agricultural-waste digesters are designed to run gas-engine generators and here waste engine heat can be used for producing hot water for digester, and possibly other, heating purposes. Some 25% of the fuel energy can be obtained as electrical energy and up to 65% more of the fuel energy can be recovered from engine and exhaust heat-exchangers. A very approximate figure of 30% of the biogas energy is usually used to suggest the heating requirements of a digester in a temperate climate, but this obviously varies.

The situation all over the world at the moment with regard to the bigger agricultural-waste digesters is one of development and testing. There is no difficulty about the microbiological side of the process; digestion once started is stable. What problems are being encountered concern the handling of the feedstocks, and sometimes on farms provision of feedstocks of suitable consistency and uniformity from day to day. Other aspects being tested are the life of the gas engines being used as these differ froœ the large dual-fuel engines which have been used for many years in most of the sewage works using biogas energy. The life of pumps and other components of the actual digester construction has still to be assessed. While some digesters are having more difficulties than others, many are now running successfully and a problem in some cases is to find uses for the energy being produced.

It is difficult to find out how many of the small-scale, 'developing country', digesters are continuing to run successfully, but there is no doubt that many are running. However, one of the problems here is to find a design cheap enough for the very poor farmer, as well as to improve the efficiency of the digesters.

While there remains research work to be done on optimum conditions for digestion of some feedstocks and, particularly, mixed waste feedstocks, testing of different digester designs, use of digested sludge for other than fertilizer purposes, and so on, digestion has now got into the large-scale testing and development stage and the next few years should see the number of working digesters increasing. Digestion is the alternative fuel source of most widespread possible application, using, as it does, almost any organic waste, and its ability to use fibrous vegetable matter is putting the energy-farm nearer practical application in countries where crop production and energy requirements of the population are suitable. Digestion can also be used in conjuction with other forms of bio-energy production to utilize vegetable residues from sugar or starch production – there are many possibilities now being or to be exploited.

Some books and review papers on anaerobic digestion:

P.N. Hobson, S. Bousfield and R. Summers, The anaerobic digestion of organic matter. Crit. Rev. environ. Control *4*, 131 (1974).

M.P. Bryant, Microbial methane production – theoretical aspects, J. Anim. Sci. *48*, 193 (1979).

P.N. Hobson, Biogas production – agricultural wastes, in: Energy from the biomass, p.37. Watt Committee on Energy Report 5, London 1979.

P.N. Hobson, S. Bousfield and R. Summers, Methane production from agricultural and domestic wastes. Applied Science Publishers, Barking, England, 1980.

Proceedings 1st Int. Symposium on Anaerobic Digestion, Cardiff 1979. Applied Science Publishers, Barking, England, 1980.

P.N. Hobson and A. Robertson, Waste treatment in agriculture. Applied Science Publishers, Barking, England, 1977. (Amounts of wastes produced, anaerobic, aerobic, physical and chemical methods for pollution control).

## Possibilities of gas utilization with special emphasis on small sanitary landfills

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*Summary.* Based on general observations on gas production in sanitary landfills, properties of some important landfill gases are discussed, especially with regard to the potential heat recovery. It has been shown, based on practice oriented considerations, that the utilization of landfill gases can be worthwhile even in small landfills. A scheme has been given which shows all the possibilities for collection, pretreatment, storage and combustion of the gases. The question of energy storage and energy utilization has also been addressed. The scheme has been discussed, as well as some of the processes, using the example of the hot water generation plant in the Croglio sanitary landfill in Tessin (Switzerland).

Calculation of the running costs shows that this plant, which is designed for a 335 MJ/h production, is working economically.

The term 'refuse management' implies the re-utilization of materials and/or energy. It is very seldom however, that one encounters good examples for such re-use, especially when dealing with small refuse disposal areas.

Since even in small landfills (landfill volume up to

$10^6$ $m^3$, refuse quantity up to 100 t/d), a considerable gas quantity can be produced, a pilot plant has been constructed[1] to study the possibility of utilizing the generated gas. The data thus obtained on gas utilization in a sanitary landfill serve as the basis of the following report.

*Methane production*

Knowledge of the production of methane, including that created in landfills, has been available for a long time. However, only recently, now that it has become clear that such gases can create safety hazards as well as problems in recultivation of the land[2,3], has one started paying much attention to its generation in landfills. In answer to the question why these problems have arisen only recently, there are any number of hypotheses. The following, however, seems to be most probable: In the past, refuse was buried by the communities in small, uncontrolled dumpings, which allowed aerobic decompositon. Today, we have large sanitary landfills, where the organic materials are mostly decomposed anaerobically.
Aerobic fermentation is caused by microorganisms which are also responsible for sludge digestion[4]. These organisms are able to convert part of the organic materials present in refuse into methane (table 1).
For a detailed summary of organic substances in refuse, refer to Stegman[3].

