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Process design of agricultural digesters

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1. Introduction

The three areas of interest to most potential purchasers of anaerobic digesters for use on farms are pollution control (reduction of methane emission odour control), improvement of manure quality as a fertiliser and energy production. With energy production as the major objective there is likely to be more technical equipment and design needed for producing a maximum amount of gas and its efficient utilisation than is needed for a digester which is designed primarily for pollution control. In practice digesters are usually required to meet all three objectives. Even though pollution control might be the driving force to construct a digester, the energy is the interesting part to financially support the cost of the installation.

In the USA pollution control becomes an important argument to build a digester within the AgStar program of the EPA, the USDA and the DOE, much more than energy production. Sales prices of electricity of lower than 3 cts per kWh are sufficient to stimulate interest purely on the basis of energy . In parts of the European Union on the other hand - in particular in Denmark, Germany, Luxembourg and Austria - the on-farm energy production is an important income for many farmers due to a number of positive income and operation factors including:

- High electricity prices for renewable energies
- State subsidies
- Optimised designs based on modular constructions
- Utilisation of serial parts
- Reduced material cost thanks to collective purchase and construction of farm-scale plants
- Do-it-yourself construction with the help of engineers
- Co-fermentation of organic waste from household and industry bringing additional income from gate fee and through higher gas production
- Availability of proven low-cost, turn-key installations due to higher competition among manufacturers
- Centralised biogas plants

2. A short history of Anaerobic Digestion

Anectodal evidence indicates that biogas was used for heating bath water in Assyria during the 10th century BC and in Persia during the 16th century BC (Lusk, 1998).

The science of AD is as old as scientific research can be and includes the names of world's most famous searchers: Benjamin Franklin described as early as 1764 that he was able to light a large surface of a shallow muddy lake in New Jersey. This experiment was reported in a letter to Joseph Priestly in England who published in 1790 his own experiences with the inflammable air (Titjen, 1975).

Alexander Volta was the first researcher describing the formation of inflammable gases in (low-temperature) marshes and lake sediments scientifically. His letters on the formation of "Aria inflammabile nativa delle Paludi" where published in Italy in 1776. The importance of these findings was fully recognised by the scientific community, which is reflected by the fact that his letters were translated into German only two years after their appearance (Volta, 1778). In 1804, Dalton gave the correct chemical formula for methane.

The oldest publication of the temperature influence on methane formation was written by Popoff (1875). He found that river sediments could form biogas at temperatures as low as 6°C. With increasing temperature up to 50°C the gas production was stimulated. He also observed that the composition of the gas formed did not change with temperature.

The first digestion plant was built at a leper colony in Bombay, India in 1859 (Meynell, 1976). Gayon, a pupil of Pasteur, recorded a success in his experiments with animal manure in 1883-84 (Titjen, 1975). The volume of gas collected at 35°C was so great that Louis Pasteur concluded anaerobic manure fermentation might supply gas for heating and illumination under special circumstances. But the proposal, made in jest by the newspaper "Le Figaro" to improve the street illumination of Paris by manure fermentation from the numerous horses of the taxis and public works was not executed.

Based on the findings that higher temperatures stimulate the biogas formation, heating systems were developed to increase the digester temperature. In particular, Imhoff and Blunk patented between 1914 and 1921 a number of procedures such as internal, double walled heat exchangers, addition of hot water to the fresh sludge, steaming of the digester content or injection of hot biogas. However, considerable technical problems prevented the full-size application of their inventions: internal heat exchangers (particularly those made in copper) corroded within no time, and the addition of water or steam led to an undesired dilution of the sludge. Hence, the Imhoff-tank (Emscherbrunnen) working at ambient temperatures, still gave the best results. However, the start of the first continuously heated digester in 1926 in Essen (Roediger, 1955) indicated the break through of high temperature industrial digestion (mesophilic or thermophilic).

In the world of AD technology, farm based facilities are the most common. In China alone four to six million family-sized, low technology digesters are used to provide biogas for cooking and lighting and to sanitise the manure and the night-soil.

One of the most significant scientific developments in agricultural biogas goes back to the thirties when Buswell made his basic experiments on manure digestion in combination with most possible types of organic waste (Buswell and Hatfield, 1936). Buswell became the father of co-digestion.

The first full-scale (albeit small, approx. 10 m^3) agricultural biogas installation developed in 1938 by Isman and Ducellier in Algeria (van Brakel, 1980) was operated on solid waste. However, the further development of the solid waste system was stopped during world war II.

Towards the end of the second world war when the fuel was limited, AD of liquid manure and sewage sludge became quite popular again (Fig. 1 & 2). In France, more than 40 small-scale, mostly batch digesters were operated. The number increased to 800 in the fifties (van Brakel, 1980). In Germany some 48 facilities of rather large size and high technical standard mainly on sewage works were put in operation (Titjen, 1975). Half of the gas was utilised to run vehicles.

Today, biogas production has become a standard technology in waste water treatment and upgrading of biowaste from household and agriculture. The developments of the last 20 years allows not only low-cost gas production but also its upgrading and efficient utlisation in gas engines to produce electricity and fuel vehicles (Wellinger and Lindberg, 1999).

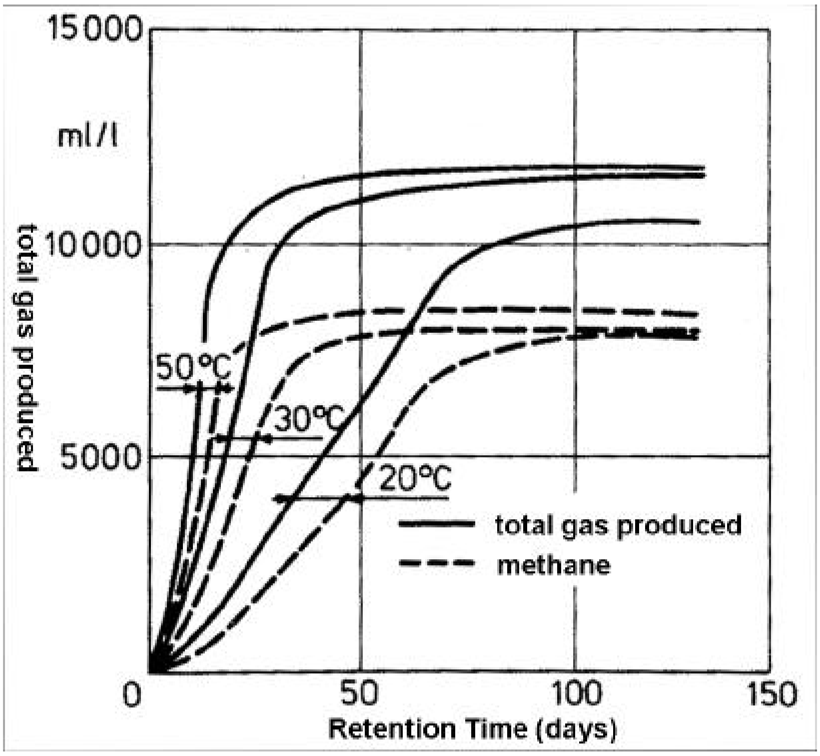


Figure 1: Gas yield of sewage sludge in function of HRT and temperature.

