Rapport SGC 204

Detection and quantification of methane leakage from landfills

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Följande parter har gjort det möjligt att genomföra detta utvecklingsprojekt:

Avfall Sverige
Nordvästra Skånes Renhållnings AB
SÖRAB
SYSAV Utveckling AB
SITA, Sverige
SITA Environnement, Frankrike
Energimyndigheten

SVENSKT GASTEKNISKT CENTER AB

Jörgen Held

Foreword

The project description that formed the basis of the funding application for the current project included a brief presentation of the problems relating to measurement and mapping of methane emissions from landfills. The presentation was based on research literature and experiences from an EU project, the VOGUE project (Visualisation of Gas for Utilities and the Environment, NNE5-1999-20031, 2004). The project application to RVF and SGC included results and conclusion from a pilot study for detection and mapping of methane missions using remote sensing at Filborna landfill.

This project was the product of cooperation between waste companies in Sweden and France, and with funding from Avfall Sverige (Swedish Waste Management), Svenskt Gastekniskt Center (Swedish Gas Centre) and SITA Environnement, France.

The project concerns development and research relating to the use of laser and IR technology for detecting and quantifying methane emissions from landfills. The laser instrument used in all field studies was the Siemens AG, CT PS 8 Remote Natural Gas Leak Detector Field Unit used in the VOGUE project. We were able to use two prototype instruments from Siemens throughout the project period. FLIR SYSTEMS AB, Danderyd, Sweden, contributed to the project with a recently-introduced IR camera for gas detection, the FLIR ThermaCAM™ GasFindIR LW.

SIEMENS AG, Munich, through Dr Rainer Strzoda, kindly provided expertise in gas-laser technology. From FLIR Systems AB in Danderyd, Anders Andreasson kindly assisted with expertise in IR technology, and acted as discussion partner regarding field measurements of methane emissions.

A reference group comprising members from the funding bodies and participating waste companies met five times during the project period to discuss different parts of the project.

The reference group comprised the following members:

Development Manager	Stig Edner	SYSAV Utveckling AB
Development Engineer	Staffan Salö	SYSAV Utveckling AB
Environmental Manager	Herman Brundin	SÖRAB
Operations Manager	Tor Sivesind	SÖRAB
Product Manager	Per Olsson	Gästriklands Avfallshantering AB
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Environmental Manager	Olle Adolfsson	SITA Sverige
Techn. Advisor	Mikael Jonsson	Avfall Sverige
Head of Research	Håkan Rosqvist	NSR AB

In addition, many of the employees at the waste facilities helped with field measurements, provided us with information of different types, and made valuable comments.

Professor Anders Lagerkvist, Luleå University of Technology (LTU), assisted with the planning and analysis of the chamber (flux box) measurements, and provided valuable suggestions and views on the importance of different vegetation types as indicators of methane emission from landfills. Roger Lindfors (LTU) provided significant assistance by operating the chamber measurements at the different landfills in Sweden and France. Magnus Lindsjö, NSR AB provided valuable assistance at the different field survey measurements with remote gas detection laser and infrared technology, and the chamber measurements, at the Swedish and French landfills. Professor Mats Sandberg, University of Gävle, contributed his expertise in fluid mechanics in relation to landfills. Senior Lecturer Gunnar Börjesson Swedish University of Agricultural Sciences (SLU) assisted with processing and analysing data from the chamber measurements and gas chromotography.

We would like to thank everyone who participated in the project, and especially those named above who contributed with valuable expertise and useful comments.

The Authors

NOMENCLATURE

Technological and methodological terms

Remote sensing: genetic term for technology used to record and measure properties of an object remotely, without physical contact with, or affecting, the object.

Remote gas detection: detection and mapping of gas emissions using passive (IR) or active (laser) technology with direct measurement in real time without physical contact with, or affecting, the gas.

Operative wavelength range: The spectral range within which the laser or the IR system detects and records methane.

Active remote laser gas detection: Measurement technique where a laser beam is transmitted and records the methane concentration along a beam path. The laser beam is reflected from a background surface (backscatter surface).

ppm: parts per million, measurement of gas concentration.

ppb: parts per billion, measurement of gas concentration.

ppm x m: Measurement of gas concentration along a measurement distance.

IR absorption: The amount of infrared radiation absorbed by a gas at defined wavelengths.

Beam path: The path along which the laser beam is transmitted and returned from a background surface.

Laser technology: In this case, the VOGUE Siemens AG, CT PS 8 Remote Natural Gas Leak Detector Field Unit, working with an infrared laser, 1,651 nm.

Technical data relating to the Siemens laser system:

Time response	100 ms
Detection range for the laser-gas concentration	$0 \geq 1{,}000$ ppm x m
Operative distance/range	$\geq 10 \leq 30$ m, depending on the characteristics of the backscatter surface

Outlier: a data item that shows a significant numerical deviation from the rest of the data.

Passive remote gas detection: Technology that detects and records methane emissions with a passive detector, in this case especially sensitive within the infrared spectral range of methane.

Infrared technology: In this case, the FLIR ThermaCAM™ GasFindIR LW thermal image camera.

Real time: Recording, presentation and storage of measurement data directly at the time of measurement. Applies to laser, IR and field reference data.

Scanning: General detection and mapping of methane emissions.

Pinpointing: Detection of gas leakage at the exact point of emission.

GPS (Global Positioning System): used in this case for determining the exact position of methane emissions from landfills using high-resolution GPS.

Indicator method: Method that directly or indirectly indicates/proves the emission of methane as a secondary effect of elevated radiation temperature or deviating radiation temperature pattern caused by methane leakage.

Visualisation method: Method using a detector that is sensitive within the gas's specific wavelength range and that visualises methane and the dispersion pattern.

Concentration data: Methane emission expressed in ppm.

Flow data: Gas emission expressed in the flow unit l/min or other unit; many other units are used in research literature, such as l/m^2, l/year, g/m^2, etc.

Backscatter surface: Surface against which the laser beam is transmitted and from which it is reflected.

Reflector surface: Surface with reflective material that is used to strengthen the reflected signal to the laser in order to increase the range when measuring with a gas-laser system.

Static chamber (chamber method): Measurement of landfill gas emission on the surface of a landfill using an enclosed chamber. The increase in methane concentration in the chamber is used to calculate the flow from the landfill surface.

Dynamic chamber (chamber method): Measurement of landfill gas emission on the surface of a landfill using an open chamber. The flow is calculated through simultaneous measurement of the flow through the chamber and the concentration of methane.

Gas chromatography – partition chromatography: Chemical analysis method to distinguish between chemicals, gases, etc. in a sample, used together with evaluation of chamber method measurements.

Field laboratory measurements: Field measurements at facilities that permit simulation and measurement under controllable conditions.

Geoelectricity (resistivity) measurements: Measurement of electrical conductivity in the soil or waste. Electrodes are placed on the surface and the electrical resistance between the electrodes is measured.

Logs: Media for storing field measurement data in real time.

Temperature reference system: Temperature panel with radiators that permit regulation and determination of reference temperature with computer-controlled equipment.

Mass flow regulator: System for regulating gas flow.

Cost-effective techniques and methods: Measurement techniques and methods that are cheaper and easier to use than more labour-intensive and expensive technology and field methods.

Landfill terms

Anaerobic degradation of organic material: Degradation of organic material without access to oxygen.

Hydrolysis step: First step in the anaerobic degradation process.

Natural gas: Gas from fossil material.

Biogas or landfill gas: Gas from landfills or digestion plants.

Methane (CH_4): Chemical name and symbol of gas derived from fossil sources (natural gas), and produced in landfills and digestion plants.

Emission: Gas that escapes/is emitted from a landfill surface, gas distribution system, or natural sources (peat bogs, lake systems with organic sediment, etc)

Diffusion: The natural tendency of a gas to attain a uniform concentration in a space.

Jet: Powerful flow through a narrow passage with an upwardly moving stream of gas.

Anthropogenic CH_4 emissions: Methane emissions caused by human activity.

CO_2 equivalent in a 100-year perspective: Translation of an emission's greenhouse effect to an emission of carbon dioxide in a one hundred-year perspective.

Organic carbon: Carbon that is found in plants or animals**.**

Hydraulic conductivity: The ease with which water can move through a material.

Pressure gradient: Pressure difference.

Energy aspect: Produce information relevant to preventative control and maintenance of energy-related methods to utilise methane as an energy source.

Environmental aspect: Measures taken to reduce methane emissions to the atmosphere.

Safety aspect: Information used in decision-making relating to various safety measures.

Zone: Surfaces whose form and occurrence differ from each other, and that are representative of the most common landfills in Sweden. In this study, zones are defined as top surface, slope, crest and toe of slope.

Wind inducement: Effect of wind turbulence on emission and transport of methane on the surface of a landfill.

Covering layer: Top covering layer on a landfill surface.

Gas recovery system: Facility for recovery and transport of methane from a landfill.

Leachate system: Facility for collection and transport of leachate from a landfill.

Barrier system: In a landfill, a system for limiting discharges to the air or water, usually comprising a sealing layer that prevents, for example, the flow of water. This is usually combined with a drainage function that leads material away in a controlled manner.

Landfill cell: A physically defined area for waste deposition, with bottom sealing and constructed sides. The cell is filled in a controlled manner and, when filled, is covered.

Lift: The physically defined area in a cell that is filled from one level to another. The height is usually 3-5 m.

Lift joint: Interface between a lift and the one above.

Permeability: Measurement of how easily gas and water flows through soil for example.

Biocell reactor: Enclosed unit for controlled biological degradation of organic waste.

Other terms

LANDGEM: Method of calculating gas formation in a landfill.

EU E-PRTR regulations, 2007: EU regulations for management of landfills.

VOGUE: Visualisation of Gas for Utilities and the Environment, an EU project.

SUMMARY

Landfills make a significant contribution to anthropogenic emission of greenhouse gases through emission of methane. Greater knowledge is needed about how methane leakage occurs and how to calculate its magnitude.

The purpose of this project was to detect gas leakage and to measure and quantify methane emission from landfills using modern remote sensing techniques. In this project, a handheld laser instrument and an IR camera were used. The overall objective was to develop cost-effective methods for detecting and quantifying methane emissions from landfills. There are many methods available for measuring the methane concentration in air, both from close-up and from long distances. Combined with the use of a tracer gas, the methane emission from entire landfills can be measured relatively accurately. A number of methods are used to detect leakage from parts of landfill surfaces, but there are few methods for quantifying leakage from sub-zones.

The laser instrument used in the project (Siemens AG, CT PS 8 laser system) can detect methane concentrations of ≥10 ppm, and has a maximum range of 30 m that can be extended to 150-200 m using reflective material as a backscatter surface. The concentration of methane is measured in ppm x m and can be stored in logs together with supplementary field data, such as landfill and atmospheric pressure, and weather and radiation conditions, for subsequent analysis after the fieldwork. The IR camera (FLIR ThermaCAM™ GasFindIR LW) has recently been introduced to the market, and was used in the project for detection and visualisation of gas emissions from landfills. The camera produces a thermal image of the gas emission. The thermal image data is stored digitally on a DVD unit connected to the camera.

Field measurements with the laser instrument and the IR camera were carried out at seven Swedish landfills and two landfills in France. The investigated surfaces at the Swedish landfills were divided into different zones, such as top surface, slope, crest and toe of slope. The field measurements in France were taken over entire landfills. The methane emission varied between the different landfills in the project, and also between the different landfill zones. The results from repeated field measurements indicated that a landfill with a final cap and a successful gas recovery system produces barely measurable emissions. The weak points at a landfill are generally slopes, including crests and toes of slopes. Where the covering of the waste is inadequate, leakage often occurs at lift joints and in areas where waste protrudes through the cover. Other weak points are deficiencies in the gas recovery system. Leachate systems can lead landfill gas and thereby cause methane leakage.

The laser instrument detects point source emission of methane by measuring the methane concentrations above the emission points. The IR camera detects and visualises the occurrence of methane emissions, and can be used to trace emission points and to illustrate the dispersion pattern of methane. Both laser and the IR instrument can be used to determine the exact position of the leakage source. Diffuse emission can only be detected if the emission is large, such as at the tipping face. Both the laser instrument and the IR camera are easy to use. The laser instrument can scan over an area of approximately 1 ha per hour. The smallest measurable point source emission gives a concentration level of approximately 60 ppm, which corresponds to a point source methane emission of the order of 35 – 290 m^3 CH_4/year.

Scanning of the landfill surfaces showed that leakage could stop, increase or slow down. There are many reasons for these dynamics. Wind conditions, air pressure changes, and changes in the moisture content of the covering layer seem to be the most important.

Along with wind velocity and variations in atmospheric pressure, moisture content in the ground is an important factor that affects methane emissions from landfill surfaces. Results from field measurements of the same feature/surface at different points in time and with different ground humidity showed that pores in the surface layer close when the moisture content is greater, reducing the landfill gas leakage. The large and sometimes rapid changes make it very difficult to get a picture of the distribution of the methane leakage over the landfill surfaces.

Methane emissions were measured in different seasons, and also when the landfill surfaces had snow cover. The results showed that methane is emitted easily through porous snow. The same methane concentrations were recorded for GPS-fixed leakage features with and without snow cover.

