LANDFILL GAS MIGRATION IN THE SUBSOIL: EXPERIENCES OF CONTROL AND REMEDIATION

Mauro Gandolla, Cinzia Acaia, Catherine Fischer

Published in: *International directory of solid waste management 1997/8. The ISWA yearbook* (L. Uhre, ed). James & James Science Publishers, Ltd, London, UK, p. 237-245, 1997. - rev. nov. 2002

Rev. 10 / 2002

ECONS
environmental engineering

1 Introduction

The migration of biogas outside sanitary landfills for municipal solid wastes is a very common issue. Migrations occur very often even in modern, so-called "controlled sanitary landfills". The reason for this is that, in spite of our firm belief that a controlled tipping site is efficiently isolated from the surrounding environment, this proves not to be true for the great majority of existing landfills.
The walls of the landfills usually are their weakest point: both in design and construction indeed, the emphasis is set on protecting the subsoil and reinforcing the bottom of the site, but the walls are even more delicate points and always more difficult to deal with. As a consequence, countless wall linings rupture every day in landfills throughout the world. They are weaker than the bottom liners and at the same time subject to much stronger strains (just think of the friction brought about by the waste settling and moving down a fixed membrane lying on a slope of natural soil).
Moreover, our modern, compacted landfills tend to stratify horizontally, and the permeability to fluids (both liquid and gaseous) of the deposited waste becomes much greater horizontally than vertically. This makes lateral migration even easier, and causes the formation of supended water layers inside the landfill body. Many of the failures in the wall linings thus result in the migration of biogas outside the landfill, if one or both of the following conditions occur:

- the natural soil outside the walls of the landfill offers a possible migration path due to unsaturated permeable layers (resting above the groundwater table);
- the biogas extraction system operating inside the landfill is not sufficient to compensate, in the peripheral portions of the waste body, for the positive pressure caused by the generation of biogas.

This last condition is very often the case also in well managed landfills: biogas extraction systems indeed seldom recover all the biogas that is produced, generally due to underestimation of the landfills production capacity. Even if they can vent all the gas generated, they are usually operated at less than their full capacity to prevent the adverse effects that would result if atmospheric oxygen penetrated inside the landfill (dilution of the biogas, with a subsequent lowering of its heating capacity, creation of explosive mixtures, disturbing of the methanogenic bacteria, composting of waste or oxidation of methane with production of excessive heat, etc.).

Biogas is essentially composed of a mixture of methane (ranging between 45 and 65 % in volume) and carbon dioxide (between 35 and 55 %), with other minor components (2-4 % of water vapour and less than 1 % of trace elements). Methane is responsible for the explosivity and flammability of biogas, carbon dioxide for its asphyxiating potential, and the trace components may be toxic (like, for example, carbon monoxide or hydrogen sulphide, or some chlorinated hydrocarbons at very low concentrations).
Sooner or later, whenever biodegradable organic matter is deposited in a landfill, biogas will be produced, though the rate of production may vary. Municipal solid waste always contains a certain amount of biodegradable organics, depending essentially on the economic level of the country which produces it. The percentage of putrescible materials in MSW (yard, food and market wastes) ranges from 20% in the richest

countries of the planet (where other less readily biodegradable organics like paper and plastics account for the biggest fraction) to 80% in certain developing countries.
Biogas production cannot be inhibited in the long term, even if under certain conditions its evolution may be difficult to predict. In very dry climates, for example, putrescible materials may rest for a long time before a rain shower sets the bacteria to work again. Moreover, once it is produced, biogas cannot accumulate within the landfill. If it is not evacuated in a controlled fashion it will simply escape, either through the surface of the waste deposit, or through the sides.

If biogas is left to escape through the landfill surface, it will contribute to the greenhouse effect and increase odour emission.
If, on the contrary, it is allowed to migrate through the sides, it may constitute a very serious hazard to people and property by accumulating in confined environments either on-site or off-site, where it may cause asphyxia, fire or explosions. Cases of death due to asphyxia and of accidents involving landfill gas explosions or ignitions have been reported by newspapers several times in recent years. Moreover the migration of biogas, and its progressive dilution with air, do not lower its dangerous potential at least for a while: methane is in fact flammable when mixed with air in proportions between 15 and 5 %.

In short, biogas must be controlled for the following reasons:

1. *safety:* biogas is a dangerous fluid, for it is not easily detected, can cause asphyxia and is flammable, explosive, and in certain conditions even toxic;
2. *environmental protection:* sanitary landfills are one of the most important sources of methane emissions into the atmosphere, thus contributing greatly to the greenhouse effect. Biogas is also a source of offending odours, and its presence in the soil may damage the vegetation;
3. *energy recovery:* biogas is a source of energy that is often well worth recovering (in the form of heat or electricity).

Biogas migrations are a particularly pernicious hazard, bacause they may go undetected for considerable lengths of time and occur over very long distances (> 1 km). The gas may travel unseen through the permeable layers of the subsoil, before emerging unexpectedly. This may in particular happen in built-up areas, where the underground parts of buildings come into contact with porous layers of soil. This puts people at risk, who have no reason to expect such a hazard and are therefore totally unprepared for it.
However, the consequences of exposure to biogas (asphyxia, explosion, fire) are not of the kind which allow for second chances.

Fig. 1 - The waste (right, under the surface of a closed landfill) settling along a steep slope of natural soil (left in the photo) may cause cracks in the peripheral portions of the waste body. An insufficient gas extraction system causes biogas to flow through those fissures. Biogas presence is revealed by the barren patches that are clearly visible in the vegetation of the final cover, and can be detected on-site with a simple, portable gas detector.