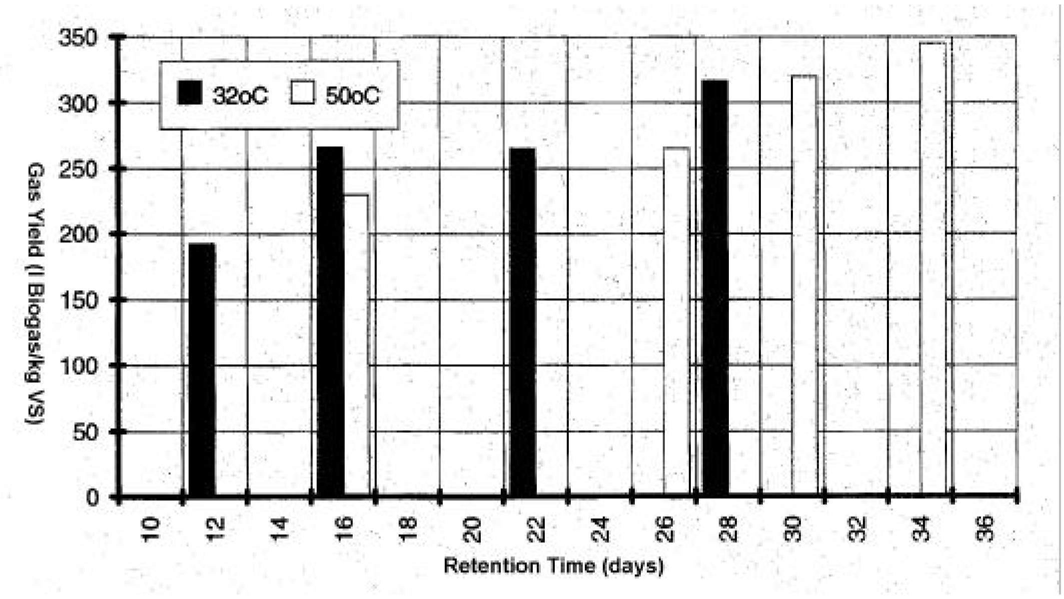


Figure 2: Gas yield of straw-rich solid cattle waste in function of HRT and Temperature

3. The process parameters

The anaerobic degradation of organic substances to its most reduced form, methane (CH_4) is a purely microbial process. The energy released during the degradation steps which was originally stored in the substrate is predominantly recovered by the methane formed (equation 1). This distinguishes the process from aerobic degradation, where the energy is predominantly recovered in new biomass and carbon dioxide (CO_2) and some low temperature excess heat (equation 2). All three forms are not suitable for a technical utilisation of the energy.

Anaerobic degradation:

33g org. material (CH_2O) = 22g CO_2 + 8g CH_4 + 3g biomass (equation 1)

Aerobic degradation:

33g org. material (CH_2O) + 12.8g oxygen = 17.6g CO_2 + 7.2g H_2O + 21g biomass (equation 2)

The anaerobic degradation is not a one step process. It occurs in three steps by at least four different groups of bacteria.

Step 1: Hydrolysis

In a first step the solid material, i.e. the complex and long chain substrates are broken down by exo-enzymes to soluble molecules which are taken up by the bacteria.

Step 2: Fermentation

The products of the hydrolysis are degraded by fermentative bacteria predominantly to volatile fatty acids (VFA)

Step 3: Methane formation

Approximately 70% of the methane is formed from VFA, 30% from hydrogen and CO_2 by methanogenic bacteria.

The thermodynamic limits of anaerobic digestion are very narrow. The formation of methane is only maintained as long as all the bacterial consortia involved in the chain are working under optimal conditions. Some of the degradation steps will not yield energy unless their products are efficiently removed by the next group of bacteria. The bottleneck is propionic acid, which is only degraded when the hydrogen in the system is cleaved by the methanogens.

As a consequence, there are few parameters which allow the process to be controlled. In fact, there are only four parameters which can be altered within limits.

3.1 Temperature

Methane is formed in nature over a wide temperature range from close to freezing (Mc Ghee, 1968) e.g. sewage in the arctic, up to over 100°C such as in the steams of Geyers (Zillig et al., 1981).

In technical applications three different temperature ranges are distinguished:

- Psychrophilic temperature (or cryophilic)
  from 10° to 25°C
- Mesophilic temperature
  from 25° to 35°C
- Thermophilic temperature
  from 49° to 60°C

A number of mesophilic and thermophilic anaerobic bacteria are described in the literature with temperature optima between 28° and 42°C and between 55° and 72°C respectively. So far no anaerobic psychrophilic bacteria have been found with a relative temperature maximum below 25°C. The work of Zeemann et al. (1988) and Wellinger et al. (1985) rather suggest a slow adaptation of mesophilic bacteria to lower temperatures.

The methanogenic bacteria seem to be ubiquitous at least in all anaerobic environments and obviously survive a wide temperature range.

It is therefore not surprising to find that the change from mesophilic to thermophilic temperatures or vice versa is not a problem in animal waste digesters as long as the change occurs smoothly (slow change, low loading). However, it might take months before mesophilic cultures are adapted to psychrophilic temperatures. Once the adaptation to low temperatures is complete, the system reacts very well to stress situations (Wellinger et al., 1985).

The ultimate gas yield of psychrophilic digestion is lower than at mesophilic temperatures. Differences reported are in the range of 30% for cattle manure (Wellinger et al. 1985) and 22% for sewage sludge (Maly and Fadrus, 1971).