Table 1. Waste composition[5]

| Waste classification | Switzerland 1973 (%) | Federal Republic of Germany 1971 (%) |
|---|---|---|
| Paper | 36 | 22-25 |
| Synthetics | 4 | 2-3 |
| Textiles, leather | 8 | 2-4 |
| Rubber, wood Kitchen scrap | 20 | 10-20 |
| Glass, gravel Ceramics | 12 | 10-16 |
| Metals | 5-8 | 4-9 |
| Miscellaneous | 4-7 | — |

Table 2. Constituents so far found in landfill gases (from Winter[7])

| Constituents | | |
|---|---|---|
| Methane | $CH_4$ | 0-85% by vol. |
| Carbon dioxide | $CO_2$ | 0-88% by vol. |
| Carbon monoxide | CO | 2.8% by vol. |
| Ammonia | $NH_3$ | 0-0.35 ppm |
| Hydrogen | $H_2$ | 0-3.6% by vol. |
| Oxygen | $O_2$ | 0-31.6% by vol. |
| Nitrogen | $N_2$ | 0-82.5% by vol. |
| Hydrogen sulphide | $H_2S$ | 0-70 ppm |
| Ethylmercaptan | $C_2H_5SH$ | 0-120 ppm |
| Acetaldehyde | $CH_3CHO$ | 150 ppm |
| Acetone | $C_2H_6CO$ | 100 ppm |
| Benzene | $C_6H_6$ | 0.08% by vol. |
| Argon | Ar | 0.01% by vol. |
| Heptane | $C_7H_{16}$ | 0.45% by vol. |
| Nonane | $C_6H_5CH_3$ | 0.09% by vol. |

Besides methane, a large amount of carbon dioxide is produced in landfills. Other gases are present only in small quantities (table 2).
With respect to the total attainable gas quantity, the information given in the literature varies from 60 to 290 $m^3$ gas/t refuse[3]. From our own experience, a gas quantity of 100 $m^3$ methane/t refuse can be expected to accumulate during 20 years.
Immediately after the deposit of refuse, a high production of $CO_2$ begins which reduces gradually in favor of methane production. The gas production varies greatly in quantity and composition during the first months. The primary unstable phase is followed by a second stable phase, where $CH_4$: $CO_2$ can reach a constant value of 3:2 (fig. 1).

*Properties of some landfill gases and gas mixtures*

It has already been mentioned that the gas mixture of landfill refuse consists mainly of methane and carbon dioxide. Relatively large amounts of nitrogen and oxygen are often present as well, especially in cases of forced suction, or in areas directly influenced by the atmosphere. Carbon monoxide and hydrogen, if they appear at all, are present at a low concentration (see also table 2).
Even in the stable phase the concentrations can vary, thus changing the ignition and combustion parameter. Table 3 shows the physical and chemical properties of the individual gases. The properties of the various gas mixtures are not yet well known.

Due to the high $CH_4$ content, the combustion parameter of methane itself is often used for the entire mixture. This yields on the one hand, an over-estimation of the energy properties of the concerned mixtures, and on the other hand, an under-estimation of the danger caused by the presence of a small quantity of CO and/or $H_2$. From the experiences with

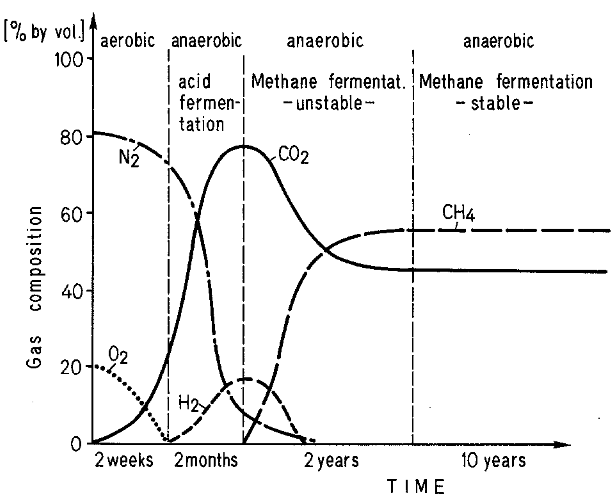


Figure 1. Gas composition during decomposition of municipal refuse (from Farquar et al.[6]).

Table 3. Properties of some gases[7-11]

| Gas | Formula | Density (kg/m³) | Net calorific value (kJ/m³) | Critical temperature (°C) | Ignition range in air lower/upper (% by vol.) | Flame velocity (m/sec) | Minimum ignition energy (mJ) | Ignition temperature (°C) | Water solubility (g/l) | Common properties |
|---|---|---|---|---|---|---|---|---|---|---|
| Methane | $CH_4$ | 0.717 | 35,600 | − 82.5 | 5/15 | 0.4 | 0.6–0.7 | 600 | 0.0645 | Odorless, colorless, non poisonous |
| Carbon dioxide | $CO_2$ | 1.977 | 31.1 | 31.1 | – | – | – | – | 1.688 | Odorless, colorless, non poisonous at low concentrations[7] |
| Oxygen | $O_2$ | 1.429 | | − 118.8 | – | – | – | – | 0.043 | Odorless, colorless, non poisonous |
| Nitrogen | $N_2$ | 1.250 | | − 147.1 | – | – | – | – | 0.019 | Odorless, colorless, non poisonous, non inflammable |
| Carbon monoxide | CO | 1.250 | 12,640 | − 139 | 12.5/74 | 0.5 | – | 600 | 0.028 | Odorless, colorless, poisonous, inflammable |
| Hydrogen | $H_2$ | 0.090 | 10,760 | − 239.9 | 4/74 | 2.8 | 0.05 | 560 | 0.001 | Odorless, colorless, non poisonous, inflammable |
| Hydrogen sulphide | $H_2S$ | 1.539 | | 100.4 | 4.3/45.5 | | | | 3.846 | Colorless, poisonous |
| Air | | 1.29 | – | – | – | – | – | – | – | Odorless, colorless, non poisonous, non inflammable |