To avoid this danger, every measure should be implemented to prevent biogas from migrating and accumulating both in on-site structures and off-site locations.
As a minimum, routine monitorings should be frequently carried out of structures potentially at risk on or near the landfill, such as:

- gas migration probes purposely installed outside the landfill
- underground trenches filled with permeable materials
- underground sewers and mains
- manholes, vaults, pits, basements or any enclosed spaces at ground level or lower
- outside of foundations and any cracks or holes they may present
- surface of the landfill and nearby fields or woods (to check for any sign of stress or damage to the vegetation, or any discontinuity in the final cover).

Concentrations may be measured by means of portable or fixed combustible gas indicators (explosimeters) and/or gas detectors (CO_2, CH_4, O_2).
The security concentration limits for confined environments where people live or work, or any rooms which people may enter, are as follows:

- **asphyxia:** the concentration of carbon dioxide must lie below 0.5 % in air (=5.000 ppm)

- **flammability, explosion:** the concentration of methane must be less than 1 % in air (=10.000 ppm, = 20% of the Lower Explosivity Limit).

In the following paragraphs a few typical cases will be described where landfill gas migrations occurred, with the investigation techniques that were used, as well as some of the remediation actions that were undertaken.

2 Examples of landfill gas migration

The following examples illustrate three occurrences of biogas migrations detected outside the boundaries of three large landfills situated in northern Italy, in the plain of the river Po. The three deposits were built by backfilling old sand and gravel quarries with waste, and their walls are therefore in contact with very permeable soils. All three landfills are quite deep (reaching 15 to 30 m below ground level) and rise only a few meters above the level of the surrounding territory, in order not to disrupt the flat landscape too much. The walls of the landfills are very steep, because sand and gravel quarries in the plain are usually exploited to the limit of the geotechnical stability of their slopes.

2.1 Landfill no. 1

This is a very old landfill: it opened in 1974 and was in operation for the next 8 years, during which 2.800.000 t of municipal solid wastes were deposited in this site. It then closed in 1981, before the first specific laws concerning landfill construction were passed in Italy. As a result, the landfill had no impermeabilization and no leachate collection system, and, initially, no gas extraction system was planned.
People's complaints about bad smells far away from the landfill culminated two years after its closure, when a few small accidents involving biogas ignition and little explosions took place in the sewer along the road east of the landfill and in some buildings north of the highway (Figure 3). An aerial thermography carried out in 1984 showed thermal anomalies all around the landfill (Figure 3), where afterwards the presence of biogas was detected by analysis at ground level. As a result, a biogas extraction system was built in 1984: this however did not improve the situation decisively, because it had insufficient capacity (Figure 2). Extracting biogas from a closed, "uncontrolled" landfill like this is indeed not an easy task: the deposit here is very large, but not very deep (10-15 m) so that extraction wells tend to have a very small radius of influence, and is not isolated from the surrounding permeable ground or from the atmosphere. No wonder then that the planned extraction system was insufficient. Also, we must remember that in Italy in 1984 biogas treatment, and, even more so, aerial thermography as a means of detecting biogas migration, were pioneer undertakings (see following chapter for more details on the technique).

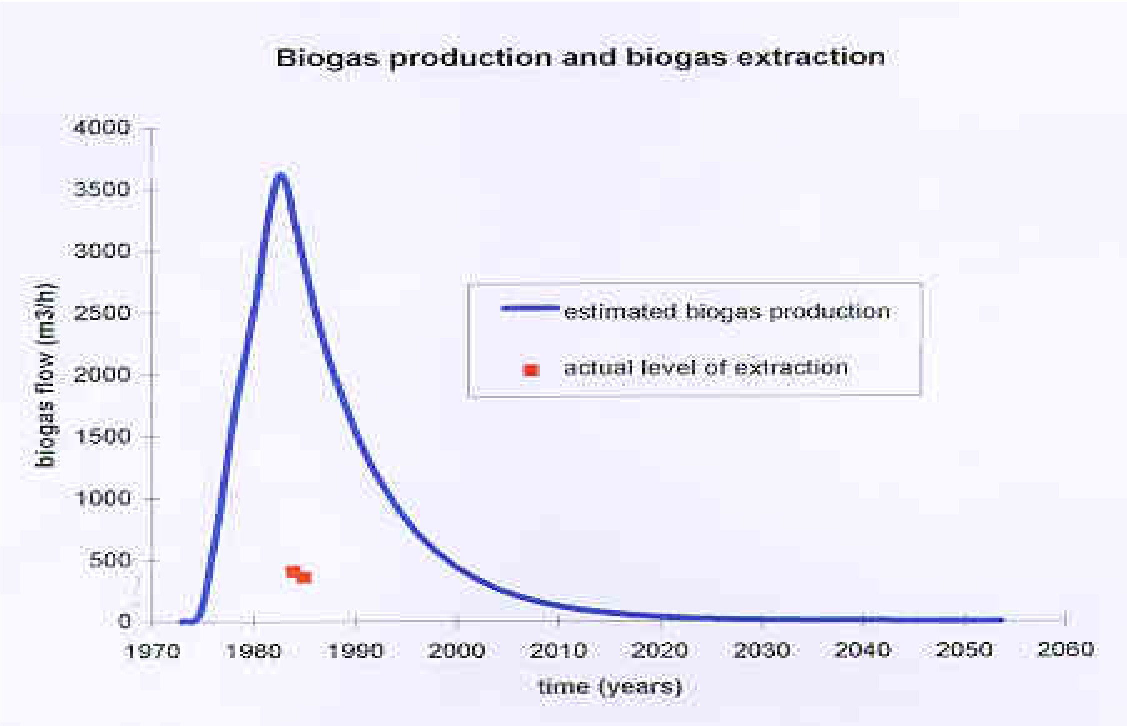

Fig. 2 - Curve of the expected biogas production in landfill no. 1. The red dots correspond to the portion of biogas that was collected and burnt at the time when the aerial thermography was carried out.