Within practical time limits (up to 100 days) it was found that the degradation at 22°C of sewage sludge (Fair and Moore, 1934), cattle manure (Wellinger et al., 1985) and swine manure (Stevens and Schulte, 1979) takes about two times longer than at 35°C.

On the other hand, there is hardly any difference between mesophlic and thermophilic digestion. Obviously there is a faster degradation at the higher temperatures as was shown by Maly and Fadrus (1971; Fig. 1) for sewage sludge and Baserga et al. (1995) for solid animal waste (Fig. 2), but ultimate gas yields are fairly comparable.

Until the late eighties when the biogas was used for heating purposes only, psychrophilic digesters were quite popular. Suter and Wellinger (1987) demonstrated that the net heat production of mesophilic digesters was lower than that of psychrophilic digesters when operated at 23°C. Low temperature digestion in covered lagoons is still applied in the USA (Lusk, 1998).

When the price paid for the production of electricity from renewable energy was increased after 1990 in a number of European countries most of the biogas installations were equiped with combined heat and power plants (CHP). Since they produce excess heat during most of the year the majority of the agricultural plants are currently operated at mesophilic temperatures.

Thermophilic temperatures are applied in most of the large-scale centralised biogas plants with co-digestion, where more stringent sanitation requirements are required.

3.2 Hydraulic retention time

The hydraulic retention time (HRT) describes the average time the substrate remains in a digester. It is defined by

$$\text{HRT} = \frac{\text{liquid volume}}{\text{daily flow}} \quad \left(\frac{m^3.d}{m^3}\right) \quad \text{in days.}$$

In a continuous-flow digester HRT has to be longer than the doubling time of the bacteria to prevent wash-out.

The minimal HRT is dependent on the type of material to be digested. The lower the degradation rate, the slower the doubling time of the bacteria, the higher the HRT. The rate limiting step for agricultural waste usually is the hydrolysis. The velocity of degradation of the basic classes of compounds increases in the following order:

- Cellulose
- Hemicellulose
- Proteins
- Fat
- Carbohydrates

As a result, the digestion of pig manure with its high fat content requires lower HRTs than cattle manure which contains comparably high cellulose and hemi-cellulose concentrations. Average HRTs for mesophilic digestion are:

Cattle manure	12 to 18 days
Cattle manure with straw bedding	18 to 36 days
Pig manure	10 to 15 days

Even though lipids (fat) are fairly rapidly degraded they may be the reason for problems with inhibition. Lipids and their hydrolysis products, the long chain fatty acids (LCFA), might absorb to surfaces and as such hinder (physically) the attack of exo-enzymes which hydrolyse the substrate and the transport of substrates through bacterial membranes (Demeyer and Henderickx, 1967; Hanaki et al., 1981; Rinzema, 1988). High concentrations of LCFA are also known to inhibit its own degradaton (β-oxidation; Hanaki et al., 1981) and also methane formation (Hanaki et al., 1981; Angelidaki et al., 1990; Angelidaki and Ahring, 1992).

As mentioned above, there is also a close relation between temperature and optimal HRT. O'Rourke (1968) found that the degradaton of VFA in sewage sludge becomes the rate limiting step at lower temperatures. Wellinger et al. (1985) comfirmed the findings with cattle waste. In continuous-flow digesters operated at 18° and 14°C respectively. VFA concentrations started to increase when HRT dropped below 30d (Fig. 3) with a subsequent decrease of gas yield.

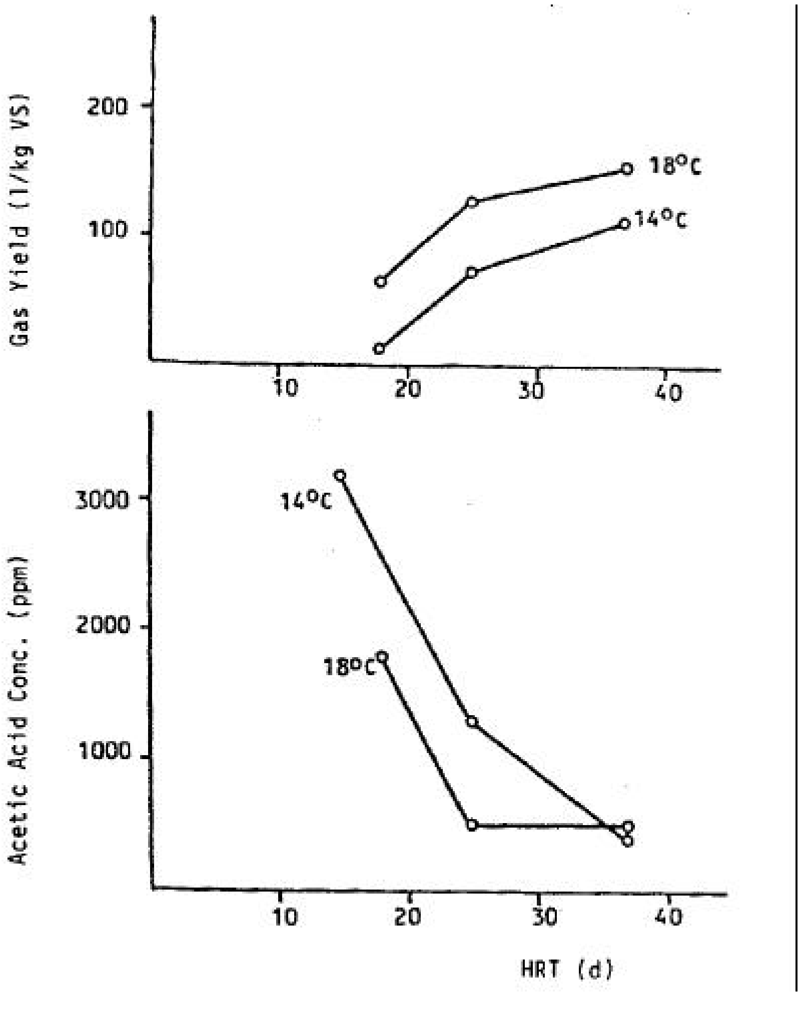


Figure 3: Gas yield and acetate concentration from cattle manure in function of HRT and temperature

3.3 Organic loading rate

The organic loading rate (OLR) describes the amount of organic material (expressed as COD or Volatile Solids (VS)) which is fed daily per m^3 of digester volume. For agricultural digesters it is usually defined as:

$$OLR = \frac{\text{daily flow} * \text{VS-conc.}}{\text{liquid volume}} = \frac{\text{VS-conc.}}{\text{HRT}} \left(\frac{\text{kg}}{m^3.\text{d}} \right)$$

Optimal OLR for mesophilic reactors

cattle manure	2.5 - 3.5 kg VS/m^3.d
cattle manure with co-substrates	5.0 - 7.0 kg VS/m^3.d
pig manure	3.0 - 3.5 kg VS/m^3.d

If heavy loads of co-substrates are occasionally fed into the digester it is advisable to decrease the basic OLR to lower values than indicated.