the Croglio sanitary landfill, where no considerable release of CO and $H_2$ was detected, the following statements can be made:
1. Under normal conditions, the flame of methane mixtures and air can reach a velocity of 0.4 m/sec. The combustion of the landfill gases released directly into the air yields a lower flame velocity (< 0.2 m/sec). This usually causes the flame to be unstable, leading to lifting and extinction.
2. While an ignition energy of 0.7 mJ is required for the methane and air mixture, a higher energy is necessary for the directly released gases from landfills. The gas ignition in the Croglio sanitary landfill has an electric arc of 15,000 V and 10 mA by an electrode gap of about 10 mm.

*Problems with release of landfill gases*

The gases produced through anaerobic refuse decomposition are easily ignited, and their combustion in absence of air can quickly set off an explosion. Control and preventive measures are therefore necessary in order to avoid this risk. Since the gases migrate underground, one should not under-estimate the danger for people and objects in the immediate vicinity. A strict management of the landfill is required to prevent such dangers. Through technical means, the leakage and underground movements of the gases can be reduced, controlled or eliminated.
Specific safety measures are required for the landfill personnel in order to ensure safety in the working areas. The gas mixtures of landfill contain a small amount of malodorous materials, which can be a nuisance to the personnel, as well as the residents in the neighborhood, if a leakage occurs. This unpleasant odor can be counteracted by the application of suitable chemical substances, or better yet, by careful coverage of the refuse with soil, and by collecting, processing or combusting of the gases.

*Advantages of methane production from landfills*

It is quite understandable that methane represents an important energy source. As we have seen from the above, 1 kg $CH_4$ is equivalent to 1.18 kg fuel oil, and 1 m³ $CH_4$ to 1 l fuel oil.
Assuming: a) that 1 kg refuse can generate about 100 l $CH_4$, b) that 40% of the produced methane can be recovered, whereas the rest is lost in the soil and atmosphere, and c) that each person produces on the average 0.75 kg refuse per day (this value has been calculated for the area of 'Consorzio eliminatione rifiuti del Luganese'), the potential methane production can be calculated to 75 l · $person^{-1}$ $d^{-1}$, of which about 30 l would be usable. The following figures illustrate the amount of methane, i.e., the fuel oil equivalence of the population of a small Swiss region (Lugano).

| | |
|---|---|
| Population, approximately | 100,000 |
| Theoretical methane production | 7500 m³/d |
| Recovery (40%) | 3000 m³/d |
| Fuel oil, approximately | 3000 l/d |

The above shows, that even in such areas, it is worthwhile to consider the possibility of energy recovery from refuse landfill.

In the following discussion, some various means of gas recovery and utilization of communal refuse in organized landfills by anaerobic decomposition are examined.

The blockscheme in figure 2 shows the most important elements of a full-scale plant for gas recovery and utilization. It should be noticed that some elements are not absolutely necessary. The different elements separated by dashed lines, numbered 0-5, indicate the elements within the boundaries of the landfill.

The quality of landfill gases can be compared with that of pure methane. A landfill produces gas of optimal quality if the composition of the mixture has more than 60% of vol. $CH_4$, and less than 50% of vol. $CO_2$ and 1% of vol. for the remaining gases. It is undesirable to have a high $CO_2$ content, and for $N_2$ or $O_2$ to be present; especially if the ratio $O_2$:$N_2$ is different from that of the atmosphere. In such cases, the atmospheric oxygen can diffuse into the landfill, causing the $CH_4$ to oxidize while the atmospheric nitrogen remains unchanged.