In the project, the chamber method was used to try to quantify methane leakage detected by the laser instrument. When chamber method results were correlated with the corresponding laser measurements, a relationship was evident. This produced a figure for emission. The relationship between the respective figures from laser and chamber method measurements was used to quantify the detected point source emissions at the French landfills. The total emissions detected with the laser instrument at the two landfills were estimated at 41 and 30 tons of methane respectively per year. These quantified methane emissions from detected points were smaller than the total emissions as reported by the landfill operators. The relationship indicates that it is the diffuse emission of methane that is predominant, and not the point source emission through holes, fissures, etc.

If the objective is to produce a reliable measurement of gas emission from a landfill, the combination of laser/chamber method is not probably sufficiently accurate. However, if the objective is, for example, to determine and prioritise where measures should be taken at different landfill surfaces to reduce emission, the combination of laser and the chamber method is very usable. The measurement method tested was application-oriented, and the aim was that the measurements would provide information on which to base the planning and implementation of short- and long-term measures. Manuals were produced for the laser instrument and the IR camera, showing how the two instruments are to be used for detecting methane emissions from landfills.

The project demonstrated how the laser instrument could be used by bouncing the beam off a simple reflector. Measurement using a beam path length of up to 200 m is possible. Examples of such applications are measurements over leachate ponds, beside a landfill and on parts of a landfill. Such measurements can give important information about emission conditions that are difficult to measure in any other way.

Geoelectrical measurements have several areas of application for landfills, primarily in studies of groundwater pollution. In recent years, interest has also grown in investigating processes inside landfills. Based on results from previous studies, one of the aims of this project was to examine whether three-dimensional evaluation of resistivity measurements could be used to provide better measurements and understanding of the processes below the surface. According to previous studies, landfill gas movements can be visualised through geoelectricity measurements. In the experiment, resistivity was measured along eleven lines in an area 10 m x 10 m on a slope adjacent to a biocell reactor.

The resistivity measurements showed results similar to or somewhat lower than the results shown in previous studies. High water content, ion content and high organic content can explain low resistivity, while high gas pressure in the ground partly explains high resistivity. It should also be noted that temperature variations affect resistivity. When the results from the resistivity measurements was compared with results from static chamber measurements and the laser instrument, no clear correlations were observed. The gas movements below the ground surface shown by resistivity measurements at the toe of the slope could not be confirmed with measurements above ground with the laser or static chamber methods.

The results from the project show that combinations of laser, IR, chamber method and geo-resistivity measurements are a successful way to describe and map methane emissions from landfills. The mapping of emissions provides precise information useful for planning maintenance or improvement measures on landfill surfaces and gas recovery and leachate systems.

CONTENT

APPENDICES

1. BACKGROUND

1.1 General

Methane is formed in certain natural environments and as a result of human activities. Examples of environments where methane occurs naturally are wetlands and lake sediments, and examples of human activities that produce methane emissions include animal husbandry, distribution of natural gas, waste disposals and combustion of solid fuel.

Methane is a greenhouse gas that affects the energy balance in the air 22 times more than carbon dioxide. Although the total quantity of methane gas emissions is 200 times less than carbon dioxide emissions in Sweden (Swedish Energy Agency, Swedish Environmental Protection Agency, 2004) it is important to reduce and prevent emissions of methane to the atmosphere. A further justification for this is that most methane emissions resulting from human activity are easier to deal with than, for example, sources of CO_2 emissions. Landfills are considered to be such a source (Crill, Riise, 2005).

The concentration of methane in the atmosphere has gradually increased, and in 2005 was 1,774 ppb, but the reason for this is unknown. The concentration shows a seasonal variation, with high concentrations in late summer and autumn (IPCC, 2007).

The total anthropogenic emissions of CH_4 in Sweden in 2003 were approximately 0,3 Mton (equivalent to 5,7 million tons CO_2 in a 100-year perspective), which is a decrease of 46 500 tons since 1990 (Swedish Environmental Protection Agency, 2003). Landfills in Sweden account for most of this decrease (Swedish Environmental Protection Agency, 2004; Crill, Riise, 2005).

In addition to the impact on the energy balance in the atmosphere when emitted, methane is flammable and, in certain cases, explosive when mixed with air. Moreover, methane has great energy value and it is economically viable to recover and use methane as a gaseous fuel for heating buildings, for producing electricity or as vehicle fuel.

Methane is formed spontaneously with carbon dioxide in landfills with organic content through anaerobic digestion of organic matter. In this context, the gas mixture is called landfill gas.

Deposition of waste in landfills was an important waste treatment method until the ban on disposal of combustible (2002) and organic waste (2005) in landfills. The landfill disposal method gradually changed, from simple dumping without environmental protection measures to a controlled method where pre-treated waste is deposited in cells with barrier systems to reduce environmental impact. Emissions in the form of contaminated water (leachate) and landfill gas are to be treated according to applicable provisions in the Swedish Environmental Code.

1.2 Description of problem

Only a small proportion of the landfill gas produced at Swedish landfills is recovered and used or rendered harmless in other ways. In Sweden, the number of municipal landfills in operation has decreased from approximately 350 in 1994 to 175 (Avfall Sverige, 2007). The number will decrease further, primarily through completion of small landfills. In addition to municipal landfills a number of industrial landfills receive organic waste. There are over 4 000 closed landfills in Sweden, mostly small tips.

Because of the large number of landfills in Sweden, there are large quantities of organic matter in landfills that form landfill gas, and this will continue for a long time. The current situation and the future landfill gas generation are shown in Figure 1.1.

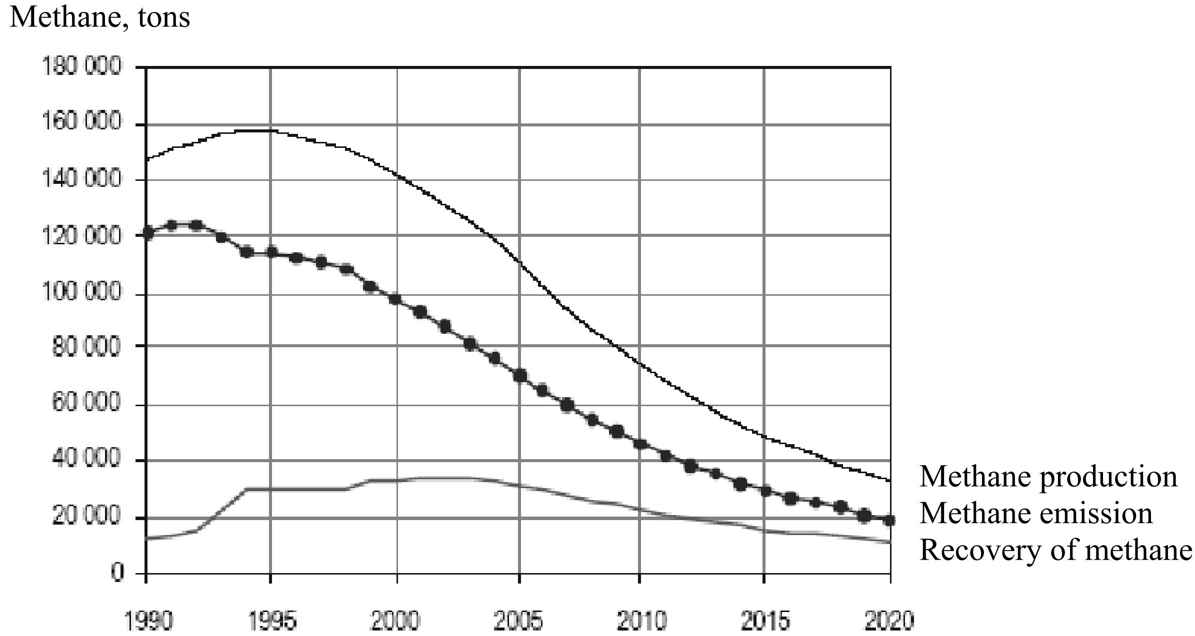


Figure 1.1. Generation, emissions and recovered amounts of methane from landfills in Sweden (Swedish Environmental Protection Agency, 2001).

In the rest of the world, the situation is different. Seen in a global perspective, very large quantities of waste are deposited in landfills, and the total amount of organic carbon in landfills is growing (IPCC, 2007). In turn, it is estimated that the amount of methane emitted from landfills will increase (see Table 1.1).

Table 1.1. Emissions from the world's landfills 1996-2006, IPCC inventory, with extrapolation, Mton CO_2 equivalent).

Source	1990	1996	2000	2005	2010	2015	2020	2030	2050
Methane from landfills, a)	760	770	730	750	760	790	820		
Methane from landfills, b)	340	400	450	520	640	800	1 000	1 500	2 900
Methane from landfills, c)	550	585	590	635	700	795	910		

a) Based on national calculations and, for non-reporting countries, on inventory 1996 and extrapolation (USEPA, 2006).
b) Based on inventory 2006 and BAU projection (Monni et al., 2006)
c) Mean of the two inventories from 1996 and 2006.

At present, the total quantity of methane emitted from landfills in the world is approximately 650 Mton CO_2 equivalent, which constitutes approximately 2.5 % of the global emission of GHG, Greenhouse Gases.

The latest IPCC report (IPCC, 2007) also shows regional variations in methane emissions from landfills. The increase in emissions is slowing because of stricter legislation and increased use of methane. Today, an estimated 105 Mton CO_2 equivalent is recovered and used for various energy purposes.

In Europe, the emission of methane from landfills is falling, as in Sweden, while emissions from landfills increasingly stem from developing countries in Africa and East Asia.

The IPCC reports state that the quantity of harmful emissions decreases when waste management changes from deposition in landfills to increased waste recycling, when more waste is incinerated, and when more of the biogas from landfills is used.

1.3 Need for simple cost-effective measurement methods

Since landfills constitute significant sources of methane emission, improved measurement methods are needed to determine the size of emissions and to detect the position of the emission source. Measures to reduce uncontrolled emissions of methane can then be implemented.

Like other member states of the EU, Sweden is now to report emissions to air and water annually to the EPER (European Pollutant Emission Register). Sweden reported emissions to the EU in 2001, 2004, and 2007. The report should according to the EU request include national totals for emission, as well as emissions from individual facilities. Only a few landfill facilities have reported estimates or measurements so far. One reason is the lack of simple measurement methods.

The methods available for measuring methane emissions from landfills are all complicated and require relatively large resources (see description of the different methods in Chapter 7). For example, the chamber method (also known as flux box method) requires a large number of measurements, and methods to measure emissions from entire landfills are costly. Methods for detecting point source leakage are also few and relatively costly.

The end user needs accurate, inexpensive and easy-to-operate measurement technology in order to:

- Map methane emissions;
- Provide data about environmental evaluation of landfills;
- Provide data for short- and long-term planning of landfills;
- Provide data for short- and long-term planning of measures to limit emissions;
- Provide training.

2. AIM

The aim of this project was to detect gas leakage and to measure and quantify methane emissions from landfills. The overall objective was to develop cost-effective methods for tracing and quantifying methane emissions from landfill surfaces, ranging from detailed emission data from a leakage source to synoptic information about the emission pattern from large landfill surfaces.

3. OBJECTIVES AND RESEARCH ISSUES

The equipment was to meet the following specifications:

- A laser should be used to scan the landfill synoptically, detect leakage sources and quantify methane emissions from landfill surfaces.
- An infrared (IR) camera should be used to detect emission sources (pinpointing) and to visualise methane gas movements and emission from landfill surfaces.
- It should be possible to use a combination of laser and IR measurements to improve landfill gas recovery systems.
- It should be possible to use a combination of laser and IR measurements to determine landfill gas emission at landfills with and without landfill gas recovery systems. The size of emission can vary considerably.
- Geoelectricity measurements should be used together with the laser and IR camera to increase understanding of gas movements in landfills and at the surface-atmosphere interface.

Objectives for the development of measurement methods:

- Use selected technology to develop a cost-effective method for detecting methane emissions from landfills;
- Develop a method that provides synoptic information about the distribution of methane emission from an entire landfill;
- Provide detailed information (precise location, concentrations measured) about the emission points on a landfill;
- Calibrate the method through simultaneous measurement with chambers;
- Develop a cost-effective method for quantifying total emissions of methane from a landfill.

A supplementary objective was introduced after the start of the study:

- Use the chamber method to try to calibrate laser measurements in order to calculate the size of the emission.

The methods developed in the project should provide information about methane concentrations above landfill surfaces, information about gas recovery systems so that they can be improved, and information about the emission status of the landfill. This information would provide data on which to base measures to reduce landfill gas emissions.

4. HYPOTHESES

- Active methane gas laser technology such as the SIEMENS remote gas detection system can be used to detect and indirectly quantify methane emissions from landfills.
- High-resolution IR technology can be used to detect and visualise methane gas, and to study the behaviour of methane and its emission from the surface of landfills.
- Measurements of the concentration of methane gas, in combination with information about the location of sources of methane leakage and the diffusion pattern and behaviour of methane, should yield information that can be used to improve gas recovery systems and reduce methane emissions from landfills.
- Low methane concentrations over a landfill area indicate low emission flows, while high methane concentrations indicate high emission flows.
- The combination of gas concentration data from laser measurements and field reference data obtained from measurements using the chamber method can be used as input in a methane flow model in order to convert concentration data in ppm to flow data in l/min.
- The combination of the gas concentration data from laser measurements, flow data from chamber measurements and geoelectricity measurements of resistivity detecting the occurrence and location of moisture conditions and methane gas movements inside a landfill, should increase knowledge about methane processes inside a landfill and about methane emissions from landfill surfaces.