Due to particular subsidy regulations in Germany (the larger the reactor the more subsidies independent of the amount of manure) most of the newer farm-scale digesters are too big with OLR around or below 1 kg VS/m^3.d and HRTs beyond 50 days.

The corresponding installations in Denmark are operated with OLR between 1.7 and 8.0 kg VS per m^3.d at HRTs of 12 to 35 day (Energistyrelsen, 1999).

3.4 Ammonia concentration

Ammonia has been known for many years as a potent inhibitor of methanogenesis. A number of publications seem to indicate that the free ammonium form (NH_3) rather than ammonia (NH_4^+) is the real inhibitor (e.g. Kroeker et al., 1979). This means that the pH and the temperature (via pH-value) have a strong effect on the inhibitory concentration by influencing the equilibrium. Angelidaki and Ahring (1994) defined an upper limit of 0.7g/l of NH_3 in their experiments with thermophilic digestion of manure.

When digesting solid slaughterhouse waste with blood, Wellinger and Fruteau (1998) found upper limits of 3.5 g/l of ammonia corresponding to approx. 150 mg NH_3/l of sludge.

There is strong evidence that ammonium inhibits the methane formation from VFA (Zeemann et al., 1985). Hence, inhibition of methane formation is always accompanied by an increase of VFA. There is a considerable adaptation of the bacterial consortia to high ammonia values possible. In his experiments with pig manure Van Velsen (1979) demonstrated an adaptation to concentrations higher than 6000 mg/l of ammonia-N. Koster and Lettinga (1988) found microbial activity up to 16g/l of ammonia despite heavy inhibition.

Spontaneous changes in NH_3-concentrations even at low levels might lead to inhibition of non adapted cultures when digesting cattle manure (Wellinger, 1985).

In agricultural biogas plants ammonia concentrations are of concern when protein rich co-substrate is digested such as slaughterhouse waste or waste from collective kitchen. Some of the proteins have degradation rates of more than 80%. A widespread sign of protein overloading - beside reduced methane formation - is an increase in VFA-concentrations and massive foaming.

4. Process Control

Process control has never been of major concern in farm-scale digestion of animal manures. Usually the digesters were planned according to the daily amount of manure fed into the digester. Since the number of animals in individuals farms has decreased in recent years, overloading of digesters rarely occurrs.

The situation changed, however, when farmers started to digest co-substrates (Steffen and Braun, 1998). This rapidly resulted in changes in composition of the feed as well as the volume, which varied from day to day. In particular in centralised biogas facilities process imbalance due to organic overloading or because of inorganic or organic inhibitors became a matter of concern.

Traditionally biogas production was the only parameter which was monitored daily, sometimes together with the CO_2-content. In rare cases pH was measured as well because it was easy to determine.

However, pH is a very poor indicator in highly buffered substrates such as agricultural wastes. It was found to vary only by 0.5 units even after severe accumulation of more than 8000 ppm VFA (Angelidaki and Ahring, 1994).

Biogas production is still a fairly good parameter at least when the amount and the composition of the feed remains more or less constant. Because production is not a very sensitive parameter it is often too late for corrections when the production drops.

Occasionally the composition of the gas (% of methane) is a good indicator. Usually the methane concentration drops when the process is imbalanced. However, since the CO_2-concentration is also strongely influenced by the feed composition a change often reflects just a change of substrate.

The concentration of VFA has been recognised for a long time to be an important control parameter for AD (e.g. Chynoweth and Mah, 1971; McCarty and McKinney, 1961). Many investigators have correlated the process stability to the concentrations of individual VFA (Varel et al., 1977; Kaspar and Wuhrmann, 1978).

All these absolute figures became useless when co-digestion was introduced. The reason is that increased ammonia concentrations or salts (NaCl), as is found in food waste, will increase the basic level of VFA anyway. Ahring and Angelidaki (1997) suggested, therefore, monitoring of the relative changes of VFA concentrations, in particular that of butyrate or iso-butyrate instead.

The disadvantage of all VFA measurements is the high price of the analysis by gas chromatography and the fact that highly trained staff have to be at the site. Determinations in a specialised laboratory take two to three days before the data are available which is often too long for a proper process control and regulation.

A number of years ago Rozzi and Labellarte (1984) suggested to monitor the alkalinity, a method which has been continuously improved and is now commercially available for on-line monitoring.

5. Process design

A biogas plant usually involves more than just a gas tight manure pit or a digestion vessel. A farm-type operation usually is built up of four elements (Fig. 4):

(1) The production unit, which includes the manure removal system, possibly an influent holding tank and/or a sanitation unit and the anaerobic digester,

(2) the safety and gas upgrading equipment,

(3) the gas storage facilities and

(4) the equipment for gas and manure utilisation.

There are countless types of designs for each of the four elements. Some of the more widespread designs are highlighted in the following text.

The core of a biogas plant is the **anaerobic reactor**. The art of building low-cost, reliable digesters is strictly dependent on the optimal adaptation of the design to the type of substrate. A wide variety of AD systems have been developed for the digestion of biowaste and other organic residues. Each has its own speciality and constraints. There is no installation which could digest all the organic waste fractions in an optimal way. The two major design criteria are the mode of feeding and the substrate characteristics (dry matter, suspended solids, etc).