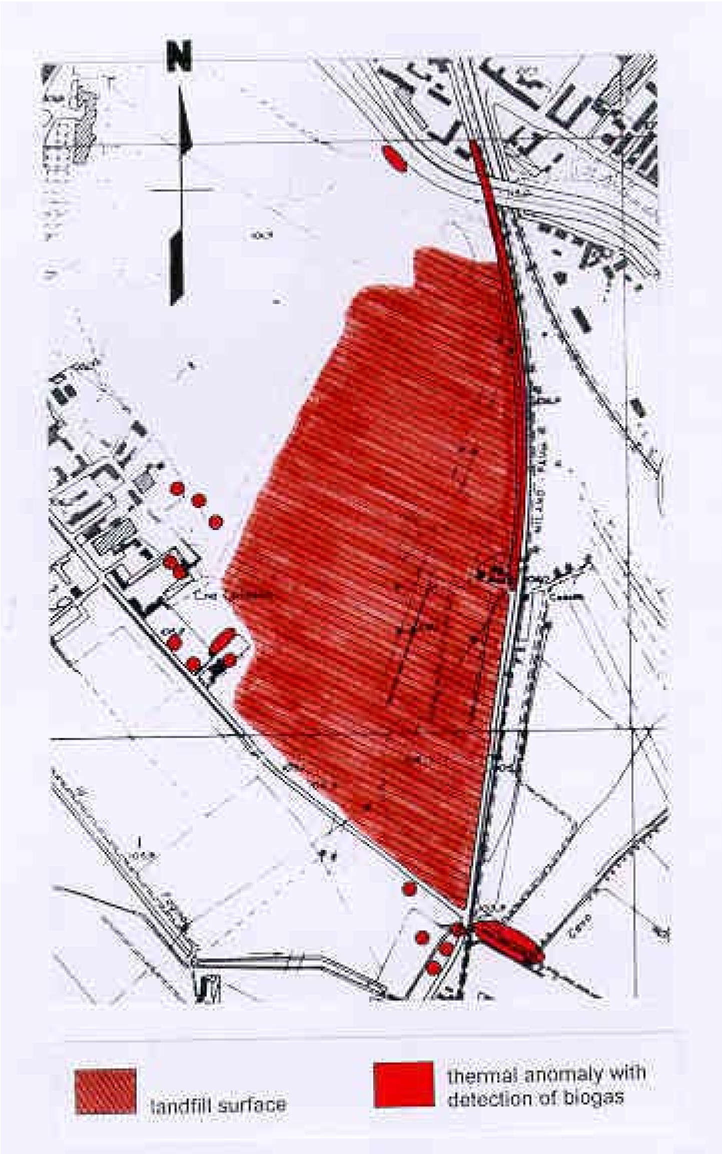

Fig. 3 - Results of an aerial thermography taken in 1984 over landfill no. 1 and of biogas detection at ground level, outside the landfill body.

2.2 Landfill no. 2

This landfill was operated between 1982 and 1994, but the information reported here refers to the year 1993, when the effects of biogas migration became evident outside the landfill.

The oldest portion of the landfill (north-east) was filled before the first Italian law on sanitary landfilling was enforced, and has neither impermeabilization, nor leachate and biogas extraction system. The largest part of the landfill, on the contrary, was lined and provided with a leachate collection network. The bottom lining generally comprised 1 m of compacted clay and a flexible membrane liner. On the very steep slopes, on the contrary, the designers required two geomembranes, separated by a geotextile.

As for biogas, no permanent structure was built from the start: following a standard very common in Italy, the designers planned to drill biogas extraction wells after the

complete filling of every single portion of the landfill. For big landfills like this though, such a practice results in a dangerous delay in the activation of an efficient gas venting system. Moreover, wells drilled “a posteriori” always have problems because they are not connected to a drainage system and are therefore soon filled with leachate.
Figures 4 and 5 refer to the year before the landfill was completed. At that time, 2.700.000 t of MSW had already been disposed of during the first 12 years of operation, but the gas extraction system was completed only in the oldest part of the landfill.
As a result, biogas was migrating from the sides of the waste deposit, and especially from the most recent portion of the landfill body (south-west). An explosion took place during the sampling of groundwater from a monitoring well 300 m south of the landfill (the thermography in Figure 5 marks the spot of this well west of the railway with a clear thermal anomaly). Biogas in concentrations above the security limits was detected in a few buildings at ground level, approximately 100 m west of the landfill, and in electricity and telephone mains in the same area.
After detecting biogas in various spots with portable gas detectors, an aerial infrared thermography was carried out from a helicopter, to get a general view at the extent of biogas migration. Hot spots were revealed further south than was expected, and successive on-site analysis confirmed the presence of biogas and damaged vegetation almost 1 km away from the landfill boundary.