5. ORGANISATION

Initially, the project was discussed and approved by four waste companies in Sweden. Later, SITA Environnement was introduced as a valuable new partner, primarily to help direct the investigations towards quantification of the methane emissions. The locations of the four companies enabled methane emissions to be studied under different climatic conditions. Furthermore, the participation of SITA Environnement allowed the inclusion of French landfills in the project, with the conditions prevailing at landfills in northern France.

Therefore, the project was managed by a reference group consisting of representatives of the companies involved, the funding research councils and researchers at Luleå University of Technology and the University of Gävle. The organisation is shown in Figure 5.1.

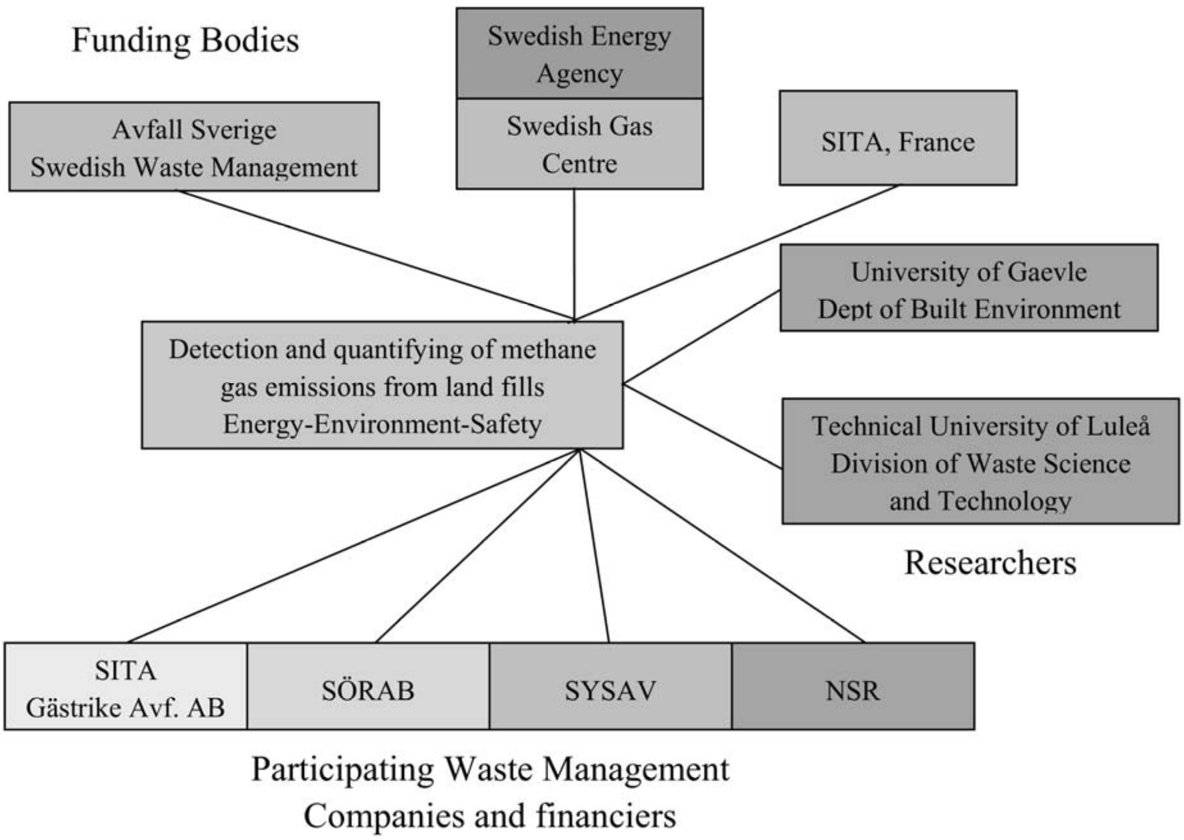


Figure 5.1. Project organisation.

6. CURRENT KNOWLEDGE

6.1 Landfill strategies

Concentrating waste products to a landfill creates an accumulation of various substances such as metals, organic substances and nutrients. The high concentration of these substances creates sharp gradients of matter and chemical energy between the landfill and its surroundings. According to the second law of thermodynamics, about spontaneous increase in entropy, a landfill strives to attain a balance with the surrounding area. Unless there is a continuous supply of energy to maintain the concentration of matter and chemical energy, a mass flow from the landfill into the surrounding environment is inevitable in a longer time perspective. The mass flow is driven by the gradients and will continue until balance between landfill and surrounding area is achieved (Bendz et al., 1999).

Modern landfill practise generally involves separating the landfill from the surrounding environment by bottom and surface sealing, and collecting and treating the mass flow in the form of leachate and biogas. The concentration and the control of the substances are maintained by adding energy.

There are two main strategies for landfill disposal. According to the first strategy, all concentrations of substances are maintained by isolating the waste from the surrounding environment for a very long time. The problem is the spontaneous degradation of organic matter and other chemical transformations. According to the second strategy, the waste should be converted into more harmless substances in a short period of time, enabling man to control the process.

Different landfill strategies can be divided into these two types, and the line is defined by the purpose of the landfill, i.e. whether the waste is to be conserved or stabilised. The second approach aims to optimise the variables (particularly high moisture content) that govern the degradation. This means that the landfill can be compared to a bioreactor, where the final product is a stabilised mass that can be integrated into the environment.

The conserving role of the landfill is introduced in EU landfill legislation. The strategy has been combined with a gradual reduction of the organic content in landfills, with the main purpose to reduce emissions of methane gas from degrading waste.

Controlled deposition of waste in landfills is a relatively young technology and no long-term observations are available. Our knowledge about emissions from landfills, mainly landfill gas and leachate, is based on experiences from the first 50 years of contemporary landfills. Therefore the time required for equilibrium to be reached between a landfill and the surrounding environment can only be speculated. However, such speculations are central to the discussion about the nature of sustainable landfill strategies.

It is important to remember that, regardless of the current trend, we must manage landfills designed according to yesterday's legislation (Knox, 1996). The overwhelming majority of all landfills, for example in Sweden, are of this type.

6.2 Landfill design

A landfill is a structure built of deposited waste, which is placed on top of a bottom liner where leachate is collected and directed to treatment. The waste is usually deposited in ‘lifts’, 2-3 m thick. Each lift is covered daily to reduce the effects of wind and smell. The total height of a landfill depends on its size. Landfills in Sweden are usually 10-30 m high, but they can reach up to 45-50 m in exceptional cases. When the landfill is completely filled with waste, the whole surface area is finally sealed with a top cover (capping). This minimises the amount of contaminated water leached. Containment to prevent gas emissions is not required.

Normally, waste is deposited in several sections or cells so that the final capping can take place as soon as possible. Figure 6.1 shows an overview of the division into areas with initiated bottom lining, cells in operation, and completed cells.

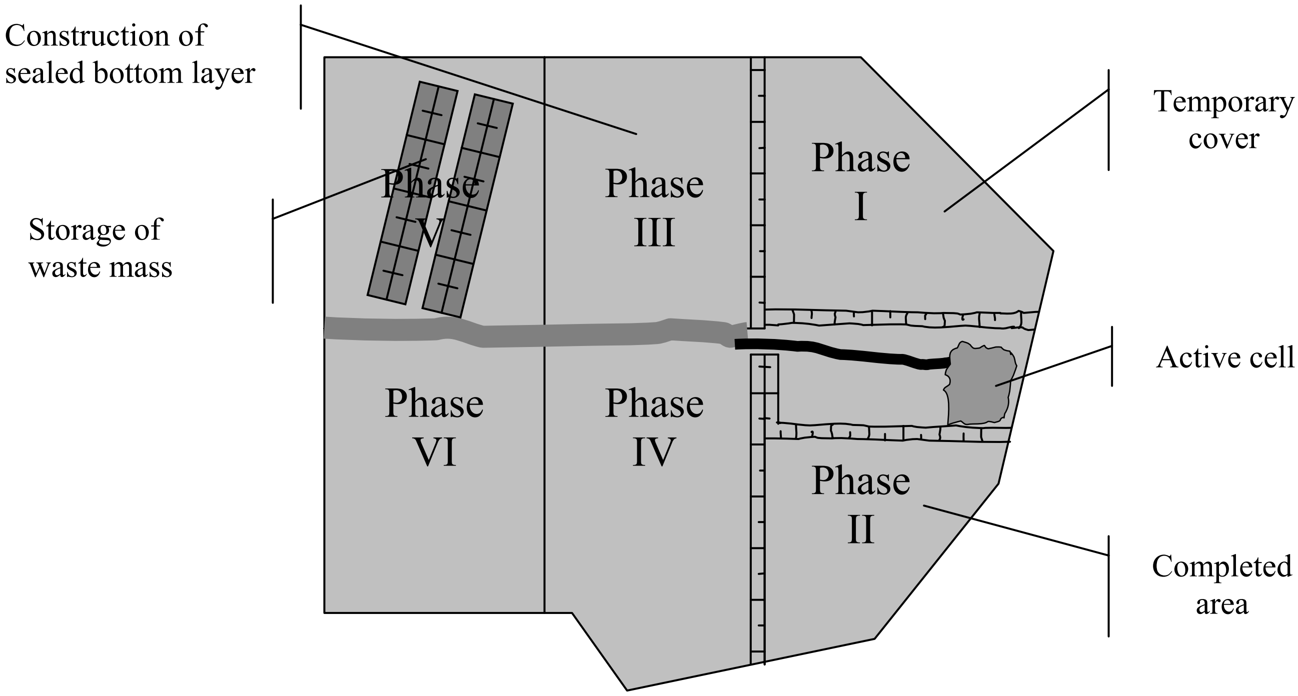


Figure 6.1. Structure of a landfill, with different phases of completion.

6.3 The degradation process

A typical landfill containing mixed waste that includes organic matter can be likened to an anaerobic reactor without mixing, with a large water deficit so the degradation process is ineffective (Bogner et al., 1993; El-Fadel, 1996, 1997). The spatial variation of the water content is large, and varies from saturated to dry. Excavation of older landfills showed that large volumes were entirely dry and that the waste was more or less unaffected by degradation (Harris, 1979, Hogland et al., 1995). Conditions for degradation are far from optimal, so only part of the organic carbon will be converted and emitted as methane or carbon dioxide. Parts of the organic matter are virtually undegradable and are only partially decomposed, even in a long-term perspective (IPCC, 2007).

Our knowledge and assumptions about the anaerobic processes in landfills are based on experiences from digestion reactors. The microbiological environment is similar in both cases, even if the environmental conditions in a digestion reactor are controlled to optimise the anaerobic degradation process, and the relative content of fat, proteins and carbohydrates in the substrate can vary (El-Fadel et al., 1997).

The organic matter is broken down in three steps – hydrolysis and fermentation, acetogenesis and methanogenesis – into mainly methane and carbon dioxide (Christensen and Kjeldsen, 1989). Before the microorganisms can break down the organic matter, it must first be digested and dissolved. This occurs in a hydrolysis step, which is the first step of the anaerobic degradation. In this way, the organic matter is first converted to simpler polymers such as proteins, carbohydrates and lipids that, in turn, are hydrolysed to amino acids, sugar and fatty acids. The reaction products from the hydrolysis step are then either fermented to volatile fatty acids or directly to acetic acid (El-Fadel et al., 1997). The hydrolysis is probably the limiting step for the whole process (Leuschner and Melden, 1983). This has also been shown in microbial growth/gas generation model simulations (El-Fadel et al., 1996). Water is not only necessary for the hydrolysis, but also for redistributing chemical substances, microorganisms and nutrients within the landfill (Augenstein and Pacey, 1991; Christensen and Kjeldsen, 1989). Consequently, both high water content (Ehrig, 1991) and water turnover (Klink and Ham, 1982) have been shown to stimulate the degradation process. Furthermore, high temperature has been shown to have a favourable effect on the hydrolysis rate (El-Fadel et al., 1996). In the second step, acetogenic bacteria transform fermentation products to acetic acid, hydrogen and carbon dioxide, which are used by methanogenic bacteria to produce methane in the final step. This can also occur through formation of hydrogen that is then converted to methane.

After the hydrolysis, methanogenesis becomes the limiting factor for the degradation process, so the factors that control the hydrolysis and methanogenesis will dominate in the degradation process and the production of biogas.