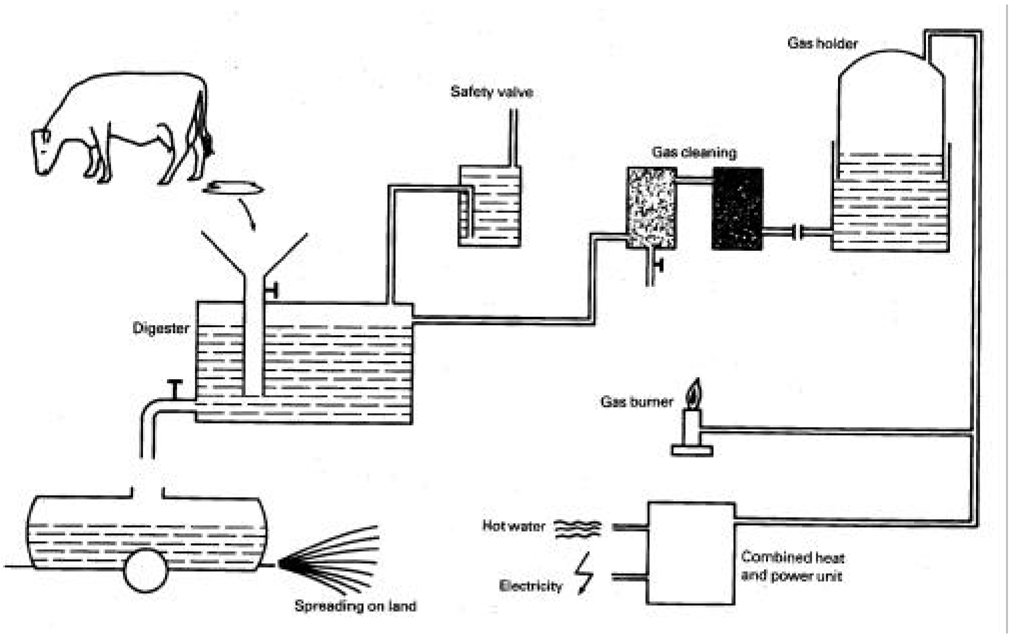


Figure 4: The four basic elements of a biogas installation

5.1 Mode of feeding

Basically, we distinguish between three genuine modes of feeding: Batch-fed, continuous-flow and accumulation systems.

In batch-systems the fresh substrate is fed together with an inoculum (approx. 10%) of digested material into a reaction vessel. During one to two days the material is aerated (composted) in order to increase the temperature. During the following three to four weeks the substrate is anaerobically degraded, at first with an increasing daily gas production. After having reached a maximum after approximately 10 to 14 days gas production decreases again to reach a plateau of about half maximum production.

To compensate the unsteady gas formation three to four batch digesters are operated in parallel but filled at different times.

The system is most often used for the digestion of straw-rich solid waste. In order to maintain digestion temperature and to moisten the solid waste, part of the liquid present in the digester is sucked from the bottom, pumped through a heat exchanger and recycled to the top of the digester.

Accumulation continuous-flow (**ACF-**) **systems** are kind of fed-batch digesters where the reactor serves at the same time as manure pit. The fresh manure flows into the digester as it is produced. The digested manure is removed occasionally when it is needed for fertilisation. In times (winter) when no fertiliser is needed the full digester overflows into a holding tank which is often covered by a rubber membrane serving as a gas storage (Fig. 5).

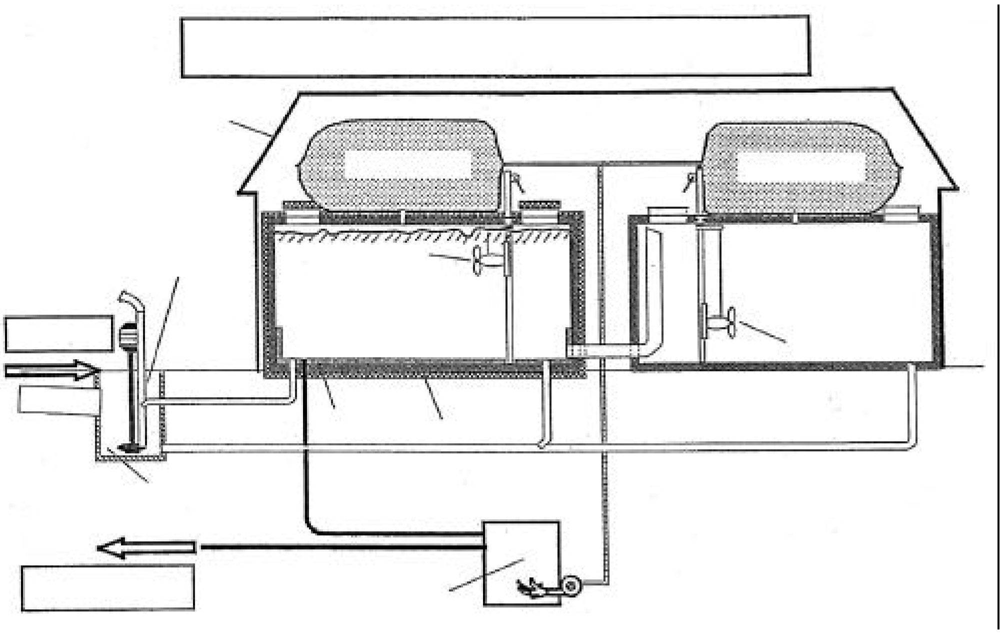


Figure 5: A modern type of ACF-system.
It is actually the most popular digester design in Germany.

The system was originally designed for farms which had to increase their manure storage capacity (Suter and Wellinger, 1987). Nowadays the system is widespread on individual farms in Germany, Luxembourg and Austria because it allows a low cost do-it-yourself construction.

The most applied digester system is the **continuous-flow tank reactor**. The raw waste is pumped regularly into a digester, displacing an equal volume of digested material. The volume in the digester remains constant. Most of the smaller systems are fed once or twice a day. The larger digester are operated more continuously with feeding intervals of less than one hour.

5.2 Substrate characteristics

The design of a digester is strongly influenced by the substrate characteristics, i.e. the homogeneity and the dry matter content of the waste. **Waste water low in total and suspended solids** is usually found in food factories, etc. It can be upgraded in high-rate digesters such as upflow anaerobic sludge blankets (UASB) or anaerobic filters (**AF**; packed bed reactors).

The idea behind high-rate systems is to increase the biomass (bacteria) in the digester to maintain a high degradation rate. This is achieved either by packed bed reactors offering a surface where the bacteria can attach and/or are withhold under non-turbulent conditions by the packing. Therefore the term "filter" is used.