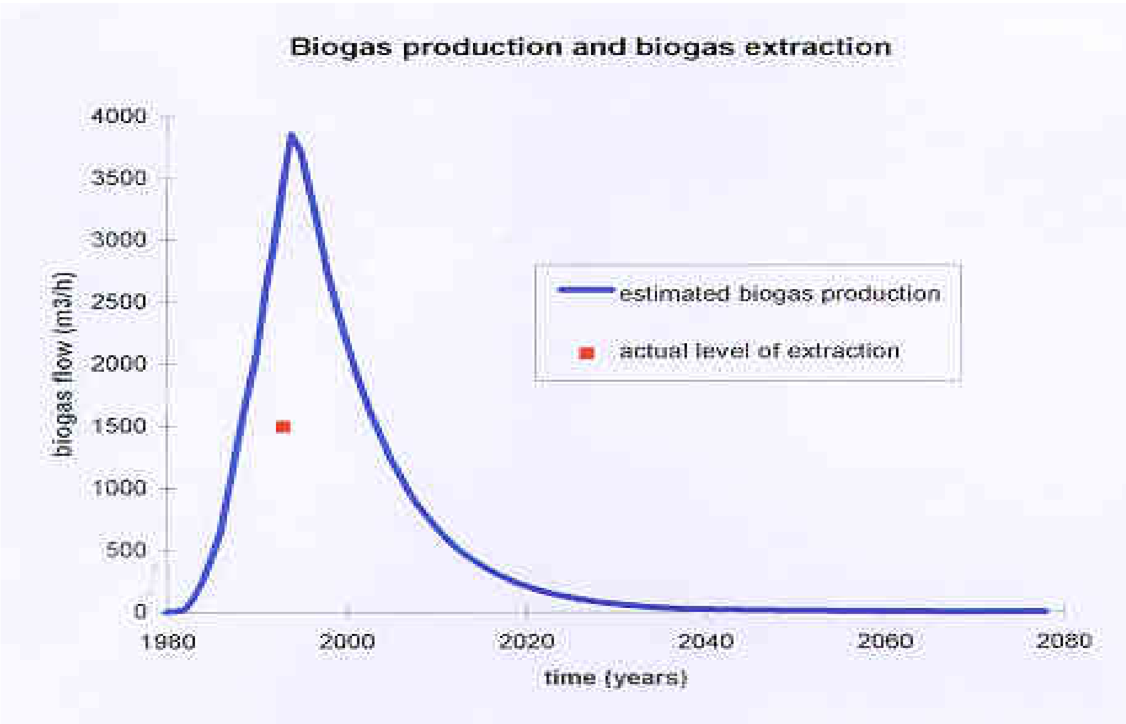

Fig. 4 - Curve of the expected biogas production in landfill no. 2. The red dot corresponds to the portion of biogas that was collected and burnt at the time when the aerial thermography was carried out.

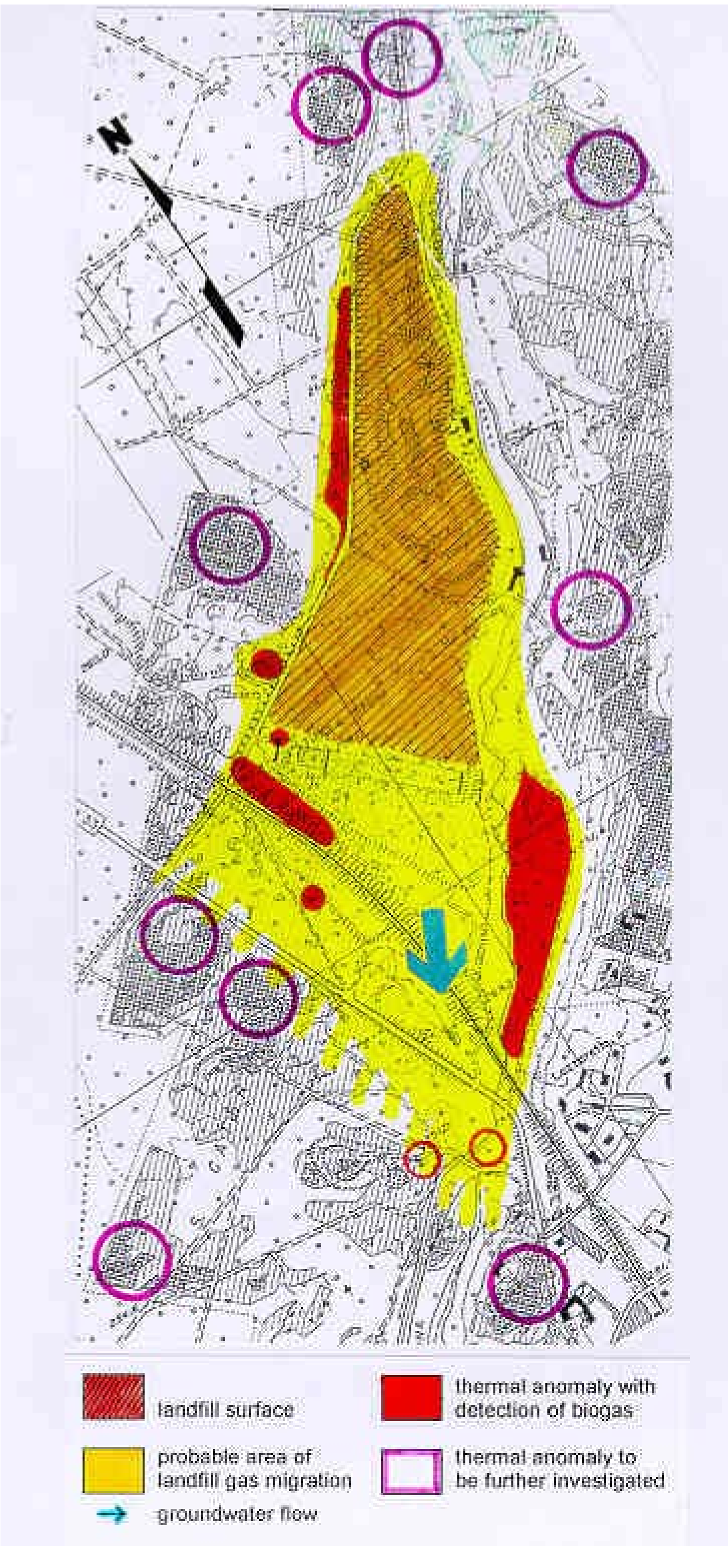

Fig. 5 - Results of an aerial thermography carried out in 1993 over landfill no. 2 and of biogas detection at ground level, outside the landfill body.

