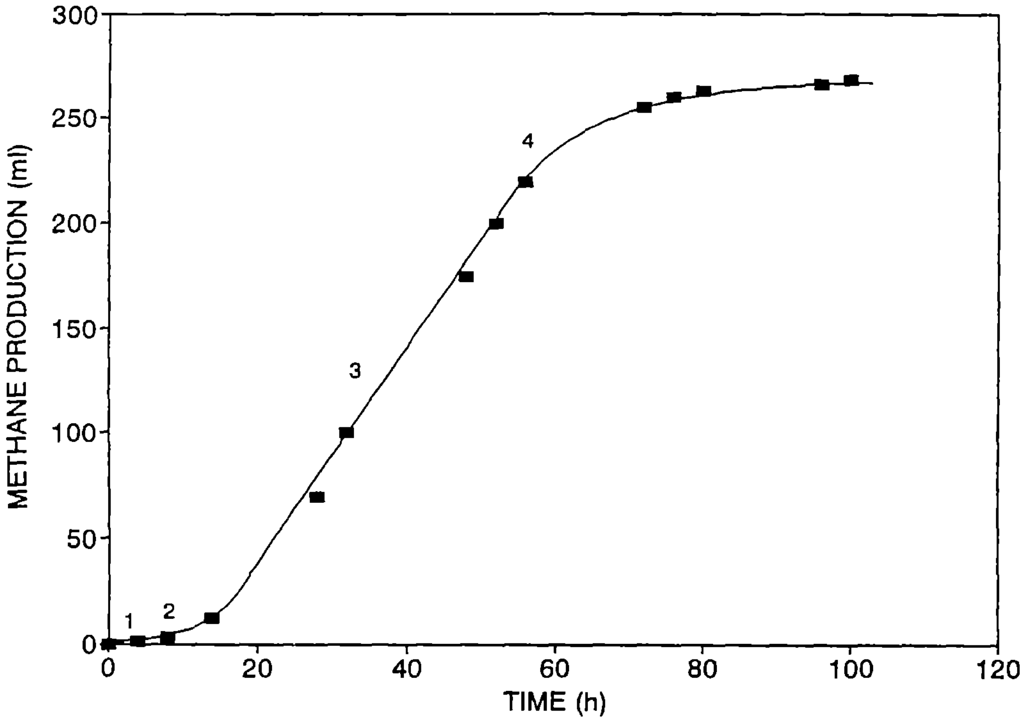

Figure 33. Example of a methane production curve in a batch activity test.

Generally, there is some methane production at the start of the experiment (1) as a result of the heating of the reactor vessel content. There may be a lag-phase (2) during which there is virtually no gas production: this lag-phase may last up to three days. The maximum methane or biogas production rate is calculated from the steepest part of the curve (3). When the substrate is nearly consumed the methane production rate will decrease (4). In a second experiment with the same sludge (after addition of new acetate) the methane production rate may be more than 30% higher.

If the increase in the maximum methane production rate is more than 30%, the increase may be assumed not to be the result of growth, but of adaptation of the bacteria. In that case, take the second value for the calculation of the maximum methanogenic activity. Methanogenic sludge activity is expressed in ml methane gas production or mg methane-COD produced per time and per g VSS sludge.
At the end of the experiment, the actual VSS content should be measured accurately.

15.9 Sludge stability

The sludge stability test provides information on how well-digested the sludge solids are, and whether the sludge solids are suited for disposal. The sludge stability test is performed with a sludge sample without soluble BOD.

1. Take a sludge sample, preferably from the sludge bed. The sludge should have a high density.
2. Take a homogenous sample of the sludge for VSS and TSS analysis. The VSS and TSS of the sludge should be known.
3. Bring an amount of approximately 5 g VSS into a serum bottle. Continue as described under the test of the methanogenic activity, **except that no VFA solution is added.**
4. The amount of CH_4 produced should be followed for a long time, at least one month.

Stability is expressed as the amount of CH_4, or CH_4-COD, per g of VSS, formed by the sludge in one month. An example of a sludge stability experiment is presented in Figure 34.