The **UASB** make use of the phenomenon that anaerobic bacteria tend to develop small clumps (granules) which manifest high settling velocities and remain in the digester.

For agricultural wastes rich in solid material the high-rate reactors are not suitable: granule formation is hindered and packed beds will clog immediately. Exceptions include waste water from silage or supernatant of pig manure (Colleran et al., 1983), where good results were achieved.

Animal waste which is the predominant waste material in agricultural digestion is an inhomogeneous material with total solid concentrations between 2% and 12%. The predominant number of manure digesters is therefore of the type of a continuously stirred tank reactor (**CSTR**). This type is also well suited for co-digestion systems, often combined with an influent holding tank.

There is a wide range of construction material available particularly for above ground constructions such as concrete, steel, glass fibre reinforced plastic and wood.

Continuously-fed **solid waste digestion** has become a standard technology for the upgrading of source separated household waste. More than 50 installations of different designs (horizontal and vertical plug-flow, gas-stirred tank reactor, sequencing batch reactor) are successfully operated in Europe (Lusk, 1997).

For agricultural solid wastes however, only a pilot plant of 10 m^3 was in operation at the FAT in Switzerland for a number of years (Baserga, Egger and Wellinger, 1994) as well as a limited number of small batch digesters (Membrez, 1998). No full-scale plant has been described so far. The reason for this limited success is the economic viability. The only income agricultural solid waste digesters is the gas produced resp. the electricity sold, where as for household waste a tipping fee can be recovered.

5.3 Mixing

The substrate in an agricultural biogas digester is usually mixed intermittently in time intervals ranging from several times daily to several times per hour. The power applied for mixing varies in function of size and form of the digester and the composition of the substrate. It covers the range from 10 to 100 wh/m^3.d. Usually a value of more than 30 wh/m^3.d is recommended.

There are several reasons for mixing:

- Inoculation of the fresh substrate with digestate
- Distribution of heat to achieve an even temperature through out the digester
- Avoid or disrupt scum and sediment formation
- Release of biogas bubbles trapped in the substrate

If the substrate is not mechanically mixed it tends to separate, i.e. it forms a sediment and a scum. The scum is particularly difficult to remove after it has dried out through continuous gas production.

As long as the particles floating to the top are incorporated into the liquid phase, they remain wet and soft and can easily be removed.

In larger digesters usually two to three mixers are applied in different depths of the digester. In small-size family plants only one stirrer is installed for economical reasons. It is therefore important that it is adjustable for the mixing of a possible scum and sediment formation (Fig. 6.).

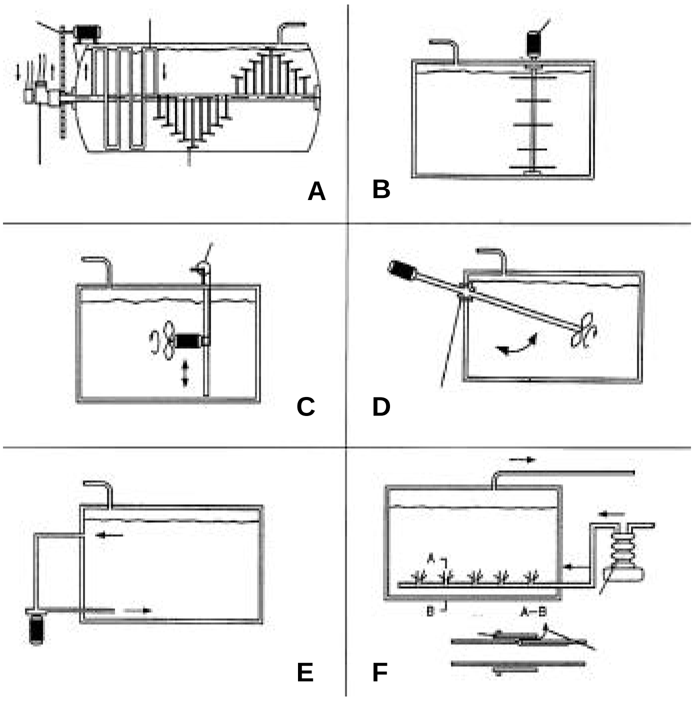


Figure 6: Different types of mixing (Schulz, 1996)

A: Horizontal paddle stirrer
B: Vertical paddle stirrer
C: Adjustable propeller mixer
D: Propeller miser on a swivel arm
E: Hydraulic mixing
F: Air lift

An equally important characteristic of stirring is the mixing of the cold influent with the warm material under degradation. It is obvious that the raw waste is inoculated with the anaerobic bacteria in the digester. But at the same time it is heated. If the temperature remains low no bacterial activity will take place for an extended period.

For all the mixing purposes mentioned, the speed of rotation is not important. Usually slowly rotating mixers are applied with rotations as low as 15-50 rpm.

Again, not all types of stirrers are equally well adapted for all possible substrates. Hydraulic and pneumatic stirrers are restricted to dilute substrates such as pig manure with little potential for scum formation. A horizontal paddle stirrer, on the other hand, is especially well designed for straw-rich cattle manure. However, it can also handle more dilute substrates.

The most widely used stirrer are the propeller mixers. They allow the most flexible application with respect to the substrate composition and the form and size of the digester.

The only limit is the temperature for submerged motors. Above a fermentation temperature of 40°C there is not enough cooling.

5.4 Pumping

Pumping of manure and similarly inhomogeneous substrates is a never ending problem of plugging and leaking. In the recent years a numer of pumping concepts have been improved through biogas installations. Previously pumps were used for a limited numer of hours, when the manure was spread on the fields. In biogas installations, however, pumps are in operation over several hours a day, 365 days a year.

For most agricultural purposes submerged **centrifugal pumps** (Fig. 7A) are used. They are robust and low-cost. However for biogas applications they have stringent limits:

- The volumetric pumping capacity is strongly dependent on pressure, i.e. on pumping height and substrate composition.

- Manure behaves like a non-Newtonian liquid (diauxy), which means the pumped volume increases with pumping time, i.e. with decreasing viscosity.
- The pump is susceptible to plugging by coarse material (pieces of string, metal, wood, etc). Protecting shields can improve the situation, but do not solve the problem.

For dilute waste streams which are low in particulate matter this pump can still be highly recommanded.