*Recovery of gases*

Water drains are often the means by which the gases

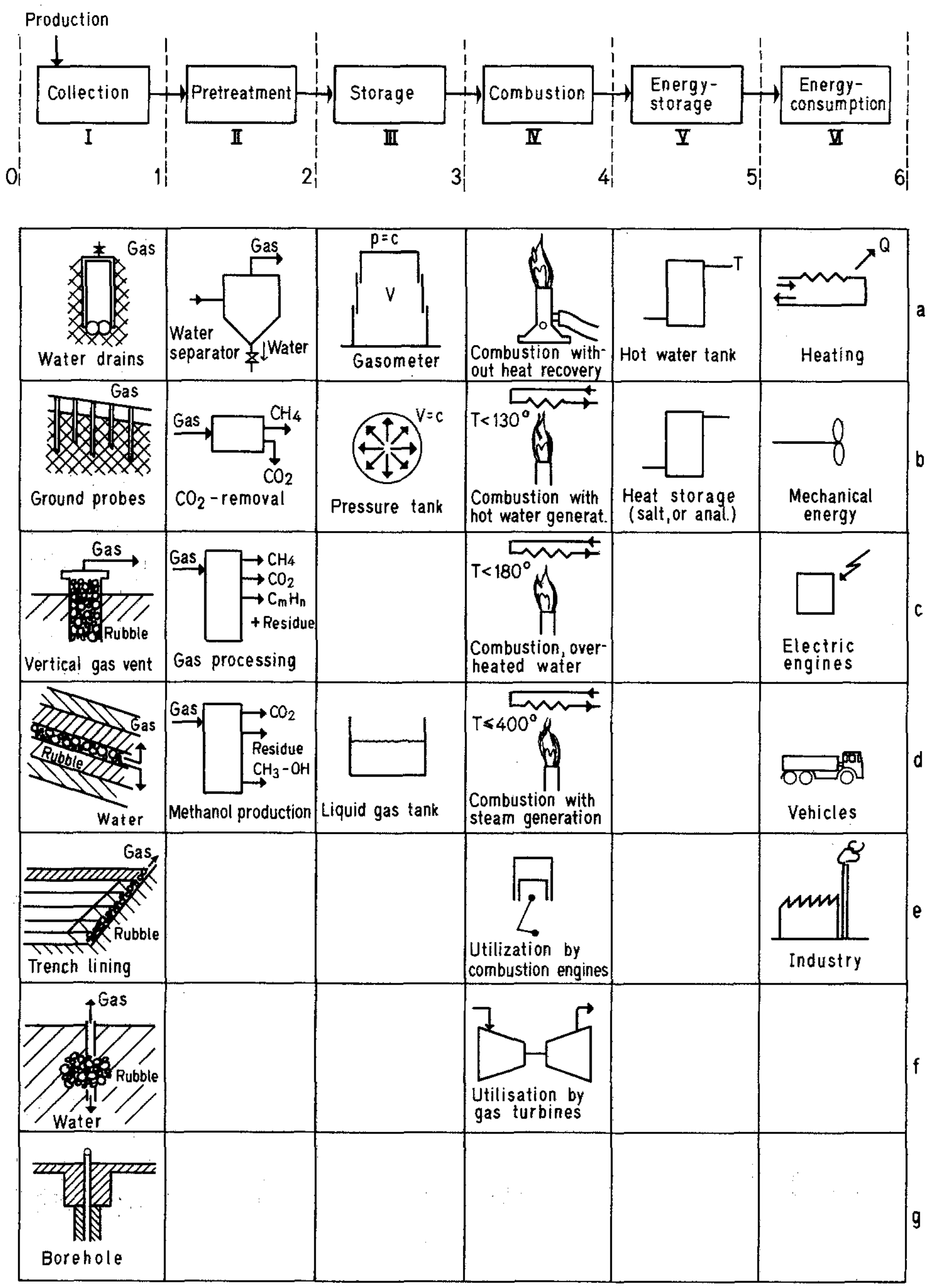


Figure 2. Possible elements of a landfill gas utilization plant.

tend to travel (fig. 2-I/a). This causes a release of unpleasant and easily flammable materials at the outlets. It is therefore advisable to use a siphon system to enable drawing of the gases without their being mixed too much with air. Experience from the Croglio sanitary landfill shows that atmospheric conditions can easily influence the composition of gases drawn. Since it is generally impossible to avoid a gas exchange between atmosphere and drainage system, the gases obtained have a large amount of nitrogen and oxygen. This means that the energy content of the gas mixture is very low. If a large amount of water flows through the drains, more $CO_2$ than $CH_4$ are dissolved (under normal conditions, about 1 l $CO_2$/l $H_2O$ and 0.01 l $CH_4$/l $H_2O$). This causes the ratio $CH_4$:$CO_2$ in mixed gases to change in favor of $CH_4$. The drainage pits can eventually become potential explosion chambers and strict safety measures must therefore be taken.

The gases can also be sucked through ground probes (fig. 2-I/b) which are driven into the landfill. This allows a relatively inexpensive collection system. At the Croglio sanitary landfill, steel-tipped, 5-cm diameter ground probes were used, driven by a pneumatic hammer and reaching 5-10 m in depth.

From an area of about 1000 $m^2$, about 40-60 $m^3$ $CH_4$/d were extracted in 2 months time by using 10 ground probes. At the time of experiment, the landfill had been closed for 3 years.

The quality of the gases drawn off depends strongly on the air diffused into the landfill. This effect can be influenced by covering the landfill. The parameters for the gas suction as well as the distances between the individual probes should be determined separately for each landfill.

This system has the advantage that it can be installed immediately after completing the landfill, and without special preparations. Also, even if the collected gases seldom show outstanding qualities, gas mixtures of relatively constant composition can be easily combusted. This system is especially suitable where there is limited vegetation caused by high gas content in the upper layers of soil.

Gas recovery by way of a vertical stone-filled gas vent (fig. 2-I/c) is only effective if the upper part is well isolated from the atmosphere. If not, the gas quality is expected to be bad or the gas mixture can even be uncombustible. If there is not enough suction, the undesirable, malodorous gases can be an additional problem. To prevent possible water infiltration, this drainage should be connected to a water drain located above the soil layer. Already during the landfill operation, the gas vents should be filled with stones, which can disturb the truck traffic within the landfill. Since the gas vents must remain opened during this phase, they present a danger and are often a source of malodorous fumes.