From the moment of deposition, the waste will pass through a number of degradation phases that will govern the emissions. An idealised detailed anaerobic degradation sequence can be divided into five phases as follows (Christensen et al., 1989; Ehrig, 1987; Farquhar and Rovers, 1973):

1. Once the waste is deposited, aerobic conditions will prevail for a short period of time. During this phase, easily degradable organic matter will be decomposed mainly to water and carbon dioxide while oxygen and nitrogen are consumed.
2. When the oxygen trapped in the waste mass is consumed, facultative and acetogenic bacteria become active, thereby forming degradation products such as volatile fatty acid (VFA), carbon dioxide and hydrogen. The presence of the organic acids will reduce pH and inhibit methanogenic bacteria. The leachate is characterised by high concentrations of COD, calcium, iron, heavy metals and ammonia.
3. During this phase, methanogenic bacteria grow slowly, and VFA are converted to methane and carbon dioxide. When the concentration of VFA decreases, pH increases and the concentrations of iron, heavy metals and COD decrease.
4. This is the stable methane-producing phase, which ends when all VFA are converted and only the virtually undegradable organic matter remains. Methane gas production continues with impaired intensity.
5. Finally, methane gas production will be reduced to a certain level when oxygen in the atmosphere can diffuse into the landfill.

In reality, several degradation phases occur concurrently in a landfill containing organic matter. Consequently, gas production can vary in different parts of the landfill, and the situation is constantly changing.

El-Fadel et al. (1997) presented a summary of factors that influence the gas production and the anaerobic degradation process in landfills (Table 6.1). The summary is based on a large number of studies published in the past 20 years. The different variables interact with each other to a large extent, and separating the influence exerted by an individual factor from the overall effect is difficult (El-Fadel, 1997; Gurijala et al., 1997).

Table 6.1. Factors influencing biogas production (El-Fadel, 1997, Bendz et al, 1999).

Factor	Stimulation of biogas production potential			Inhibition of biogas production potential		
	Low	Medium	High	Low	Medium	High
Composition		+		-		
Density	+					
Particle size	+					
Temperature		+			-	
pH		+		-		
Nutrients	+			-		
Microbes	+			-		
Moisture content			+			
Oxygen						-
Hydrogen	+			-		
Sulphate				-		
Environmental toxins					-	
Metals				-		

The growth of microorganisms largely depends on the external temperature since microorganisms cannot regulate their own internal temperature. Microbial growth usually occurs in the temperature range between 20 and 45 °C for mesophilic processes and between 50 and 65 °C for thermophilic processes. Excessively low temperatures are seldom fatal, unlike excessively high temperatures. As mentioned above, the temperature is also important for hydrolysis.

In contrast to fermentative and acetogenic bacteria, methanogenic bacteria are sensitive to the pH value, and can only survive at pH values between 6 and 8.

If the landfill is considered as a whole, there is no deficiency of the most important nutrients, nitrogen and phosphorus, but the heterogeneity of deposited waste means that malnutrition can be a limiting factor locally in the landfill (Christensen and Kjeldsen, 1989).

The moisture content is the single most important parameter for the anaerobic degradation process (Augenstein and Pacey, 1991; Bogner and Spokas, 1993; Christensen and Kjeldsen, 1989; Ehrig, 1991; El-Fadel et al., 1996; Gurijala et al., 1997; Klink and Ham, 1982). In addition to the reasons mentioned above, low moisture content could result in a local accumulation of substances that could have an inhibiting effect. The absence of oxygen is fundamental to the growth of anaerobic bacteria.

Gurijala et al. (1997) evaluated the importance of the overall effect of different factors and the individual contribution of ten different factors influencing methane gas production. They did this in a multiple regression analysis of data from 38 samples of MSW, which were collected at Fresh Kills Landfill, New York. A simple correlation analysis proved both misleading and inadequate since the interaction of the factors is important. The analysis showed that moisture content, concentration of easily degradable organic matter, sulphate, and the cellulose-to-lignin ratio were the variables of significant importance for the methane gas production. The other six variables made no significant contribution in the presence of the four mentioned above. Water content was most significant variable for methane gas production. The analysis indicated that methane gas production is stimulated at moisture content of over 55 % (by weight) and stops when the moisture content falls below 33 % (by weight). The content of easily degradable organic matter was the second most significant variable with a positive effect, but there are also indications that an excessively high content of easily degradable organic matter can inhibit the process. The third most significant variable was the concentration of sulphate, which has a negative effect on the methane gas production. Finally, a negative correlation was found between the cellulose-to-lignin ratio and the methane gas production.

Information about the proportion of organic carbon broken down varies in the literature, but it varies between 25 and 40 % of the total amount of organic carbon according to a summary by Bogner and Spokas (1993). It is clear that most of the organic carbon will remain in the landfill analogous to a sedimentary geological layer (Bogner and Spokas, 1993; Richards, 1989).

6.4 Emissions

6.4.1 General

The degradation products give rise to emissions to air, land and water. Emissions to land and water occur mainly through the infiltration of precipitation water into the landfill, followed by leaching of degradation products resulting from the processes described above and, to a certain extent, inorganic substances in the waste. Emission to the air comprises, as described above, a gas, normally referred to as biogas, but the term 'landfill gas' can be used in this context.

6.4.2 Leachate

Production, collection and treatment of the leachate comprise an extensive subject area that is outside the scope of this study. However, a certain description is justified because the design of the leachate collection system can give rise to undesirable gas leakage.

The main environmental protection measures normally implemented at a landfill are the bottom liner and a leachate collection system. The collected leachate is directed out of the landfill to some sort of treatment facility. The leachate collection system consists of a drainage layer that is placed over the bottom liner, with a thickness of approximately 0.5 m. In order to lead away the leachate that filters down from the waste layers above, drains are placed in the drainage layer, usually perforated plastic pipes. A collection system comprises drains, branches and main pipes that lead the leachate out of the landfill. All drains and pipes are sloping to facilitate leachate movement.

The leachate collection system can mean that the pipes also lead gas out of the landfill. This can be avoided by installing a water seal.

6.4.3 Landfill gas

The conditions for gas generation in a landfill have been described above. The magnitude of total gas generation and the time-lapse are most important from an emission perspective. From a total emission perspective, it is also important to know when gas emission stops completely and when gas recovery can be terminated.

Landfill gas comprises 40-60 % methane and 60-40 % carbon dioxide. Certain other gases are also found in small quantities. Methane has a volumetric weight of 0.71 kg/m^3 and carbon dioxide 1.62 kg/m^3.

After a short initial period, gas is constantly generated and emitted as methane and carbon dioxide. The gas flows are described in Figure 6.2 (from IPCC, 2007).

The mass balance describes briefly that landfill gas is generated, collected, oxidised in the landfill surface cover, or emitted to the environment.

The mass balance and information about the magnitude of methane oxidation show clearly that the magnitude of gas recovery is directly crucial for the magnitude of emission. A tight cover on top of the landfill simplifies the recovery of landfill gas since less air is sucked into the landfill. However, if there is no gas recovery system, the landfill gas will leak out unconditionally.

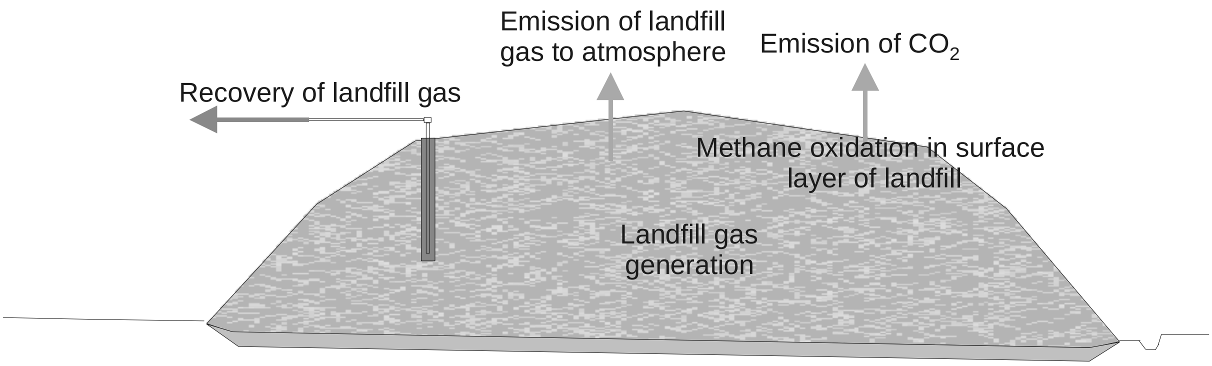


Figure 6.2. Flows of landfill gas from a landfill.

An equilibrium equation is as follows:

$G_b = G_e + G_o + G_r$

Where
G_b = gas production
G_e = landfill gas emitted to the atmosphere
G_o = the part of the landfill gas whose methane is oxidised to CO_2 in the surface layer of the landfill
G_r = landfill gas recovery

6.5 Settlement

Settlement in a landfill is an important influence on emissions. Settlement is primarily related to three processes (Huitric 1981):

- *Consolidation* is a process arising when water in the pores of the waste is forced out as a result of increased pressure caused by, for example, addition of new waste on top, sealing of the top surface, machinery, etc. The consolidation phase is therefore a process that, in principle, only occurs when the landfill is operative, since there is no increased pressure from above once it has reached full height (Wall and Zeiss 1995). However, the process can be delayed to a certain extent, since the pore water cannot always be transported away because the waste has low permeability.

- *Shrinkage* in waste is caused by the reduction in volume of solid material when organic material is converted to biogas and water (Huitric 1981). In principle, shrinkage continues for as long as organic material remains in the waste, which can be several decades. Shrinkage and compaction are the processes that contribute most to settlement in landfills.

- *Compaction* is caused by the constant rearrangement of the waste in the landfill. The rearrangement is primarily caused by changes in the structure of the waste when solid organic material is converted to gas and water. The solid skeleton that then remains is subjected to a greater burden and so collapses. Compaction is also caused by cavities that arise when organic material decomposes. The cavities are then filled with small particles resulting from the degradation processes above (Edil, Ranguette et al. 1990). This process results in compaction of the waste, which reduces the permeability for gas and water.

Settlement models for waste are based on geotechnical theories that have been adapted to the conditions that apply in landfills. Several settlement models use the same conditions that apply to settlement in peat, i.e. organic soils (Edil, Ranguette et al. 1990; Landva and Clark 1990; Morris and Woods 1990). The feature that distinguishes waste from most soil types is that waste contains a lot of organic material that decomposes over a long period. Like waste, peat has a high content of organic material, and contains a large proportion of cavities that are quickly compressed on loading (Bendz et al, 1999).

The models are generally designed to take into account the three processes described above. Consequently, models are often designed that divide the settlement process into three phases – initial, primary and secondary phases (Boutwell and Fiore 1995; Wall and Zeiss 1995).

The initial phase is very fast, often within a couple of weeks after the waste is subjected to pressure. The initial phase is dominated by rearrangements that occur in the waste mass when the largest cavities are compressed (Wall and Zeiss 1995). The primary phase is dominated by consolidation settlement. In this phase, it is the smaller pores, filled with pore water, that are compressed. Because the pore water offers some resistance to the compression, the primary phase is somewhat longer than the initial phase (Morris and Woods 1990). However, both phases continue during the period of operation because new waste is constantly being added, so the processes do not normally cause any disruption to operation. The secondary phase is dominated by volume losses caused by conversion of solid organic material to biogas and water. Because the secondary phase is directly related to the organic decomposition, it continues for as long as decomposable organic material remains in the landfill.

Research suggests a landfill containing household waste settles between 10 and 50 % (Huitric 1981; Stearns 1987; Van Meerten, Sellmeijer et al. 1997). Of this, approximately 5-30 percentage units stem from the initial and primary phases (El-Fadel, Findikakis et al. 1997). Decomposition of the organic material, which dominates the secondary phase, can theoretically account for settlement of approximately 40 percentage units. In practice however, it is unlikely that decomposition accounts for more than 25 percentage units (Huitric 1981).

Because it is the secondary phase that causes the problems arising from settlement, it is this phase that should be the most interesting one to study. However, because of the time span involved, it is difficult to find reliable data series that extend over the entire settlement process. It is also difficult for individual researchers to run projects over such a long period. Consequently, few models have been verifiable in the long term.

It is really more important to determine the scale of the uneven, differential settlement than the total settlement, because it is the differential settlement that causes problems when landfills are finally covered. The problems that arise are accumulations of water in local hollows, water seals in gas pipes, deformed structures above the landfill, deformations in the top sealing layer, etc.

The deformations can cause tension in the sealing layer. These tensions can have a negative effect on the properties of the sealing layer, or even rupture the seal. Several studies have examined the hydraulic conductivity of the sealing layer at different tensions. In order to obtain simple, comparable figures, the results are usually expressed as a distortion coefficient. The distortion coefficient is defined as the differential settlement, d, between two points divided by the distance, L (Jesionek, Dunn et al. 1995). See Figure 6.3.