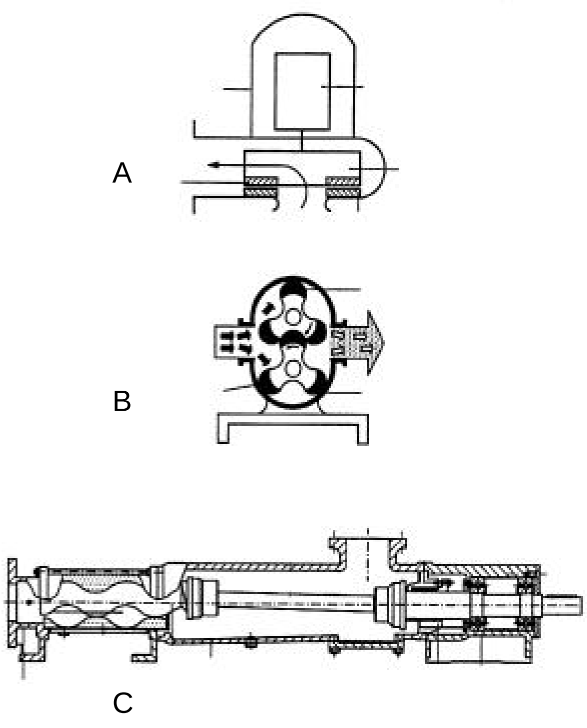


Figure 7: Popular pump types for manure

A: Submerged centrifugal pump
B: Rotating piston pump
C: Excentric screw pump

In recent years **rotating piston pumps** (Fig. 7B) have undergone considerable development. They are now the most tolerant and reliable pumps for co-digestion of particulate substrates high in dry matter. They are easy to maintain and repair. However, they are noisy.

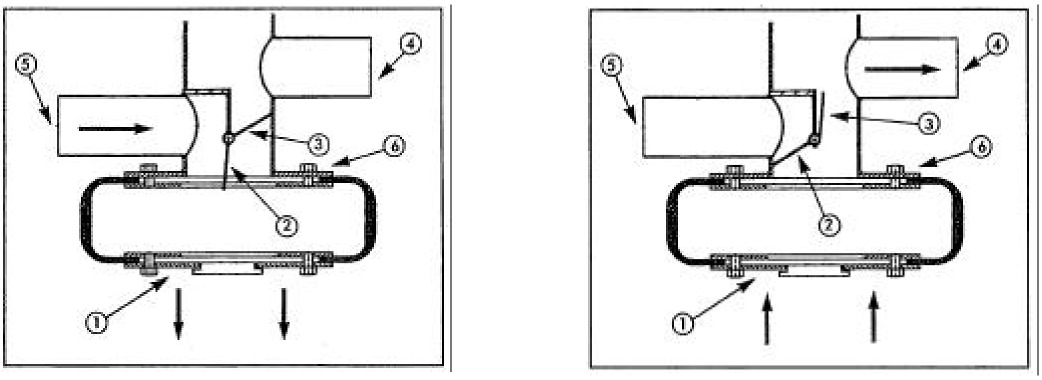
Excentric screw pumps (Fig. 7C) are very well adapted to concentrated animal manure and co-substrate (t to 12%) as long as the particulate material (straw) is chopped to sizes of less than 3 to 5 cm in length.

They display a stable pressure independent of the substrate viscosity, i.e. the pumped volume is linearly correlated to the time of operation. When they stop they are tight. Valves are therefore only a security measure but not an obligation.

However, they are very susceptible to sand, stones which lead to rapid wear of the excenter screw or strings and long straw halms which will plug the screw.

Recently a farmer has developed a new type of **membrane pump** which is completely tolerant to particles (Fig. 8). The "membrane" is in fact a small tyre of a motor bike. The pump is robust, easy to maintain, low-cost and has a very low power consumption.

Its apparent disadvantage - a low volumetric capacity - is rather an advantage for biogas plants, because feeding preferably occurs over an extended time period.



A) B)

Figure 8: A newly developed tire (membrane) pump

A excentric motor pulls the membrane (1) upwards (8A), closes the valve of the inlet (2), opens the outlet valve (3) and pushes the substrate to the outlet pipe (4).

A reversed operation is shown in Fig. 8B where the substrate is sucked into the pump (5), opens the inlet valve (2) and closes the outlet valve (3).

6. Pre- and post-treatment

Pre-treatment of substrates in agricultural biogas plants became necessary when co-digestion was introduced (Steffen et al., 1999). From an engineering point of view three processes can be accomplished during pretreatment:

- Removal of undesired particles
- Size reduction of bulky substrate
- Blending of different waste streams

- Volumetric buffering between delivery and digestion of waste material
- Hygienisation of food waste

In small-scale installations waste streams which require **sorting** like restaurant, yard and household waste should be avoided. It is strongly recommended that so called “clean” waste like residues from food factories or horticultural wastes are accepted in preference.

In large-scale plants sorting can be done either manually and/or mechanically.

Bulky material such as pieces of wood, bones, glass and plastics is best removed by hand on a conveyor belt. Alternatively rotating screens with mesh sizes between 40 and 80 mm can be applied. In both cases additional removal of iron and non-iron metals is recommended.

The legal requirements for **hygienisation** are different in the individual countries. An excellent overview is given by Colleran (1999) and Nordberg (1999).

Usually the different categories of waste streams are collected in separate receiving tanks from where they are treated. After treatment they are either homogenised in an influent holding tank or are fed to the digester individually. In either case, care has to be taken that the nutritional composition remains as balanced as possible.

There are actually two major **post-treatment processes** for the digestate:

- Hygienisation
- Solid/liquid separation

In Denmark for most waste types a sanitation step after the digestion is required. This is a very reasonable and low-cost solution. The digestate has to be retained in a vessel over a guaranteed time. The time is defined in function of the digestion temperature and the sanitation temperature. Typical treatment times range from 2.5 hours to 8 hours (Colleran, 1999).

Solid liquid separation usually is applied when part of the digestate has to be transported over a long distance, i.e. more than 10-15 km, in order to reduce the volume.

In some instances only a small partial stream is separated. The liquid part is utilised for the desulphurisation of the biogas in a washing tower. The liquid part, rich in sulphur, is recycled to the digester.

References

Angelidaki, I. and Ahring, B.K. (1992). Effects of free long-chain fatty acids on thermophilic anaerobic digestion. Appl. Microbiol. Biotechnol. 37: 803-812.