2.3 Landfill no. 3

This landfill was started in 1992, and in 1994 1.200.000 t of MSW had already been disposed of in this site. The sanitary landfill was lined on the bottom with a double liner (1 m of compacted clay and a geomembrane). The very steep walls were isolated with two geomembranes separated by a geotextile and a geonet. Leachate was efficiently collected from the bottom drainages, but no gas extraction system was provided at start, as seen in the previous case.

In 1994 construction of a large commercial building was started some 70 m north of the landfill boundary, while the landfill was in full operation (Figure 7). The designers of the building called for an expertise on the problems that might arise from the presence of the nearby landfill. A first survey showed that biogas was already escaping through the west wall of the landfill (Figure 8), and soon afterwards it appeared through the north side too.

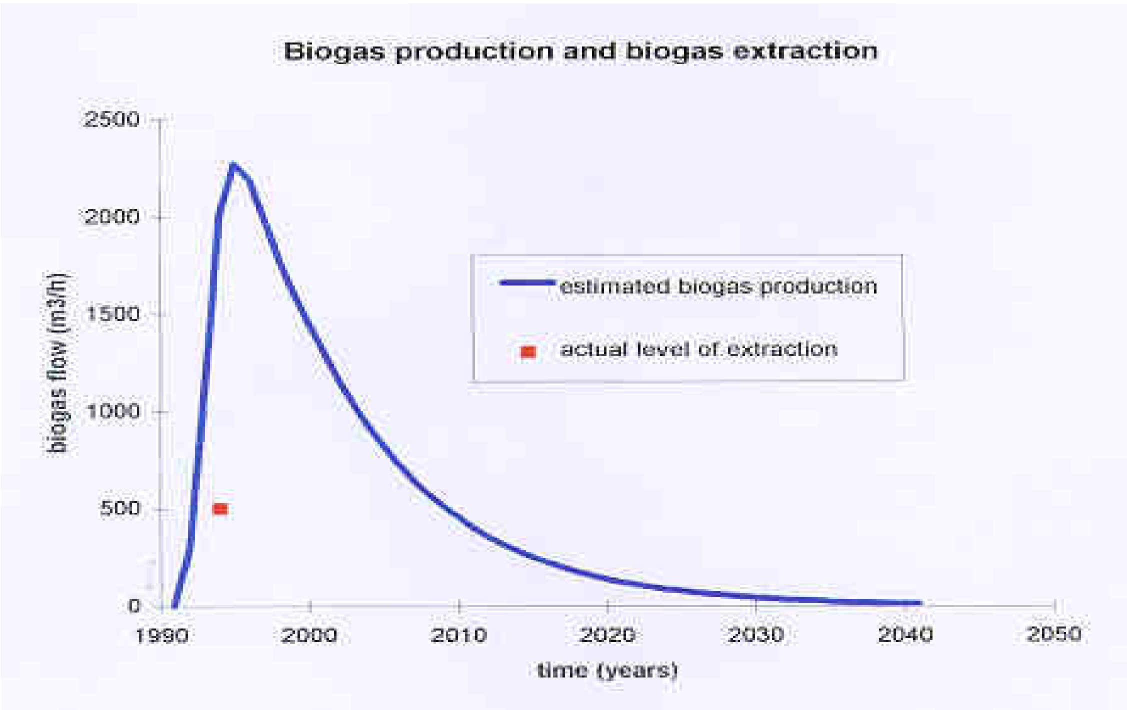

Fig. 6 - Curve of the expected biogas production in landfill no. 3. The red dot corresponds to the portion of biogas that was collected and burnt at the time when the aerial photography was carried out.

In this case biogas was not likely to migrate very far, because of the extreme permeability of the soil that allowed its dispersion through all the unsaturated portion of the subsoil and up towards the atmosphere. Biogas samplings in the subsoil (some 10 cm below the ground level) taken in line at different distances from the landfill, showed that the migration then stopped within 60 m (Figure 9).

At that time biogas was only temporarily extracted through some peripheral trenches and sparse "preferential paths", and burned by a 500 m^3/h torch (Figure 6). Soon after the discovery of the biogas migration though, a series of extraction wells were drilled in

the western part of the landfill, that was being covered, and outside the landfill body along the west and north boundaries. The active venting of these wells stopped the migration of biogas and allowed the installation of an energy recovery system.
The building itself was equipped with a complex monitoring and security system (a so-called “dynamic barrier”) independent from the one on the landfill. This ensured that even if the landfill extraction system failed, the building could be entirely and efficiently protected by its own barrier.

Fig. 7 - Aerial colour photography carried out in 1994 over landfill no. 3. The lighter patch in the vegetation west of the landfill marks the start of biogas migration outside its boundaries.