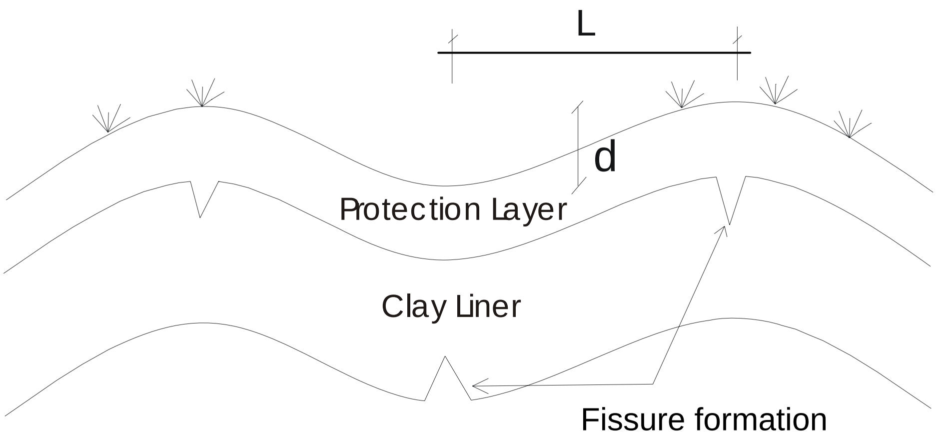


Figure 6.3. The effect of differential settlement on the clay sealing layer (Bredariol, Martin et al. 1995). The areas with fissures and a thin covering layer form leakage routes for landfill gas.

Laboratory experiments have shown that, of the common sealing layers, compacted clay is most affected by tension. At a distortion coefficient of between 0.05 and 0.1, clear fissure formation has been observed, corresponding to differential settlement of 5-10 cm per metre. In an experiment where kaolinite clay was subjected to tension equivalent to a distortion coefficient of 0.1, the hydraulic conductivity increased from 1×10^{-9} m/s to 1×10^{-5} m/s (Jessberger and Stone 1991), a permeability equivalent to that of fine sand. Similar experiments were carried out on geosynthetic clay liners (GCL). These were subjected to tension 20 times greater than that to which the clay liner was subjected, but resulted in no significant increase in the hydraulic conductivity (LaGatta 1992; Daniel and Scranton 1996).

Differential settlement, and damage caused by this, creates leakage routes for the biogas in a landfill. The gas leakage is concentrated to fissures of different types, including differential settlement fissures, but also fissures formed, for example, when a covering layer of clay dries out. The latter types are also often permanent, i.e. they close and open depending on the moisture content of the clay.

Differential settlement and its effects can be counteracted in a number of ways. Extra compaction immediately before covering using especially heavy vehicles or dynamic compaction, using a thicker protection layer that can even out locally powerful differential settlement, and using a geonet to reinforce the resistance of the sealing layer to deformation.

When the height of a landfill decreases as a result of the settlement types described above, the top surface also sinks and also the gradient of the landfill's slopes is reduced. If a landfill is built up with embankments on each lift surface, the settlement will affect the stability of the outer embankments, and therefore the covering of slopes, and fissures and openings arise.

Figure 6.4 below illustrates where fissures and impact on the cover occur.

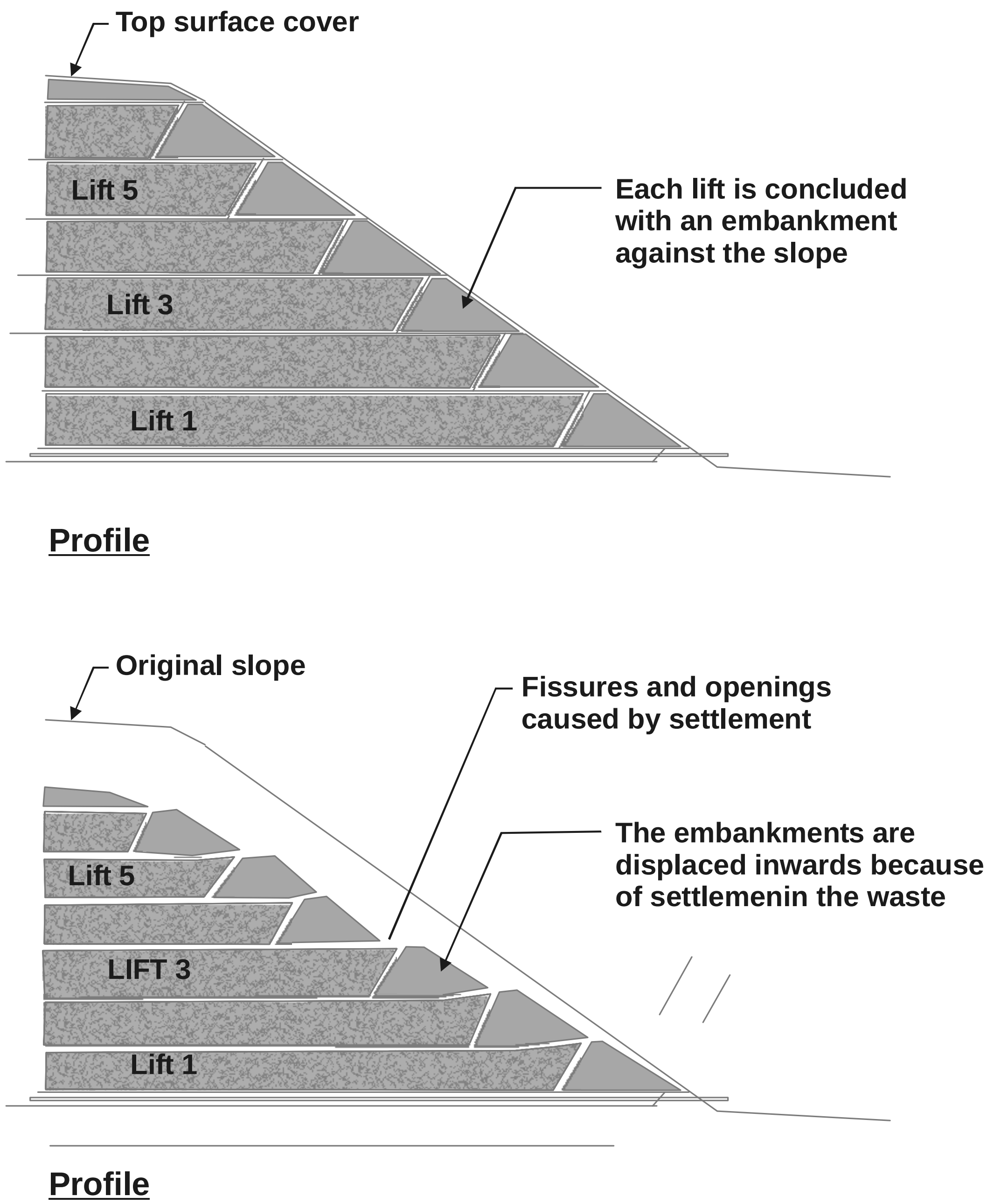


Figure 6.4. Changes in a slope after settlement, causing fissures and openings and allowing biogas to leak out of the landfill. The leakage is exacerbated because the permeability in the waste is greater for gas moving in a horizontal direction compared with vertical.

6.6 Recovery systems for landfill gas

According to Börjesson et al. (2000), the following measures could reduce emission of landfill gas from landfills:

- Prohibit the dumping of organic waste, which will considerably reduce the generation of landfill gas in the long term. This has already been prohibited in landfill regulations from 2002 and 2005.

- Permanently cover landfills. This measure is currently taking place because many landfills lacking adequate environmental protection measures must be completed by 2008, so they must be covered.
- Collect and use the methane, or render it harmless through flaring. There are currently 70 facilities where landfill gas can be recovered. Figure 6.5 shows the design of a gas recovery system at a landfill.

The introduction of an active recovery system for landfill gas with vertical wells or horizontal gas drains is the biggest single measure that can be taken to reduce methane emission from existing landfills. Field studies of a number of different systems that apply different procedures have shown that 90 % of the landfill gas generated can be treated at landfill cells that have been permanently covered and that have an adequately dimensioned recovery system (IPCC, 2007). Recovery levels at landfills with less efficient recovery systems, or with only part-systems, and where the system was installed late, are as low as 20 %. This indicates that the recovery system must be installed at an early stage. Installation of horizontal gas drains while waste is being deposited in the landfill, frequent adjustment to the system, monitoring of efficiency, repair of leaks in the recovery system, and covering of the waste are all measures that reduce emissions of landfill gas.

At present, landfill gas is used for heating purposes in conventional gas boilers, or for producing electricity. Piston engines, gas turbines or steam turbines are used to convert the energy to electricity. In individual cases, the landfill gas is upgraded and used as vehicle fuel. However, there are obstacles to this, primarily financial but also technical. Using the landfill gas to produce electricity and vehicle gas requires landfill gas with high methane content, which affects the recovery rate of the landfill gas. If, for example, methane content of 50 % is required, the recovery system must be regulated to 50 % methane content, and this often increases leakage in parts of a landfill where the methane content is low, because this gas cannot be used.

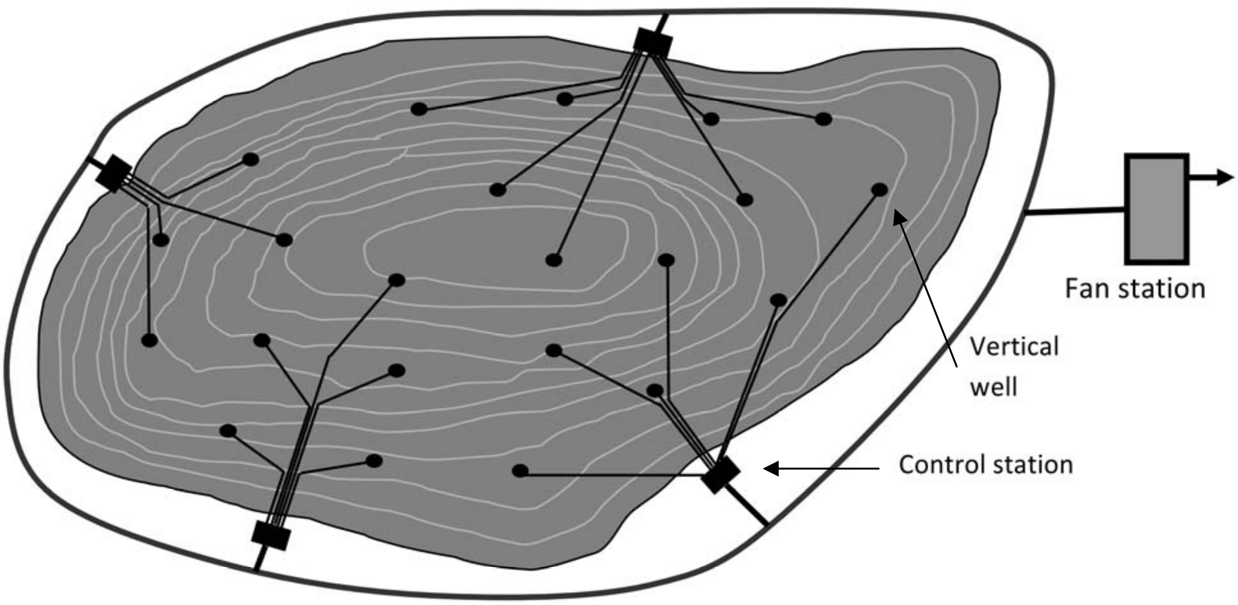


Figure 6.5. Example of a gas recovery system.

Figure 6,5 shows the gereral design of an landfill gas recovery system. The gas recovery is regulated in the control stations. A suction fan in the fan station applies sufficient negative pressure to the recovery system to extract the landfill gas to the fan station and onward for recovery or flaring.

This general introduction gives the impression that recovery of landfill gas is a relatively simple process to carry out and manage. However, there are a large number of complicating factors:

- During the operating phase, new waste is constantly being added, so new parts must constantly be added to the gas recovery system. The new parts comprise recovery wells, drainage systems, stem pipes, control units, pump capacity, and facility components where the landfill gas is used. At an active landfill, one or more of these parts is usually under construction.

- The drains and wells that are installed have a limited life. The installations are subjected to major stresses through the settlement that occurs in the landfill, pipes then develop water seals and the gas cannot be transported to the pump station and energy production plants. Collections of water in the landfill sometimes cause the wells to be filled with water and put out of action.

- A landfill gas recovery system is very dynamic in terms of flows and pressure in different parts of the system, and must therefore be constantly regulated and balanced.

In reality, these management difficulties mean that leakage is largely unavoidable. In individual cases, 100 % recovery of the landfill gas has been reported (Lagerkvist, 1996) in very small landfill cells. Recovery is usually between 50 and 75%.

6.7 Landfill gas movements

It is difficult to translate concentration data to a flow from the landfill. In order to understand the possibilities and difficulties, the outflow of landfill gas from a landfill must be described. By way of introduction, it can be said that many variables influence the magnitude of the outflow of landfill gas (Figure 6.6.).