Gas recovery from slanted combined drains (fig. 2-I/d) is possible when, during the filling phase of landfill, canals are built to let the water and gases travel through. These canals are easily built, are constructed in the form of a dry stone wall, and are slanted towards the surface of the landfill. These drains have the same properties as the gas vents. However, they can be more easily isolated from the atmosphere and disturb the landfill less during the filling phase.

Due to the fact that the landfill body is sinking while the surrounding ground stays stable, canals are often formed where gases travel easily to the surface. Such gas emissions can be accelerated by building a wall of stones or gravel (fig. 2-I/e). The extraction technology should proceed similar to the stone gas vent. The underground gas migration to the open should be controlled or reduced.

The gas recovery out of a landfill via a specially incorporated stone lens (fig. 2-I/f), can yield good results if this is located deep enough (beyond atmospheric influence), and if it can function as a collecting place for natural and man-made preferred flow channels (see also fig. 2-I/d). Seepage accumulation, however, should be avoided by, for example, connecting the base of the lens to a water drain or to a safe percolation zone. Experiences in the Croglio and other sanitary landfills confirm that the stone lenses will retain seepage if not drained. The recovered gases are generally of good quality as long as no air is sucked in through the drains.

Recovery with boring probes (fig. 2-I/g) is a relatively expensive system but gives the best results. Such borings are usually possible even after the completing of the landfill. The sucked gas is of a very good quality containing 95-99% of $CH_4$ and $CO_2$. In order to prevent the gas quality from deteoriating by infiltrated air, the upper part of the bores must be isolated from the atmosphere with 1-3-m-thick layer of concrete surfacing or other similar materials. Even with such boreholes there is a danger that they will eventually fill with water so that they must be taken out of service. According to our experience, the diameter of the borehole is determined by the gas quantity to be drawn off. However, the costs of the borehole increase disproportionally to the diameter. It is therefore not economical for small and medium landfills to have a borehole more than 20 cm in diameter.

*Pretreatment of gases*

The recovered landfill gases, depending on their utilization must be pretreated to a greater or lesser extent.

The emanating landfill gases usually have a temperature of about 30 °C and a relative humidity of 100%. The cooling down of gases in the pipes causes water condensation such that the deepest places fill with water. It is therefore necessary to separate water from the gases. How much needs to be taken out depends on how the gases will be utilized. A certain amount must be removed to prevent retention of water in measuring apparatus, pipes, ventilators, etc. The simplest water separation technique is to place a sufficiently large tank in the coolest area. These tanks should also have an emptying device, and are to be located at the lowest part of the pipes. When such tanks are filled additionally with fine gravel, they can function as a safety device against backfiring (fig. 2-II/a).

The $CO_2$ content must often be reduced in order to optimize combustion requirements or because the customers request it. One possible way of removing $CO_2$ is through the absorption by liquids, for an example, trietylamine (fig. 2-II/b). The $CO_2$ can be then released by heating up the liquid. The evaporated $CO_2$ can be reutilized in the event that this is economical. Unfortunately, such plants are only economical if an amount over 1000 $m^3$ $CH_4$/h is produced. They are thus unsuitable for small and medium landfills.

In some cases the separation of $CO_2$ is not sufficient, and other components (for example, $C_nH_m$) must be removed as well (fig. 2-II/c). In these cases, advance processes are needed (for example, by using a molecular sieve). Such a plant with an advance processing stage exists in Palos Verdes landfill near Los Angeles[13]. Also these plants are not economical for small and medium landfills.

The conversion of gaseous methane into liquid methanol (fig. 2-II/d) has significant advantages with regard to transportation and storage. Processes for chemical conversions have been known for a long time, but are not economical. Processes for biological conversions are presently being tested, and depending on the results produced, they could provide a good alternative in the future[14].

*Storage of gases*

Since the gas production in a landfill is relatively constant and cannot be influenced within a short time, and since the energy utilization is nevertheless subject to changes, the following points must be considered: a) If gas production is higher than peak demand, intermediate storage is not required. During the remaining time, a considerable loss of gas is to be expected. b) If gas production is lower than peak demand, a possibility to store the gas must be foreseen, so that the gas supply can best be utilized. The different possibilities of gas storage are shown in the following paragraphs. In principle, only gas mixtures of good quality should be stored, whereby the oxygen content should be kept minimal for safety reasons.

Gasometers (fig. 2-III/a) are systems which have for a long time been known as digesters in sewage treatment plants. They consist of a container with a variable volume, in which the gas is stored almost without pressure. Such containers seem to be uneconomical for small landfills.

Compression containers (fig. 2-III/b) are unsuitable for storing landfill gases. This is due to the fact that the critical temperature of these gases is too low to be liquidized at room temperature ($T_k = -82.5$ °C for methane). This is also true for propane and butane. If these gases are to be utilized as fuel, they should be stored in compression containers which can endure a pressure up to 200 bar. Compression containers can also be installed in small landfills if the gas quality is good, and if safety measures are taken.

The conversion of gaseous methane into liquid methanol would enable easier storage, since a normal liquid container could be used. Unfortunately, such conversion procedures are still in the development stage (fig. 2-III/d).

*Combustion*

The gas obtained from refuse landfill is usually burned in order to eliminate foul odors or to utilize it as an energy source.