Fig. 8 - Taking a closer view at the lighter patch visible in the previous photo, evident signs of stress are seen in the corn field west of the landfill. The portable gas detector shows concentrations of almost 40% CO_2 and 44% CH_4, 10 cm below ground level, explaining why vegetation cannot grow in this area

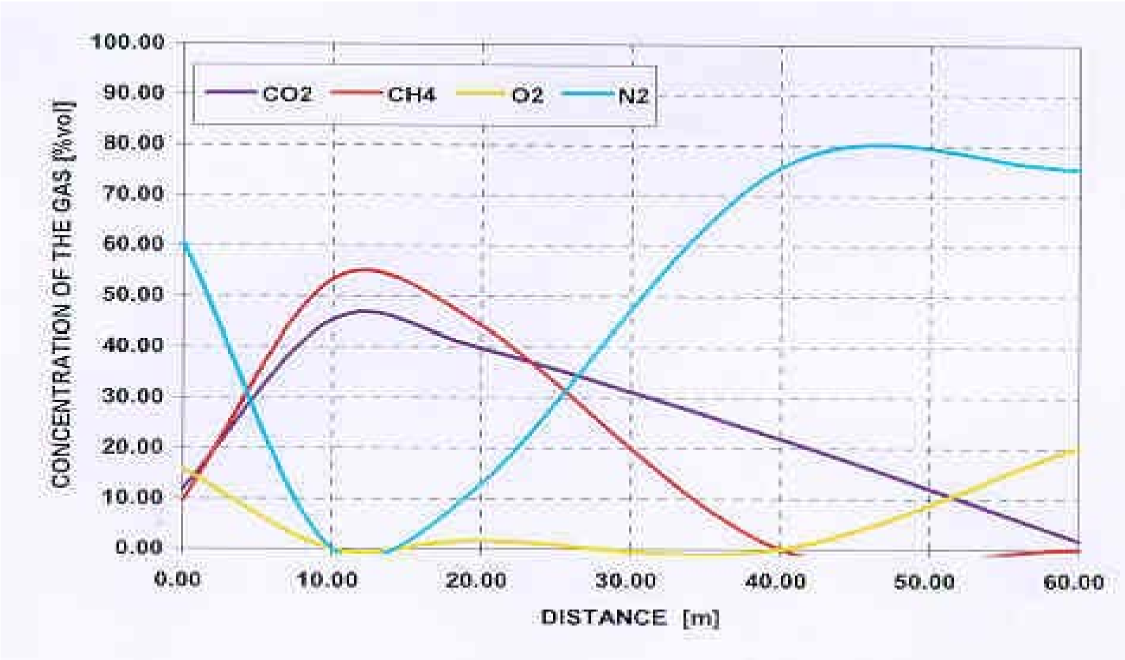

Fig. 9 - Variation of the biogas concentration at different distances from the landfill. Close to the waste body the sample appears to be very much contaminated with atmospheric air, testified by the presence of high concentrations of oxygen and nitrogen. The concentrations of CO_2 and CH_4 measured at 15 m from the landfill are those typical of pure biogas, that is evidently emerging here into the atmosphere from a deeper migration pathway. Further away from the landfill the concentrations measured indicate that biogas is being oxidized (CH_4 is transformed into CO_2), while at 60 m from the deposit the biogas has completely dispersed and the gas sample is constituted by air only.

3 How to detect biogas migrations

In the preceding examples a few methods of biogas migration detection have already been described. Generally, specialists in biogas migration problems are asked to deal with a landfill after some accident has occurred, but in well managed landfills a routine monitoring should spot biogas migrations before any accident occurs.

A well-designed gas extraction system and its careful maintenance are the most important requisites for handling the problem correctly. Nevertheless, biogas may escape also from the best managed landfills, and a careful surveillance is therefore always necessary.

As already pointed out, the monitoring should include the detection of landfill gases (methane and carbon dioxide) in all enclosed spaces at ground level or lower. Surveys must be repeated frequently, because biogas emissions outside the landfill are generally influenced very much by the atmospheric conditions (pressure variations) and vary continually.

It may be useful to have different portable gas detectors at one's disposal. To monitor a well known migration path, an instrument measuring the range of percent in volume (Figure 8) may be all that is needed. To detect traces of biogas though, especially on the surface of the ground, where it is strongly diluted with air, a very sensitive instrument detecting ppm levels of methane may prove necessary.

Once an anomalous concentration of methane or carbon dioxide has been detected, it may be difficult to prove that it comes from the landfill, especially if the place where it has been found is very far from the site (biogas was found as far as 1.500 m away). Generally, the approach consists of excluding any other possible source for those gases. The problem lies in the transformations that biogas undergoes in its path through the soil. If the external conditions allow the development of the biological oxidation of methane, the resulting gas will be richer in carbon dioxide and poorer in methane than it was in the landfill. This happens for example where, in a permeable portion of soil, a continuous interchange between biogas and atmospheric oxygen is provided. If the sampling point of biogas is near enough to the oxidation area the gas will also be much warmer than it was in the landfill (up to 70°C). On the contrary, if the migration path is isolated from the atmosphere and biogas flows through a damp soil, part of the carbon dioxide may dissolve into the water: the gas will then appear richer in methane than expected.
A clear and specific marker of landfill gas has not been found yet. However, the detection on ^{14}C and the ratio of stable carbon isotopes ($\delta^{13}C$) in the gas may be used as indicators of its origin and of the transformation processes it has undergone during its migration.

One of the best indicators of an ongoing biogas emission through the soil is the status of the vegetation (both on-site and off-site). Where high concentrations of biogas, or the oxidation of methane, reduce the amount of oxygen in the pores of the soil, the roots are suffocated and the plants die. Dying trees, barren patches in the grass or a reddish-brown moss may all indicate the presence of biogas in the soil: this may then be confirmed using a sensitive gas detector. An aerial colour photography carried out during the vegetation blooming period (Figure 7) may help to detect the presence of biogas at a larger scale.

Aerial thermography is also very often used to detect biogas emissions and migrations through the soil (Figures 3 and 5). Thermal anomalies near the landfill are due to the temperature of the biogas, that is often higher than that of the soil surrounding the site. More evident anomalies, appearing also at greater distances from the landfill, are caused by the heat produced by landfill methane oxidation.