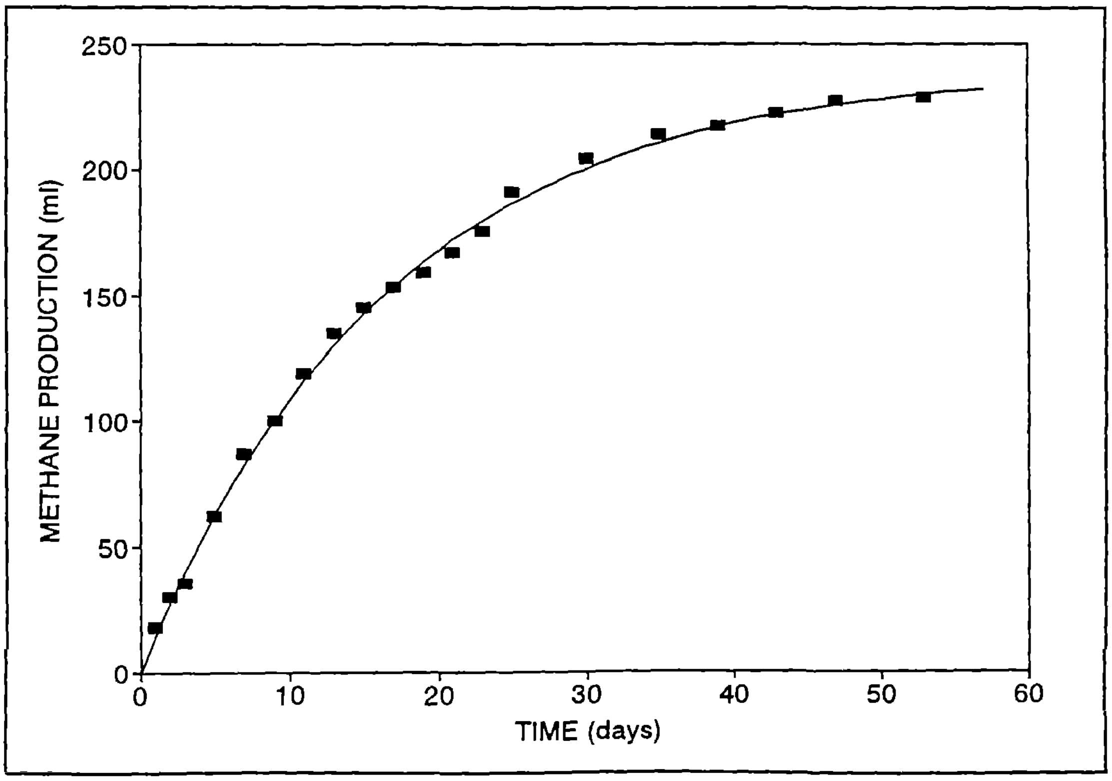

Figure 34. Example of a sludge stability test.