In most cases, the heat produced by combustion of landfill gases is not utilized (fig. 2-IV/a). This type of energy waste is only reasonable if there are no consumers for the heat produced, and if the gas quantity is small or the gas quality is poor (a minimum heat equivalent of 125 MJ/h is required).

The easiest way to obtain energy from landfill refuse gases is by producing hot water of relatively low temperature (< 130 °C) (fig. 2-IV/b). The water must be pressurized so that a temperature above 100 °C can be reached. If the hot water is not utilized in the area of production, this system is limited because large, well isolated pipes are required for transportation. Such an installation was built in the Croglio sanitary landfill and is working successfully (see fig. 4).

Combustion with production of super-heated water (fig. 2-IV/c) differs from the above in that the temperature of the water reaches 180 °C. The advantage of this system lies in the fact that the produced heat can be transported more economically.

Combustion with steam generation (fig. 2-IV/d) is suitable for combustion of a large quantity of gases, and in cases where the heat has to be transported over a long distance (several km). Such a system works up to a pressure of 50 bar and a temperature up to 400 °C. Among the 4 systems mentioned, this system is the most expensive and is not economical for small and medium landfills.

The combustion of digester gases has been in practice

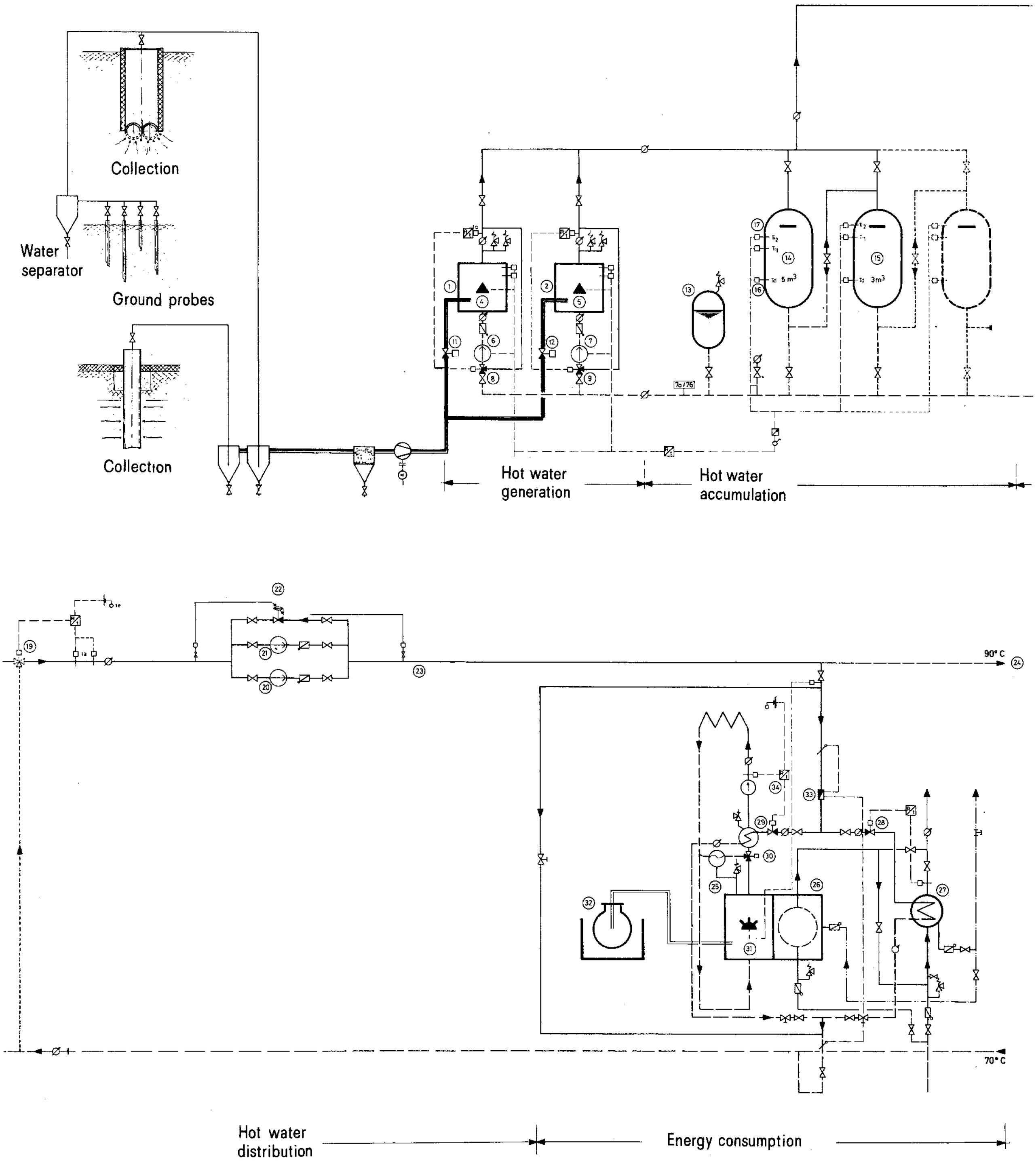


Figure 4. Hot water supply plant system of Croglio's sanitary landfill.

for a long time. Such systems are often found in sewage treatment plants, but little is known about the application in landfills. This combustion of digester gases usually produces mechanical energy (fig. 2-IV/e), which can of course be transformed into electrical energy. The heat waste of the engines is also utilized in some cases. Examples are the 'Fiat Totem'-engine for smaller plants and the 'Caterpillar'-engine for larger plants.