Aerial photography and aerial thermography both supply information at a large scale: they have often been proved very useful to spot the main paths of biogas migration, but every piece of information obtained with these techniques must then be verified with on-site measurements. Vegetational stress or thermal anomalies may in fact be due to many different causes, independent of the landfill.

4 How to stop biogas migrations

Once a biogas migration has been detected, the first step to be taken is of course to check that the landfill gas extraction system is functioning properly and, if possible, to increase its capacity. When biogas has found a pathway through the landfill walls though, it is very difficult to draw it back from the inside. Simply powering up the internal extraction system has often proved insufficient to solve the problems of biogas migration.

Therefore to stop biogas from migrating and potentially threatening people and property, an efficient "barrier" should be opposed to its movement. Barriers can be continuous or discontinuous, static or dynamic, depending on the characteristics of the site. To be secure though, all barriers must block every possible path followed by the gas during its migration. This means, they must cover a vertical area corresponding to the entire unsaturated zone (between the water table or an impermeable soil layer under the landfill bottom and the ground surface). The horizontal extent of the barrier must be defined either with respect to the potential risk for people and properties, or considering the position of the lining ruptures, if they can be detected with certainty. In a landfill where biogas is found to migrate in different directions, and which is situated in a densely populated area, the barrier should cover the entire perimeter of the site.

In most cases, in the authors' experience a cost/benefit analysis resulted in choosing discontinuous, dynamic barriers as the optimal solution to biogas migration problems. These consist of a series of wells on a line drilled in the natural soil outside the landfill, from the surface to the water table level (or to an impermeable layer of soil below the bottom of the landfill). Their principal advantages are their extreme flexibility, and their comparably low cost: every single well can be regulated in order to maximize the efficiency and minimize the operation costs, and to adapt the barrier to any change in the biogas migration patterns.

Dimensioning a dynamic barrier means finding the right distance between the wells and predicting the flow of gas necessary to catch every molecule of biogas that escapes from the landfill. A few mathematical models have been developed recently to describe the movement of water and, rarely, gas through porous soils, but the results they provide tend to be valid only at a rather larger scale: so far they have proved unsatisfactory for describing this particular kind of flow in the unsaturated zone of the aquifers.

The authors always chose to base the dimensioning of dynamic barriers on the results of tests actually carried out on a few wells drilled in advance along the perimeter of the landfill. These tests consist of measurements of the radius of influence of the wells and of their characteristic curve (Figure 10). These two curves allow the designer to choose the optimal distance between the wells and the optimal flow of gas from each well, in order to cover the entire surface of soil through which biogas could migrate. It should be possible then for every gaseous particle moving away from the landfill to be caught by the barrier.

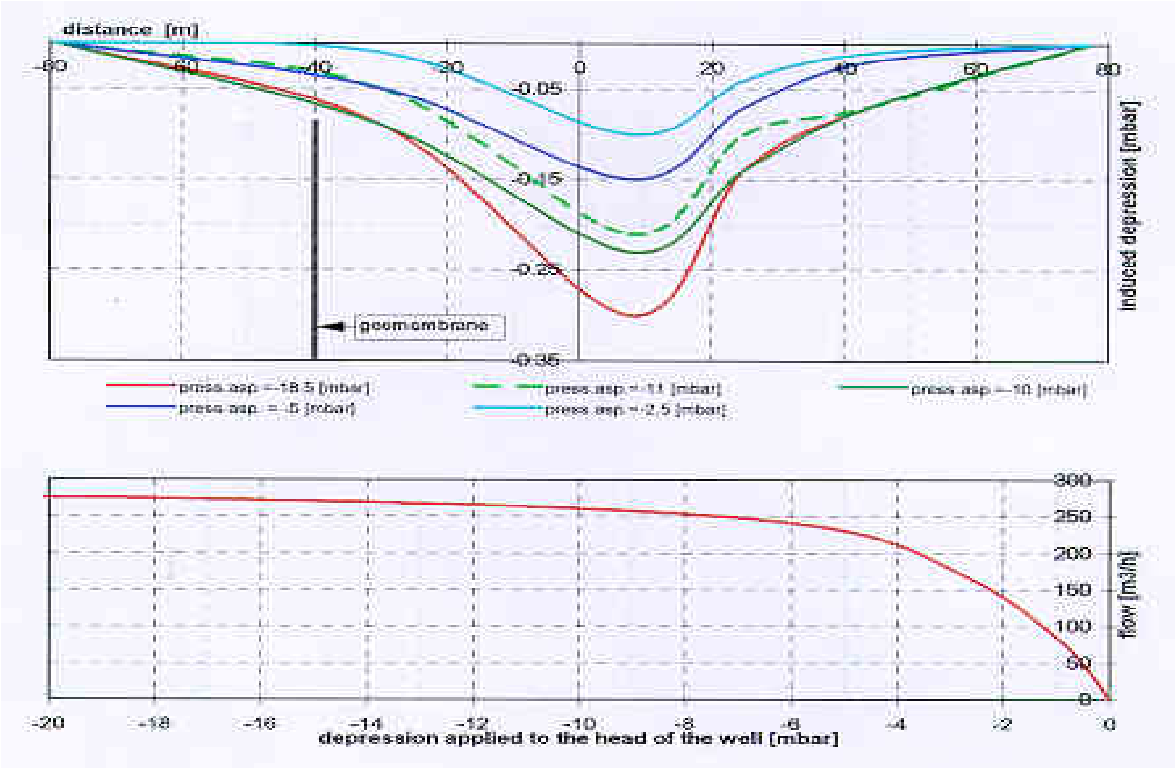

Fig. 10 - Determination of the radius of influence of a well in a natural, permeable soil, and characteristic curve at the well head.