ANNEX : LIST OF SYMBOLS AND ABBREVIATIONS USED

ΔSS	delta SS, increase of solids per day (kg TSS/day)
ΔX	delta X, increase of biomass per day (kg TSS/day)
μ	specific growth rate (h^{-1})
μ_{max}	maximum specific growth rate (h^{-1})
AA	approximate reactor surface area (m^2)
A_B	servicing area of one disrtibution box (m^2)
A_{BED}	ash percentage of sludge in sludge bed (%)
A_D	definitive surface area of the UASB reactor (m^2)
A_F	area per feed inlet point (m^2)
A_{MAX}	maximum methanogenic activity of purely methanogenic sludge (kg CH_4-COD.kg VSS^{-1}.day^{-1})
$A_{MAX,METH}$	maximum methanogenic activity of the sludge (kg CH_4-COD.kg VSS^{-1}.day^{-1})
AP	aperture percentage (%)
AW	aperture width (m)
b	coefficient for maintenance and decay (h^{-1})
B	biogas production of the wastewater (m^3/m^3)
$BCOD$	biodegradable COD (kg/m^3)
$BCOD_{IN}$	biodegradable COD_{IN} (kg/m^3)
CH	average cross-sectional height of the settling zone (m)
COD	chemical oxygen demand (kg/m^3)
CW	gas collector width (m)
D	particle diameter (m)
d_l	density of the liquid
D_{MAX}	maximum pipe diameter (m)
D_{MIN}	minimum pipe diameter (m)
d_s	density of particle
DW	deflector width (m)
E	kinematic viscosity
E_{COD}	efficiency of conversion of COD into methane (-)
F	fraction of the total ammonium-N concentration which is in the form of free ammonia NH_3 (-)
F_M	fraction of methanogenic sludge (-)
F_{MG}	fraction of methane in the biogas (-)
F_S	fraction of the total S concentration which is in the form of free H_2S (-)
g	gravity acceleration (9.81 m/s^2)
h	height of the V-notch (m)
H	reactor height (m)
h_1	water height in gutter (m)
h_2	water height in gutter (m)
H_E	the height of the effluent gutter (m)
H_G	height of the gas collector (m)
HRT_{MIN}	minimum hydraulic retention time to satisfy demands on SRT (h)
HRT_{SZ}	hydraulic residence time in the settling zone (h)
H_V	the depth of the V-notch (m)
HW	gas hood width (m)
K_s	substrate half-saturation constant (mg/l)
L	total length of the gutters (m)
L_N	length belonging to the number of width units (m);

M	amount of methane sludge (g VSS/l, or kg VSS/m^3)
N_{DB}	number of feed inlet boxes (-)
N_F	number of feed inlets per distribution box (-)
N_U	number of width units (-)
N_V	number of V-notches per m (-)
N_W	number of width units
OV	overlap between deflector and gas collector sides (m)
PH	height of the gas collector plate (m)
pKb	negative logarithm of the dissociation constant of NH_3 (-)
pKw	negative logarithm of the dissociation constant of water (-)
PP	gas collector plate projection (to the horizntal plane) (m)
P_{VSS}	amount of VSS produced per litre of wastewater (mg/l)
Q_{avg}	average wastewater flow (m^3/h)
Q_{max}	maximum wastewater flow (m^3/h)
Q_{min}	minimum wastewater flow (m^3/h)
Q_V	flow-rate per V-notch (m^3/s)
R	ratio between the cross-sectional surface of the settling zone to the total width of gas collector system (-)
S	substrate (wastewater BCOD) (mg/l)
SP	sludge bed percentage, the percentage of the height from the bottom of the reactor to the gas collectors, which is occupied by the sludge (%).
SRT	solids retention time (days)
SS_R	total amount of solids in the reactor (kg)
T	temperature (°C)
TSS_{ACC}	amount of solids allowed to be accumulating (g TSS.l of reactor^{-1}.d^{-1})
TSS_{AVG}	average sludge content in the reactor (kg TSS/m^3 of reactor)
TSS_{BED}	average sludge bed concentration (kg TSS/m^3)
TW	total width of gas collector plus aperture (m)
UW	unit width (m)
v	angle of the V-notch (°)
V_O	settling velocity (m/s)
V_A	aperture velocity (m/h)
V_B	biogas loading rate (m/h)
V_{max}	liquid upflow velocity allowed during maximum flow (m/h)
V_{min}	minimum wastewater velocity through the pipes (m/s)
VSS_{IN}	incoming VSS concentration (kg/m^3);
V_{UP}	liquid upflow velocity (m/h)
$V_{UP,avg}$	average liquid upflow velocity (m/h).
X	biomass (kg VSS or TSS)
X_R	total biomass in reactor (kg VSS or TSS)
Y	yield coefficient, the amount of biomass (VSS) formed per unit of BCOD converted (BCOD = biodegradable COD)
Y_O	gross yield (kg VSS/kg COD)
Y_A	yield coefficient for acidifying and hydrolysing sludge (kg VSS/kg COD)
Y_M	yield coefficient for methane sludge (kg VSS/kg COD)
Y_N	net yield (kg VSS/kg COD)
Y_T	total bacterial yield coefficient (kg VSS.kg COD)
Z	percentage degradation that the solids will undergo during their stay in the reactor (%)