Such a system is now realized in Palos Verdes, where a gas compressor is driven by a gas engine. In the landfill near Turin, a Fiat Totem-engine is utilized and in Croglio, a modified 'Renault'-engine has been recently experimented with. Since the sulfur content in a landfill's biogas is generally very low, in contrast to sewage treatment plants, desulferization is not needed (table 2). The disadvantages of such a system, however, are the high initial and operational costs. It should also be taken into consideration that constant adjustments of vaporizer and ignition are required, due to the changing concentration of the gases. This system is also applicable in small landfills.

Although the initial costs of gas turbines (fig. 2-IV/f) are high, the low operational costs and their durability enables a more economical system than the alternative engines. The disadvantage of gas turbines is the necessity of processing the gases in order to reach a minimum heating value of approximately 22,000 $KJ/m^3$ [15]. In addition, the efficiency of gas turbines is very low if the waste heat is not utilized, and the system can only be operated by specially trained personnel. Therefore, the use of turbines is only worth-while and economical for large landfills.

*Heat storage systems*
The hot water produced could be stored in order to optimize the utilization of the gases, or to minimize the boiler's dimension.
The simplest of heat storage systems makes use of good insulated water tanks (fig. 2-V/a). The water temperature depends on the recovery system (see 'Combustion section'). The large storage volume required is the main drawback. In Croglio, for example, 8000 l of water are stored with $\Delta t$ of 70 °C. This corresponds to a heat amount of about 2500 MJ (equivalent to 60 kg fuel oil). Because of these drawbacks, this system is only economical for small and medium landfills.

To increase the storage capacity of the water tanks, special materials, such as naphtalin or mixtures of diphenyls, could be added (fig. 2-V/b). In this way, the heat capacity could be increased by a factor of 20 using the same volume. The costs, however, limit the usage of such heat storage systems to small and medium landfills only.

*Utilization of energy*
To utilize the energy, the following possibilities are conceivable: direct utilization of hot water or steam, as practised in the Croglio sanitary landfill (fig. 2-VI/a); usage of mechanical energy, as for example in Palos Verdes (fig. 2-VI/b); conversion to electrical energy, as it is often practised in sewage treatment plants (fig. 2-VI/c); operation of vehicles with compressed gas. (This possibility is limited practically to vehicles belonging to the plant facilities (see 'compression containers'). Processes for methanol production would greatly increase the advantages of such a system (fig. 2-VI/d)); and utilization as raw material in industries (fig. 2-VI/e).

*Standard of individual components of System I–VI*
The blockscheme in figure 2 is divided into 6 sections representing various elements either inside or outside of the landfill. The dashed lines 0–6 indicate possible boundaries between each element. It is of course not possible to formulate rules which are always applicable, however, the following guidelines can be given:
- It is not recommended to combust landfill gases directly by using normal commercial means. This is because they are often unsuitable to be operated with such gases. In addition, most of the suppliers are not able to provide specially trained service personnel.
- If normal commercial means are nevertheless desired, the gases should be processed so that they have the same properties as conventional gases (for example, natural gas). These processes are only economical for landfills from which more than 1000 $m^3/h$ methane can be recovered.
- Since the concentration of individual components of gases are subject to wide variations, combustion problems can occur if alternative engines are operated.
- If landfill gases are to be transported, a careful removal of water is necessary since the condensation of the water in the pipes creates problems.
- There is no problem with direct transportation of heat, at least for small amounts (up to 0.2 Mcal/h) over short distances. For amounts larger than 0.2 Mcal/h) and for longer distances, super-heated water or vapor should be used.
- Because of hygienic reasons, one should refrain from supplying gases directly to consumers.

In summary, it can be said that ideally the processes I–V (shown in blockscheme of paragraph 2) should be located directly in or near the landfill.

*The hot water generation in the Croglio sanitary landfill*

Using the above mentioned guidelines in Croglio, the utilization of energy is realized in the form of a hot water generation plant according to the following scheme.
The plant consists of 4 units, hot water generation, hot water storage, water distributor, and energy consumer; these are designed to enable further expansion.
Two boilers with a total production of 335 MJ/h are installed for the *hot water generation*. They are

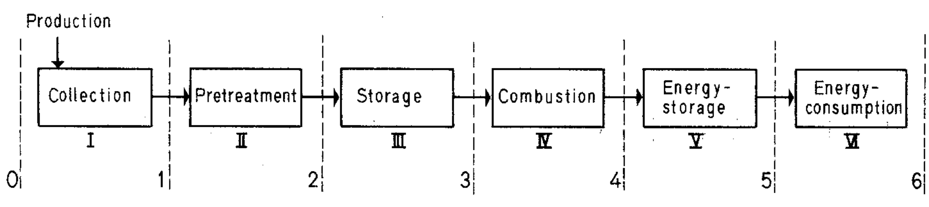


Figure 3. Blockscheme of the Croglio sanitary landfill.

especially equipped with atmospheric burners for combustion of landfill gases. Each boiler has its own individual water cycle and feeds into the hot water tank.