Angelidaki, I.; Petersen, S.P. and Ahring, B.K. (1990). Effects of lipids on thermophilic anaerobic digestion and reduction of lipid inhibition upon addition of bentamite. Appl. Microbil. Biotechnol. 33: 469-472.

Baserga, U.; Egger, K. und Wellinger, A. (1995). Biogas Produktion aus Festmist. FAT Bericht No. 451. 12 p.

Buswell, A.M. and Hatfield, W.D. (1936). Bulletin 32, Anaerobic Fermentations. Urbana, K. Dept. of Registration and Education.

Chynoweth, D.P.; Mah, R.A. (1971). Anaerobic biological treatment processes. Adv. Chem. Sci. 105; 41-53.

Coleran, E. (1999). Hygienic and sanitation requirements in biogas plants treating animal manures or mixtures of manures and other organic wastes. AD-Nett, Technical paper, 13 p.

Demeyer, D.I. and Hendrickx, H.K. (1997). The effect of C_{18} unsaturated fatty acids on methane production in vitro by mixed rumen bacteria. Biochim. Biophys. Acta 137: 484-497.

Fair, G.M. and Moore, E.W. (1934). Time and rate of sludge digestion and their variation with temperature. Sewage Works J. 6 (1): 3-13.

Hanaki, K.; Matsuo, T. and Nagase, M. (1981). Mechanism of inhibition caused by long-chain fatty acids in anaerobic digestion process. Biotechnol. Bioengg. 23: 1591-1610.

Kaspar, H.F. and Wuhrmann, K. (1978). Kinetic parameters and relative turnovers of some important catabolic reactions in digesting sludge. Appl. Environ. Microbiol. 36, 1-7.

Koster, I.W. and Lettinga, G. (1988). Anaerobic digestion at extreme ammonia concentrations. Biological Wastes 25: 51-59.

Kroeker, E.J.; Schulte, D.D.; Sparling, A.B. and Lapp H.M. (1979). Anaerobic treatment process stability. J.WPCF 51 (4): 718-727.

Lusk, P. (1997). Systems and markets overview of anaerobic digestion. IEA Bioenergy, Anaerobic digestion activity. 22 p.

Lusk, P. (1998). Methane recovery from animal manures. The current opportunities casebook. NREL, Golden, Colorado. pp. i to 7-3.

Maly, J. and Fadrus, H. (1971). Influence of temperature on anaerobic digestion. J. Water Poll. Control Fed. 43: 64.

McGhee, T.J. (1968). Low temperature anaerobic digestion. Ph.D. Thesis, University of Kansas. University Microfilms, Ann Arbor, Michigan.

McCarthy, P.L.; McKinney, R.E. (1961). Volatile acid toxicity in anaerobic digestion. J.Wat.Control. Fed. 33, 223-232.

Meynell, P.-J. (1976). Methane: Planning a digester. Prism Press, Dorcester. Dorset. p. 3.

Nordberg, A. (1999). Legislation in different European countries regarding implementation of anaerobic digestion. AD-Nett, Technical Paper, 33 p.

O'Rourke, J.T. (1968). Kinetics of anaerobic waste treatment at reduced temperatures. Ph. D. thesis, Stanford University, California. 224 p.

Popoff, L. (1875). Über die Sumpfgasvergärung. Archiv über die gesamte Physiologie des Menschen und der Tiere von Pflüger, Bd. 10.

Priestly, J. (1790). Experiments and observations on different kinds of air. Vol. I, p. 206, Birmingham.

Rinzema, A. (1988). Anaerobic treatment of waste water with high concentrations of lipids or sulfate. Ph.D. thesis, Wageningen Agricultural University, The Netherlands.

Roediger, H. (1955). Die anaerobe alkalische Schlammfaulung. gwf, Schriftenreihe Wasser, Abwasser Bd. 1. R. Oldenbourg Verlag, München und Wien.

Steffen, R.; Szolar, O. and Braun, R. (1999). Feedstocks for anaerobic digestion. AD-Nett, Technical Paper, 21 p.

Stevens, S.A. and Schulte, D.D. (1979). Low temperature anaerobic digestion of swine manure. J. Environm. Engng. Div. 105 (1): 33-42.

Sutter, K. and Wellinger, A. (1987). Güllengrube als Biogasanlage. FAT-Berichte 304: 1-8.

Titjen, C. (1975). From Biodung to Biogas - Historical review of European experience. In: (W.J. Jewell ed.) Energy, agriculture and waste management. Ann Arbor Science. pp. 347-359.

Van Brakel, J. (1980). The ignis fatuus of biogas. Delft University Press. 141 p.

Varell, V.H.; Isaacson, H.R. and Bryant, M.P. (1977). Thermophilic methane production from cattle waste. Appl. Environ. Microbiol. 33, 298-307.

Volta, A. (1778). Briefe über die natürlich entstehende, entzündbare Sumpfluft. H. Steiner & Co., Winterthur. 172 p.

Wellinger, A. (1985). Process parameters affectin methane production in mesophilic farm digesters. Process Biochem., Oktober: 131-137.

Wellinger, A. and Fruteau, H. (1998). Untersuchungen zur anaeroben Aufbereitung von Schlachthofabfällen. Report to the Swiss DOE, 19 pages.

Wellinger, A. and Lindberg, A. (1999). Biogas upgrading and utilisation. IEA Bioenergy. Task 24. 18 p.

Wellinger, A.; Egger, K. und Sutter K. (1985). Biogasproduktion und -verbrauch: Biologische und verfahrenstechnische Grundlagen. Schriftenreihe der FAT 23, Tänikon. 100 p.

Zeemann, G.; Sutter, K.; Vens, K. and Wellinger, A. (1998). Psychrophilic digestion of dairy cattle and pig manure: Start-up procedures of batch, fed-batch and CSTR-type digesters. Biological wastes 26: 15-31.

Zeemann, G.; Wiegant, W.M.; Koster-Treffers, M.E. and Lettinga, G. (1985). The infulence of total ammonia concentration on thermophilic digestion of cow manure. Agric. Wastes 14: 19-35

Zillig, W. et al. (1981). Thermoproteales: A novel type of extremely thermoacidophilic anaerobic archebacteria isolated from Icelandic Solfataras. Zbl. Bakt. Hyg., i.Abt. Orig. C2: 205-227.