Dynamic barriers can be used for injecting air into the soil, instead of drawing gas from it. This creates a diffused field of positive pressure that would stop the movement of biogas. The advantage of this method is that no biogas is collected, so it must not be treated and emitted into the atmosphere (see below). This solution must of course rely on a very efficient gas extraction system inside the landfill. In practice though, this method is very seldom used because it may prove very dangerous: generally a barrier is built when biogas is already migrating in the area. Creating an overpressure in the same area may push biogas even further, through paths that are very difficult to predict and control.

A dynamic barrier may anyway be operated as an aspiration barrier at the beginning, and then turned into an injection barrier afterwards. Aspiration may be stopped when the biogas migration is surely over and if the internal gas extraction system of the landfill is working properly. Then a very slight positive pressure in the barrier area can help maintain the gas inside the landfill, where it will be caught by the internal extraction system.

The gas extracted from the barrier is conveyed to a stack. It will generally be very diluted with air, so it may be difficult to burn it with an ordinary biogas flare. Generally, the gas should be burnt whenever the vented mixture is flammable. If it is not, it may either be dispersed into the atmosphere, or burnt after mixing it with natural gas: the local authorities are generally responsible for this decision. Energy recovery is normally out of the question.

Dynamic barriers must always rely on an efficient monitoring system. It can be automatic or manual, depending on the extent of the barrier and on the importance of the threatened properties (essentially, if there are any close confined spaces where people live or work). Each well constituting the barrier must be regulated independently, so the barrier may be continuously adapted to changes in the migration pattern. This pattern is determined by measuring a few parameters in ancillary gas probes or in the wells themselves. Carbon dioxide, methane and oxygen are the most important parameters to be controlled (Figure 11). An explosimeter may be added as a double check. Pressure at the well head is an important parameter to monitor the efficiency of the barrier. Other parameters may be added of course to refine the monitoring even further.

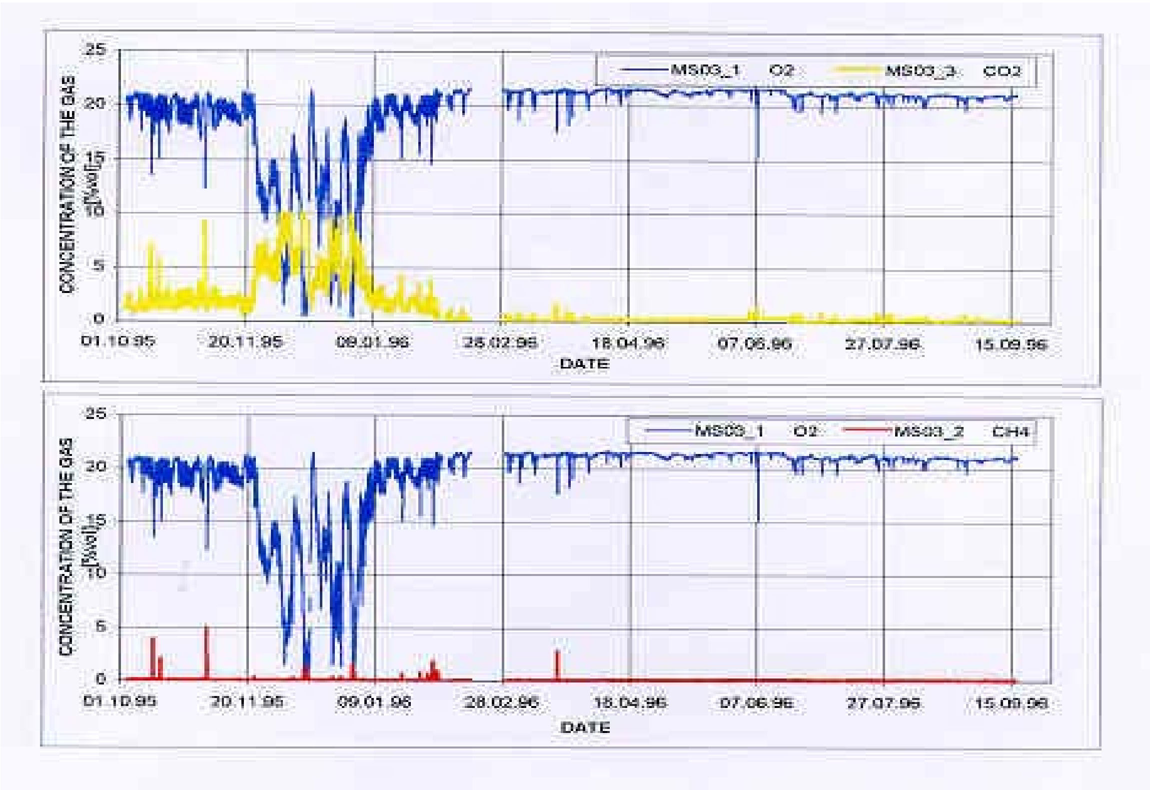

Fig. 11 - Example of output of an automatic monitoring system. The concentrations refer to a well in a barrier, situated 30 m away from the landfill boundary. The anomalous concentrations measured in December 1995 correspond to an interruption of the internal biogas extraction system of the landfill. The barrier was not started then, to enable the designers to follow the biogas migration path through the monitoring system.

An automatic monitoring system gives an alarm signal whenever the predetermined security levels are exceeded (generally two successive levels are set, and there are "attention" and "alarm" warnings). When this happens, the same system may start the barrier, or part of it, at once. If the monitoring is carried out manually, the barrier is started by the person in charge, depending on his own judgement and according to a pre-defined security protocol.