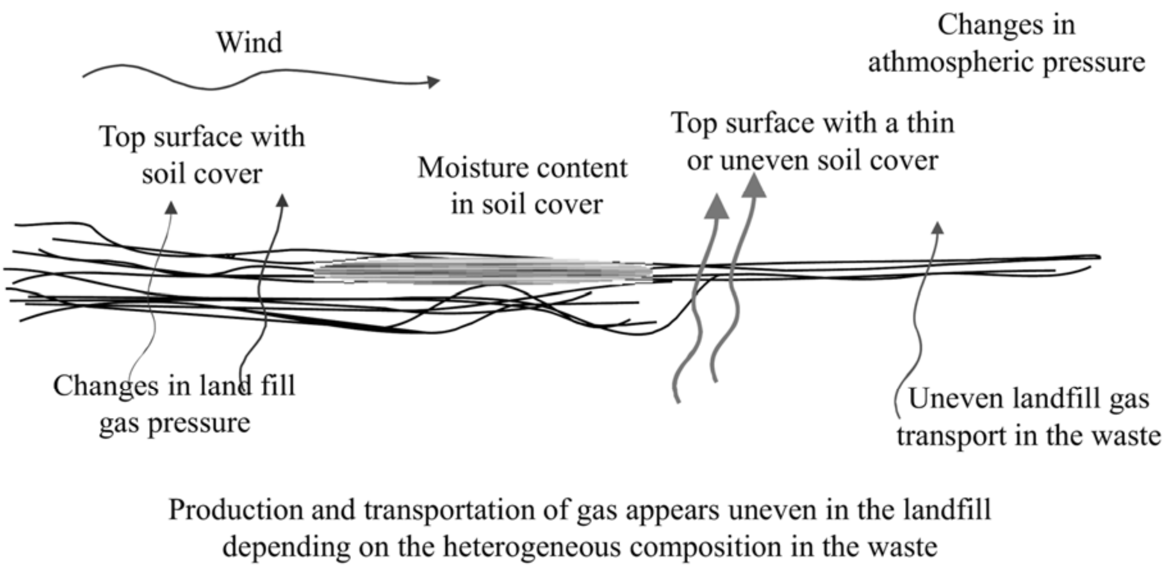


Figure 6.6. Different variables that influence the flow of landfill gas through the landfill surface.

The variables in the figure and changes over time mean that concentration measurements alone are difficult to interpret. Translation to a flow out from the landfill is even more complicated.

A landfill is a system that consists of a solid component, a pore volume (the volume between the particles of the solid phase) in which gas can move, and a liquid component. The liquid consists of water that is either bonded to the waste, the solid component, or is mobile and is found in the pore system. A certain amount of water is also bound through capillary forces to the pore system.

The landfill gas produced in the waste is confined to the pore system of the landfill. The pore system consists of both small and large pores, and these are either open or closed.

The landfill gas needs a gradient in order to move. This can either be a pressure gradient or a concentration gradient.

Pressure gradient
Gas generation and settlement create pressure in a landfill, which results in a pressure difference between the landfill and the atmosphere, a differential pressure. A recovery system for landfill gas uses negative pressure to lead the landfill gas out of the landfill to a gas facility. This changes the pressure conditions in the landfill.

Diffusion
Diffusion is a natural tendency for gas to attain an equal concentration in a space. In a landfill, gas moves from areas of high concentration (e.g. of methane) to areas of lower concentration. Since the concentrations of both methane and carbon dioxide are higher in a landfill than in the atmosphere outside the landfill, the gases are diffused out of the landfill (e.g. O’Leary P, Walsh P. 1995).

Because the landfill gas generated is constantly filling the pore volume with new gas, this creates a pressure that forces the gas out of the landfill. While the landfill is in operation, new waste is constantly being added, and the weight of this gradually decreases the pore volume, creating pressure.

A pressure gradient is also created when the gas is extracted from the landfill via the gas recovery system (active gas recovery, see above). An important question is how far the negative pressure reaches out from the recovery system. In recovery systems that use vertical wells, negative pressure is believed to reach 1.5 times the depth of the well.

Gas moves more easily in a horizontal than vertical direction because the waste is deposited in layers and compaction takes place horizontally, so the waste becomes more compressed and impermeable in a vertical direction. The gas permeability is up to ten times greater in a horizontal direction compared to vertical (O'Leary P, Walsh P. 1995).

The pressure gradient can also cause the gas to leave the landfill via the leachate collection system, if the pipes for leachate lead directly out to the atmosphere.

7. REVIEW OF EXISTING MEASUREMENT METHODS

7.1 General

There are a large number of methods for measuring methane gas. The methods applicable depend greatly on the criteria applied. The operator responsible for a landfill has specific criteria, and there can be criteria placed by authorities for various reasons.

In Sweden, no official emission limits have yet been placed, neither qualitative nor quantitative, for landfills.

Techniques and methods for detecting and quantifying methane from landfills can be divided as follows (Envirotech Engineering 2007):

1. Methods for detecting point source emissions and measuring concentration;
2. Methods for quantifying the size of leakages;
3. Methods for measuring areas, both leakage detection and quantification.

Methods for detecting point source emissions are those developed in the natural gas and petroleum industries, principally for measuring leakages from main pipelines (primary networks) and local pipeline networks (secondary networks). The methods available for measuring large areas cover parts or all of a landfill.

The measurement methods are presented in Figure 7.1. The methods are described in more detail in Appendix 5. The methods are divided into those for measuring concentration and those for measuring flow. Subdivisions then distinguish between methods used for surfaces and larger areas and those for measuring the source. Finally, a separate category shows the methods used for measuring methane emissions from entire landfills.

	Measurement of methane concentration	Measurement of methane flow
Entire Landfills		Concentration Measurement in Combination with a Tracer Gas, use of LIDAR, FTIR, TDLAS
Parts of Landfills, surfaces	Horizontal Radial Plume Mapping (HRPM) Remote Passive IR-gas Imaging Technologies Remote Passive IR-gas - Imaging Visualisation Remote Quantitative laser gas Detection TDLAS LIDAR	Vertical Radial Plume Mapping (VRPM) Chamber Method (Flux Box) Flame Ionisation (FID) + Chamber Method Laser + Chamber Method
Point Souces, Meausement Near Point Emmision	Flame Ionisation (FID) Catalytic Combustion Solid State IR absorbtion TDLAS *Indication Methods* Bubble Test Vegetation Changes Acoustic Detection	Containment Rotameter (Flow Measurements in pipes, many methods)

Figure 7.1. Division of detection methods and quantification methods for methane mixed with air.

There are a relatively large number of methods for measuring the methane content in the air mixture near the source of emission. In addition, methods such as gas chromatography can accurately measure concentration. Some of the methods are used to monitor the recovery of landfill gas in a gas recovery system, such as IR absorption and catalytic combustion.

Flame ionisation (FID) is used today for detecting point source emissions on landfills. IR measurement is also used, and equipment is available commercially for these methods.

FID is an instrument where the gas mixture that is to be measured is sucked into the instrument via a nozzle that is held approximately 5 cm above the surface. The survey is carried out by examining the surface in transects 25-50 m apart. Coverage is not complete but, by closer investigation where elevated concentrations are measured, the survey is satisfactory. Where elevated concentrations are recorded, a refined grid is the subject of further study in the area where elevated concentrations are discovered (UK Environment Agency, 2007). A hand-held instrument is available commercially. A GPS is supplied with the instrument for simultaneous determination of position.

An IR detector is used for detecting methane over landfill surfaces. An IR detector can be placed on a cross-country vehicle that is driven over the landfill surface. The measurement procedure can be combined with positioning using GPS, and large areas can be scanned.

Relatively few methods are fully developed and available for direct quantification of methane leakage from surfaces. The most commonly used method is the chamber method. The method was used in this project and is described in detail in Section 10.

In the manual produced by the UK Environment Agency, FID combined with chamber (flux box) measurements are prescribed as a method for examining methane emissions from landfills. FID is then used as a detection method and for classifying landfill surfaces from an emission perspective, and the chamber method is then used to calculate the methane emission expressed as a flow from the landfill surface. According to the manual, the number of chamber measurements is to be calculated using the formula:

$$n = 6 + 0.1 \sqrt{Z}$$

where
n = number of chamber measurements in a sub-zone
Z= area of the sub-zone (m^2)
The distance between the sites of the chamber measurements $\sqrt{(Z)}/n$

This calculation method is taken from US Environmental Protection Agency (USEPA 1986).

The method that is often used for quantification of methane leakage for entire landfills is tracer gas together with methane measurements. A tracer gas, such as SF6, is released with a known flow on the landfill, and the plume from this discharge is assumed to coincide with the emission of methane from the landfill. Both the methane and tracer gas concentrations are then measured in the plume that is formed downwind from the landfill. The following methods are used for measuring and calculating the emission:

1. Detection with light, differential absorption (LIDAR/DIAL), quantitative method in kg/hr or mg/m^3;
2. AIR detection and AIRDAR, quantitative method with results in E^3m^3/yr;
3. Tunable Diode Laser Absorption Spectrotroscopy (TDLAS), semi-quantitative, results in ppm x m;
4. FTIR, open beam Fourier Transform, semi-quantitative, results in ppm x m.

Firma Afvalzorg has launched a modified measurement technique for measuring flows from entire landfills. The technique also uses tracer substances and concentration measurements downwind (Jakobs, 2007). Atmospheric samples are taken over 4 hours using 14-15 vacuum bottles, at the same time as tracer gas is released from a site on the landfill. Otherwise, calculations are made in the same way as above.

VRPM, Vertical Radial Plume Mapping, is a new method that has been developed by the US Environmental Protection Agency. This method can measure the flow from parts of landfills. A laser instrument is used, fixed on a tripod. Pre-programming allows the laser instrument to be aimed at different reflectors that are placed in the corners of the area for which flow is to be determined. The principle is shown in Figure 7.2.

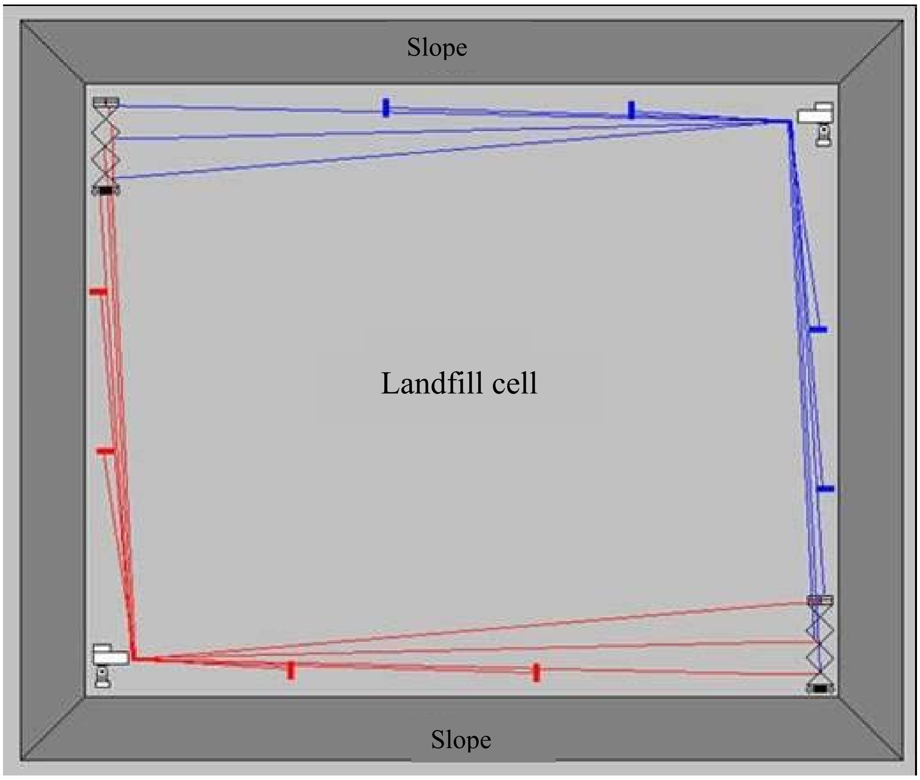


Figure 7.2. Measurements using a laser aimed at reflectors for determining emission from a landfill cell according to the VRPM method.

The laser instrument is aimed using special automation for approximately 10 seconds towards each reflector, and the concentration data is recorded. The beam is then moved to the next reflector and a new measurement taken. Several series of measurements are taken.

All concentration data is processed and converted to flow data using a special computer program. Unfortunately, this computer program is not available commercially, and the data processing is performed at the University of Virginia, USA.

According to Boreal, the company that developed the equipment, the method can be developed into a method for use in the field in the future. The method is currently too complicated and needs to be developed further.

Chambers have long been used to measure long-term flows from landfill surfaces. Their method of use in this project is described below.

8. THE NEED FOR COST-EFFECTIVE TECHNIQUES AND METHODS

There are few cost-effective methods for detecting gas leakage and for mapping emissions from landfills. The tasks are to obtain an overview of the scale of gas emissions from the landfill in question, and also to pinpoint the exact positions of leakage sources and to quantify the size of the gas leakage. There is also a need to produce information on which to base urgent and more long-term measures within the framework of continual monitoring, condition analysis, and a programme of measures for a landfill (condition monitoring).

Results from current research literature show that established field methods, such as static or dynamic chambers, TDL laser, the combination of the chamber method and measurements using lasers in horizontal and vertical planes, etc. are often limited to recording gas emissions from flat surfaces (Chanton et al. 2007). The static and dynamic chamber method can be used to measure on flat surfaces, slopes, crests and toes of slopes, but it is technically difficult to carry out chamber measurements on steep and vegetated slopes. Furthermore, various studies show that the chamber method is labour intensive, and requires a substantial number of chambers for complete measurement of methane emissions or methane oxidation at landfills. In order to describe the spatial variation and to estimate the mean flow of methane emissions for a landfill of 1.6 ha, calculations show that measurements must be taken using 5 275 chambers (Börjesson, G., Svensson, B. 1997). For more reliable data, a grid system should be applied (Nozhevnikova et al. 1993) or some type of remote sensing system (Jonas and Elgy 1994).