The *hot water storage* consists of 2 isolated cylindrical tanks, which function according to thermal stratification, and are placed in series. The storage volume is 8 $m^3$, and the temperature between 60 and 130 °C. The tanks are connected to a pressure equalizing tank.

*Hot water distribution* consists of fixed and flexible isolated pipes (heat transfer coefficient of polyurethanfoam isolation at 20 °C: 0.084 kJ/mh °C)[16], of hot water pumps and additional pressure regulators. The flexible pipes to the consumers are put under ground. A part of the hot water produced is used directly for the operation of the landfill heating and sanitary installations, while the rest is transported to private consumers. Heat exchangers are installed between the hot water cycle and the consumers for operational safety reasons. In order to ensure independence of consumers during disturbances, the heat exchangers are installed parallel to the existing heating plant. If the hot water supply cuts out, the heating plant of the consumer starts functioning automatically.

*Costs*

Based on the data obtained from the Croglio sanitary landfill, several cost aspects are given below to show the amount of investment required for a plant which can function economically if hot water consumers are in the immediate vicinity.

| | |
|---|---|
| *Investments (including salaries)* | |
| Burners and boilers (pipes 335 MJ/h) | SFr. 15,000.- |
| Hot water storage (2 tanks with a 3-$m^3$ content) | SFr. 11,000.- |
| Installations for heat transport (pipe lines, circulating pumps, valves, etc.) | SFr. 6,000.- |
| Underground pipes to the consumers (flexwell-pipes 30 m each way) | SFr. 10,000.- |
| Additional installations at the consumer (heat exchanger, boiler, electrical controls) | SFr. 15,500.- |
| Miscellaneous (costs for planning, etc.) | SFr. 7,500.- |
| Total investments | SFr. 65,000.- |
| *Revenues* | |
| Savings at the landfill operation itself by the conversion from electricity to landfill gas combustion for the production of hot water | SFr./y 8,000.- |
| Estimated energy supply to the consumers (introduction price) | SFr./y 1,570.- |
| Total revenues and savings respectively | SFr./y 9,570.- |
| *Amortization* | |
| Yearly amortization of 6% interest in 10 years | SFr./y 8,450.- |

*Experiences with the plant*

The mentioned plant has been operating automatically since November 1979 without failures. The daily methane consumption is presently 150 $m^3$, and the estimated efficiency is around 0.6.

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1 M. Gandolla, Gasverwertung bei der verdichteten Deponie Croglio, ISWA Journal *25,* 16 (1978).
2 W. Ryser, Überlegungen zur Gasentsorgung und praktische Hinweise zur Zwangsentgasung, ISWA Journal *25/26,* 25 (1978/79).
3 R. Stegmann, Gase aus geordneten Deponien - Allgemeine Problemstellung, Entstehung und Anfall, ISWA Journal *26/27,* 11 (1978/79).
4 A.J.B. Zehnder, B.A. Huser, Th.D. Brock and K. Wuhrmann, Characterization of an acetate-decarboxylating, non-hydrogen oxidizing methane bacterium, Archs Microbiol. *124,* 1 (1980).
5 Stand der Abfallbeseitung in der Schweiz. Stand Januar 1978. Bundesamt für Umweltschutz, Bern, Switzerland, 1978.
6 G.J. Farquhar and F.A. Rovers, Gasproduction during refuse decomposition, Water, Air and Soil Poll. 2 (1973).
7 K. Winter, Kriterien bei baulichen Einrichtungen auf Deponien hinsichtlich Gefährdung durch Gase. Forschungsbericht 10302102. Erich Schmidt Verlag, Berlin 1979.
8 Sicherheitstechnische Kennzahlen von Flüssigkeiten und Gasen, Schweiz. Unfallversicherungsgesellschaft, eds. Luzern 1976.
9 F. Schuster. G. Leggenwie und I. Skunca, Gas-Verbrennung-Wärme. Essen 1964.
10 P. Hostalier, Die industriellen Gasbrenner. München/Wien 1974.
11 Handbook of Chemistry and Physics, Chemical Rubber Company Publishing.
12 W. Foerst, ed., Ullmanns Enzyklopädie der technischen Chemie, Bd 1, S. 333. München 1951.
13 R.H. Collins, Upgrading landfill gas to pipeline specifications, ISWA Journal *28/29,* 1 (1979).
14 J. Nuesch, personal communication.
15 M. Piazzini, communication Turbomach AG.
16 Kabelwerke Brugg, communication.

## Future systems

As the previous section indicates, methane cannot easily be stored. Converting it to methanol would reduce its volume and facilitate handling - can this aim be achieved with the help of microorganisms? Knowledge to date on this subject and projects for the future are presented by O. Ghisalba and F. Heinzer.

The final article deals with yet another topic of relevance for the future. Can man mimick photosynthesis in artificial systems? P. Cuendet and M. Grätzel discuss the efforts to overcome the problem of the rather low efficiency in photobiological processes by simplifying the energy storing process as well as the molecular system which transforms light energy into a usable chemical form.