Jacobs, J. et al. (2007) report on a study involving a test of a low-cost method for measuring methane emissions from landfills. The authors start by presenting the EU regulations for management of methane emissions from landfills, the E-PRTR regulations that came into effect in 2007. These regulations state that methane emissions from landfills must either be (a) measured on site, (b) calculated using emission models, or (c) estimated by field experts.

- Measurement of annual methane emissions from a landfill is considered too expensive.
- Existing emission models are considered (a) to be too inaccurate, (b) to be not mutually comparable, (c) to have poor accordance with reality.

Jacobs et al. point out the need to develop simple and inexpensive methods for measuring and quantifying annual methane emissions from landfills. Such methods would increase knowledge about methane emissions from landfills, improve the model parameters over time, and thereby increase comparability, correspondence, accuracy and reliability of emission data in the E-PRTR database.

Results reported in research literature in the past decade confirm the need for cost-effective methods for detecting and mapping emissions of methane gas from landfills, from Börjesson, Svensson (1997) to Jacobs, et al (2007). Similar observations and conclusions are shown through results from field laboratory studies of natural gas emissions performed within the framework of the VOGUE project, an EU project on remote methane gas detection (Ljungberg, et al. 2004), through field measurements at Filborna landfill (biogas) (Ljungberg 2000), and through conclusions in a global inventory of state-of-the-art of technologies for remote detection of natural gas (Ljungberg et al. 2000).

Bearing in mind the experiences reported in the above research literature, and the opinions and wishes expressed in the working group of researchers and end users in the current project, there is clearly a great need for cost-effective technology that is easy to use in the field in order to, remotely and without physical contact with the gas, detect, measure and spatially locate methane emissions and leakage sources at landfills.

Cost-effective technology is defined here as measurement techniques and methods that are inexpensive and easy to use in relation to the value of the information about methane emissions that the end user obtains compared with the established, more labour-intensive and expensive, techniques and field measurement methods.

Operative methods also need to be developed in which different types of remote sensing techniques and complementary field measurement techniques are coordinated and integrated into an arsenal of methods that are simple for the end users to use. In addition, instructions and guidelines are needed to assist in the choice of suitable techniques and methods for detecting, mapping, storing, presenting and evaluating information about gas emissions from landfills. It is also desirable that the end users, using similar instructions, can find guidance in assessing the usability and limitations in performance and expected benefits when choosing different types of measurement techniques and methods for mapping and determining the status of gas emissions from all or part of a landfill.

A landfill comprises a large volume of waste that is deposited at intervals over a longer or shorter period of time. Until recently, the waste deposited in Sweden largely comprised biodegradable waste. The biochemical process in a landfill and the production of methane gas can vary considerably, depending on the properties of the organic material that is deposited, the management, and the storage conditions in the landfill, and also on the age of the different sub-areas (the cells) in a landfill. Because a landfill normally comprises a large volume and has large variations in the organic process, it is important to develop operative methods for measuring in the field that provide both a synopsis of the methane gas emission from the entire landfill and, at the same time, give detailed information about localisation and concentration of methane gas from different gas leakage sources. Experiences from the VOGUE project (Ljungberg, 2004) indicate that modern remote sensing, such as hand-held, mobile and airborne laser and IR techniques, are suitable for tracing, detecting and mapping gas emissions, and give both general and detailed information about gas emissions from small and large areas.

9. REMOTE SENSING METHODS FOR DETERMINING THE STATUS OF GAS EMISSIONS FROM LANDFILLS

9.1 Remote sensing techniques and methods

Remote sensing (RS) is the generic term for a group of stationary, hand-held, mobile, airborne and satellite-borne technical systems that can be used to record and measure properties of an object remotely, without physical contact with, nor affecting, the object. Remote sensing technology has its origins in military research and military applications, with the primary aim of tracing and identifying objects and gaseous phenomena on land and in the air, and for surveillance. Nowadays, modern remote sensing technology is also developed at civil research institutions, universities of technology, and at companies in the private sector. Remote sensing technology most familiar to the general public includes analogue or digital cameras, satellite systems for weather observations and medical systems for visualising the condition of the human body.

Remote sensing is a young field of technology related to many different disciplines such as applied physics, electronics, optics (optronics), computer sciences, geodesy, disciplines for manufacturing precision instruments, and applied methodology, etc. From the start of the 1980s, remote sensing technology for civil applications has developed rapidly, principally in infrared, laser and radar technology. Examples are technologies for detecting gas emissions from pipeline systems placed above and below ground. Other examples of remote sensing technology are environmental applications, such as mapping of gas and particle compounds in the air, pollution of seas, lakes and rivers, medical applications such as lasers, ground-penetrating radar for mapping the status of objects placed in the ground and for detecting hazardous waste deposited in the ground, infrared technology and radar for determining the status of buildings and technical infrastructure, and airborne laser and radar for large-scale measurements of environmental applications.

9.2 State-of-the-art product and method development

In December 1997, an international working group was set up, with the task of carrying out a global inventory of state-of-the-art remote gas detection technologies. The working group comprised representatives from universities and international research institutions, and from many of the world's biggest gas producers and distributors, including scientists from Sandia National Livermore, USA, the Royal Institute of Technology (KTH) Sweden, the Gas Research Institute (GRI) USA, VNIIGAZ Gazproom Russia, Japan Gas Association, Gasunie France, British Gas, Danskt Gasindustri Denmark, and the Swedish Gas Centre (SGC). The working group submitted a report in 2000 and a number of different research groups were set up with the aim of implementing R&D projects on remote gas detection technologies. As a result of the work of these research groups, Japan Gas Association and Tokyo Gas presented a hand-held laser system for remote detection of methane gas in 2002, and Sandia National Livermore presented a prototype laser system for gas detection in 2004. An EU-financed R&D project, the VOGUE project (Visualisation of Gas for Utilities and the Environment) produced five laser systems for remote detection of methane gas that were tested by European end users for the gas distribution network in 2004. A final report from the VOGUE project was submitted to the EU Commission in August 2004.

Two of the authors of this report (Ljungberg and Meijer) participated in the international working group for the global inventory of state-of-the-art remote gas detection technologies, and S-Å Ljungberg was coordinator.

In the EU VOGUE project, Sven-Åke Ljungberg (KTH) and Owe Jönsson (SGC) were responsible for the R&D component concerning passive gas imaging and methane gas behaviour. The main objective of the VOGUE project was to develop laser systems for remote detection and visualisation of methane leakage from gas pipelines, placed above and below ground, and to study and increase knowledge about the behaviour of methane gas under different conditions of pressure, flows, weather and radiation, similar to those met by the end user in practical use of remote sensing technology for gas detection.

During the product development, two different prototype systems were tested. Siemens in Munich developed one of them, and researchers at Glasgow University developed the other one. Both the prototypes were tested under controllable conditions in a field laboratory at Malmö Fire Service's gas testing facility, at a field test facility at ADVANTICA (formerly British Gas) and on different distribution networks in Europe, chosen by end users in the project.

The laser systems developed in the VOGUE project measured the methane gas concentration along a beam, and expressed the concentration in ppm x m. High-resolution passive IR systems were used as supplementary technology for detecting and visualising simulated leakage of methane from gas pipes placed below and above ground, in order to study the behaviour of methane gas under different gas flows, pressure, size of gas leakage source, different filling materials, and weather and radiation conditions.

One of the conclusions from the VOGUE project was that the laser systems developed in the project for detecting methane gas leakage from gas distribution systems could also be used for environmental applications and for detecting methane gas emissions from landfills.

9.3 Pilot study testing laser and IR systems for detection of methane emissions from landfills

With the aim of investigating whether the VOGUE laser system and supplementary IR system could be used to detect, visualise and map gas emissions from landfills, a pilot study was carried out, using repeated field laboratory tests at Filborna landfill, Helsingborg for approximately a year (February 2005 – March 2006). During the test period, the prototype laser developed by Siemens Munich was used, along with different types of high-resolution thermal cameras made by FLIR Systems AB, Sweden. The study was the first of its kind, either nationally or internationally. The results of the test indicated that hand-held lasers and IR technology could be efficient instruments for detecting and visualising gas emissions from landfills.

The pilot study at Filborna was preceded by a test with helicopter-borne aerial thermography of known leakage sources at the field laboratory at Malmö Fire Service's gas testing facility and at Filborna waste facility. The following section presents a brief description of the field laboratory experiments with aerial thermography.

The airborne field experiments are of interest in relation to observations and conclusions from field measurements described in the final report of the project, and for any future R&D projects, because they show the information potential of airborne remote sensing methods for detecting gas leakage from landfills using airborne infrared technology.

The results of the experiments with aerial thermography for detecting and visualising methane gas attracted great international attention, and led to the formation of an international working group of scientists and end users. This group carried out the inventory of state-of-the-art technologies for remote detection of natural gas described in Section 9.2, and which then led to the design and implementation of the EU VOGUE project.

In the experiment, a FLIR THV 1000 long-wave thermal camera mounted in a glass sphere, GIMBLE, ARGUS 350 Stable Eye type C, stabilising platform with a Hughes 500 helicopter as instrument bearer, was used (see Figure 9.1). The thermal camera was operated from inside the cockpit using a hand-held control panel with a joystick. The thermal image data was stored on an analogue tape recorder and a selection of thermal images was stored on a hard drive for later processing and analysis in the image laboratory. The thermal camera used had a detector that is sensitive within the upper wavelength range for methane gas, 7.9 µm.

The subjects of the investigation were a test facility with culvert trenches capable of simulating gas leakage at the field laboratory at Malmö Fire Service's gas testing facility and a test surface with six vertical gas recovery pipes at Filborna landfill. At the time of the experiments, the gas pipes at Filborna were not connected to the recovery system, and the methane gas escaped freely to the atmosphere.

Figure 9.1. High-resolution AGEMA Thermovision 1000 long wave thermal camera, 8-14 µm, mounted on a GIMBLE, ARGUS 350 Stable Eye type C, stabilising platform, with a Hughes 500 helicopter as instrument bearer.

Figures 9.2 and 9.3 show variations in the radiation temperature and radiation temperature patterns in aerial thermal images from parts of the field laboratory at Malmö Fire Service's gas testing facility. The images show methane leaking from the ground surface. Light areas indicate leakage where the gas is warmer than the surrounding surface (Figure 9.2), and dark areas show where the gas is cooler than the surrounding surface (Figure 9.3). The gas leakage is simulated through perforated gas pipes placed in the ground, with a gas pressure of 0.5 bar, aerial height 60 m (180 ft.).

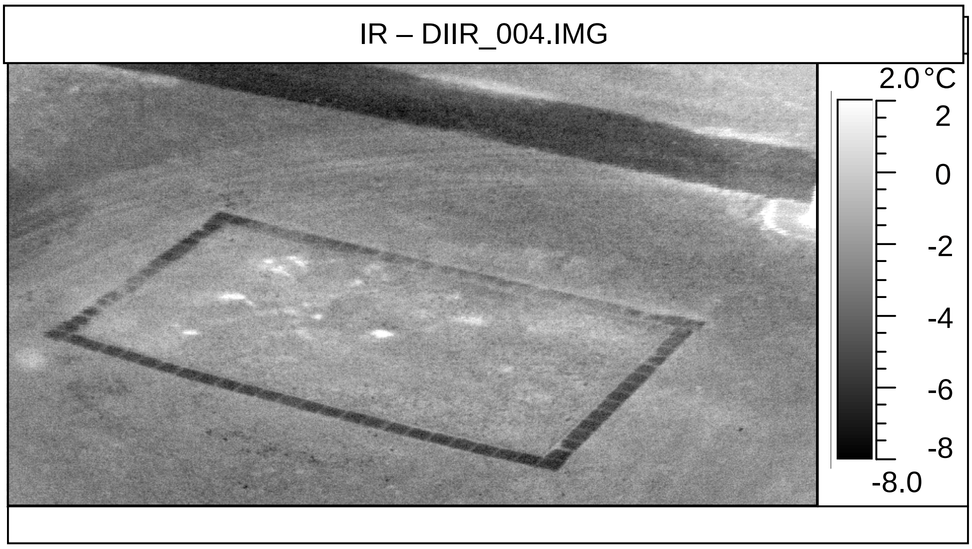


Figure 9.2. Aerial thermal image with deviating radiation temperature and temperature patterns. The light areas show where the gas is warmer than the surroundings, and indicates leakage of methane gas from pipes in the ground. Aerial height 30 m (90 ft.), gas pressure 0.5 bar.

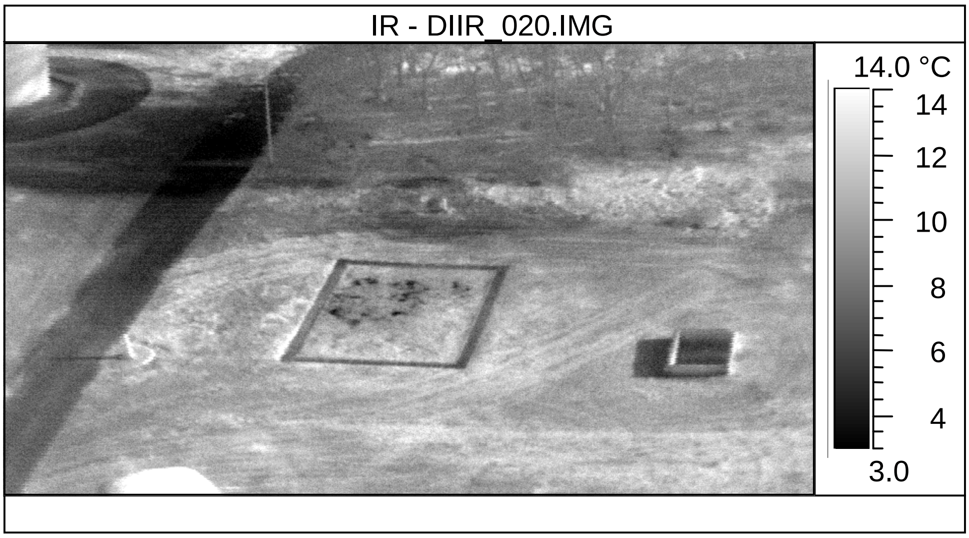


Figure 9.3. Aerial thermal image with deviating radiation temperature and temperature patterns. The dark areas show where the gas is cooler than the surroundings and indicate leakage of methane gas from pipes placed in the ground. Aerial height 60 m (180 ft.), gas pressure 0.5 bar.

Figure 9.4 shows a photograph of a test surface for ground-based and airborne tests of gas leakage from vertical gas pipes that, when the test was carried out, were not connected to the gas recovery system, Filborna landfill, Helsingborg. Figure 9.5 shows an aerial thermal image with examples of biogas leakage from one of the six vertical gas pipes on the test surface, aerial height 60 m (180 ft.), gas flow 15 m^3/hour (source: J-E Meijer, NSR). Note that the thermal image only shows a snapshot picture of the gas leakage in the form of a dark plume at the top/opening of the gas pipe. A longer sequence of the leakage of biogas from the six vertical gas pipes is recorded in real time on videotape. The videotape shows that the methane emission from the pipe pulses in time intervals from high flows to low, decreasing flows down to intervals with no visible/measurable flow, probably related to dynamic gas processes in the landfill. Similar observations were noted in repeated field measurements with the Siemens laser system and the FLIR IR GasFinder system in the completed gas project.

Figure 9.4. Test surface for ground-based and airborne tests of simulated gas leakage from Filborna landfill, Helsingborg. The vertical gas pipe shown in Figure 9.5 is circled in the picture.

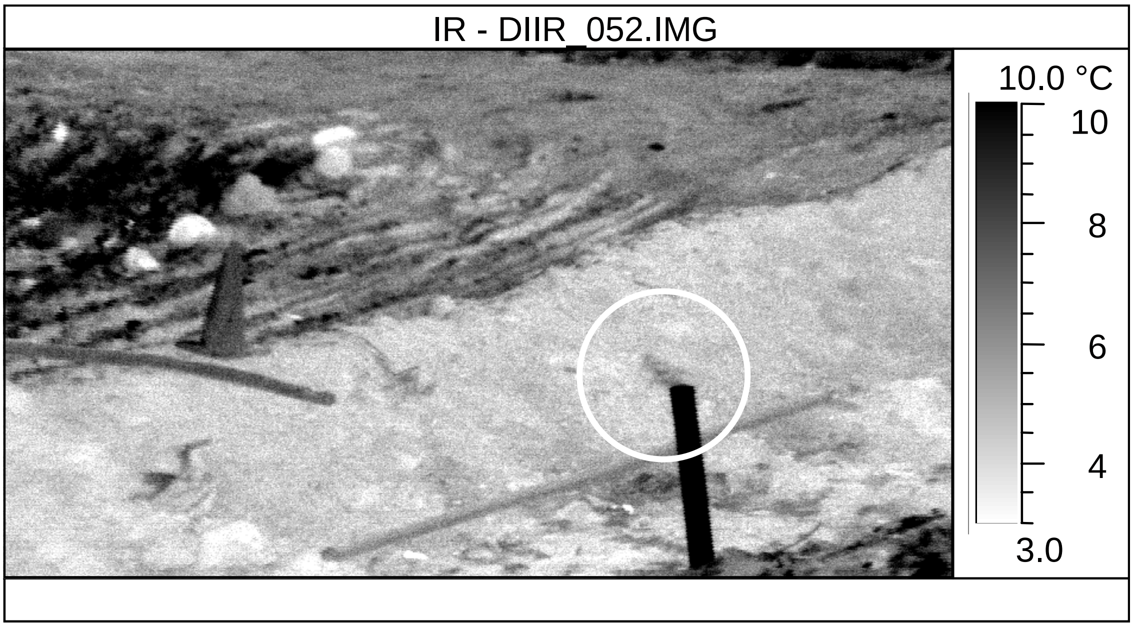


Figure 9.5. Aerial thermal picture showing leakage of biogas from a vertical gas pipe at Filborna landfill. Aerial height approx. 60 m (180 ft.), gas flow approx. $15m^3$/hour.

There are two different methods for detecting gas leakage using ground- and air-based thermography:

(1) **Indicator method**, where a comparative analysis is made of differences in radiation temperature and radiation temperature patterns at a measurement feature and a reference point. ΔT is used as a measurement and an indicator of a deviating state and is to be interpreted as a secondary effect of the occurrence of a gas leak.

(2) **Visualisation method**, where a specific gas is detected and visualised using a thermal camera with a detector that is sensitive within the spectral range of the specific gas. Thermal image data is stored here continually in real time on an analogue or digital tape recorder for interpretation and analysis in an image laboratory.

The precise location of thermal image data from both the indicator and the visualisation method can be determined using high-resolution GPS, and can be stored, preferably digitally, so computer-based analysis and interpretation can produce temperature profiles and measure delta T in the thermal image.

Modern high-resolution IR technology, with a detector that works within the spectral range of the specific gas, and GPS can be used to detect, visualise, study and locate gas emissions from landfills and from piped gas systems placed below and above ground. Note that aerial thermography in its current form is not a measurement method for determining gas flow or gas concentration. In order to measure gas flow, etc. supplementary conventional measurement methods, such as sniffers, etc. are needed.

Like other established techniques, including Siemens' laser system, the problem remains of measuring at the right time in order to get a true picture of gas emissions from a landfill. Bearing in mind that methane emissions from a landfill are probably irregular over time and emission magnitude cannot be measured at a single point in time, a longer period of measurement is required. In the field of modern remote sensing, a combination of computer-controlled surveillance systems has been developed for safety monitoring and for continual environmental monitoring, from stationary to air- and satellite-borne laser and IR systems. These are models that should also be of interest for landfill applications.

9.4 Laser systems for detecting and mapping methane gas emissions from landfills

In this project, a hand-held Siemens AG, CT PS 8 laser system was used (Figure 9.6), developed for field-based remote detection of emission of natural gas as part of the EU's VOGUE project with a final report submitted in August 2004, NNE5-1999-20031.

Technical data for the laser system in question:

Operative wavelength range	1 651 nm
Time response	100 ms
Detection range – gas concentration	0 ≥ 1 000 ppm x m
Operative battery capacity	3-5 hours, depending on ambient temperature
Operative temperature range	-10 – +40 °C
Operative distance/range	>10 ≥ 30m, depending on reflected backscatter surface; with a suitable reflector, the range can be extended to ≥ 100 m (Source: Siemens, 21 February 2008)
Lower detection limit	10-20 ppm x m, depending on reflected laser strength (for further technical specifications, see Appendix 2).

The Siemens laser system works with an infrared laser, 1 651 nm, and is a backscatter system. The laser beam is transmitted and records the concentration of methane gas along a beam length where the laser beam is reflected from a background surface. The gas concentration is measured in units of ppm x m, so the laser gives a mean concentration along the relevant measurement distance from the laser to the backscatter surface. The interpretation is that, if the measurement distance that the laser beam travels through is long, methane emissions along the entire distance are integrated, and can therefore give a misleadingly high ppm result. Horizontal scanning of large landfill areas often gives varying and high ppm results depending how the horizontal angle is varied, i.e. in a straight horizontal position, all methane gas is integrated along the entire range of the laser system, approximately 30 m.

If the length of the measurement distance is known, the ppm figure obtained can be divided by 2 x the distance in metres between the laser system and the backscatter surface, thereby giving a mean figure for the gas concentration measured between the instrument and the backscatter surface. If the amount by which the methane concentration exceeds the mean concentration in the atmosphere (1.7 ppm) is to be calculated, the calculated value in ppm is subtracted by 2 x the distance in metres x 1.7.

When scanning a gas cloud, it is not known where the gas leakage starts or ends, or where the leakage source is within the gas cloud. In pinpointing, an active search is first made for the source of the leakage through horizontal scanning to indicate gas emissions, and then vertical searching and detection until the source of the leakage is found. Consequently, it is important to develop and choose the right field measurement methods when the laser is to be used as a scanning instrument and as a method for searching for and detecting the source of a methane gas leakage. The Siemens laser system can either be held in the hand for scanning or pinpointing, or placed on a camera tripod for detailed long-term measurement of the gas concentration from a known leakage source.

Figure 9.6. VOGUE Siemens AG, CT PS 8 Remote Natural Gas Leak Detector Field Unit (for technical specification, see Appendix 2).

The Siemens laser system AG, CT PS 8 is designed with a laser for detecting natural gas, i.e. gas with a methane content of 96-98 % as opposed to a methane content of 40-60 % for landfill gas. The lower methane content of landfill gas, approximately 50 % depending on the composition of the gas at the landfill in question, makes it less detectable compared with natural gas.

9.5 High-resolution infrared technology for detecting and visualising methane emissions from landfills

In the current project, tests were carried out with a recently designed FLIR IR GasFinder in order to detect and visualise methane gas leakage from surfaces and technical installations for gas systems at landfills. The GasFinder system can be used to detect and visualise a number of different gases, including methane, from landfills, natural gas from piped systems placed below and above ground, gas and leachate wells, gas turbines, gas tank stations, etc.

The advantage of the GasFinder is that it can be used to detect and locate leakage sources, visualize the gas and to study and monitor the occurrence, diffusion and decay of a gas cloud.

The disadvantage of the GasFinder is that, like all IR technology, it is temperature dependent. With its current thermal and geometric resolution, the GasFinder requires a relatively high gas concentration before it can detect and visualize methane. The detectability limit for methane varies, depending on the size of the temperature difference between the gas and the ambient temperature, and between the gas and the emission factor for the surface material through which the methane gas penetrates to reach the atmosphere. The results of the field experiments carried out in the project indicate that a methane concentration of ≥ 1 000 ppm x m is needed, and a delta T between the methane gas and the surroundings of ≥ 2 °C, depending on the wind speed, radiation conditions, etc.

The information potential of the GasFinder system is regarded as high, and the next generation of GasFinder is likely to be more useful, with greater thermal and geometric resolution. It can already be used as a control system for checking the safety of a gas distribution system and for large methane emissions invisible to the naked eye.

Figure 9.7 shows the FLIR IR GasFinder system. The thermal image data can be stored digitally in real time on a DVD unit connected to the system. The system can be used as a hand-held system, or as a stationary or fixed-direction scanning system mounted on a conventional camera tripod. Alternatively, it can be used as a mobile system with the GasFinder mounted on a ball/mast on a vehicle, manoeuvreable with a joystick unit inside the vehicle.

Figure 9.7. FLIR ThermaCAM™ GasFindIR-SW. For technical specification, see Appendix 3.

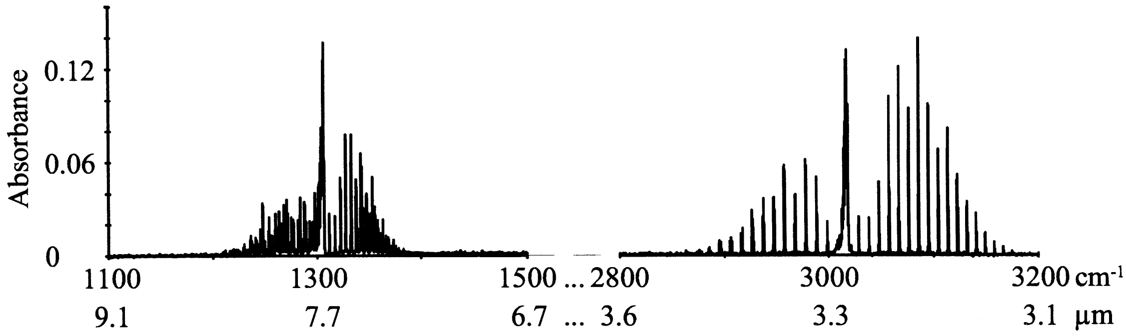


Figure 9.8. Spectral ranges for long-wave and short-wave IR systems for detecting and visualising methane emissions, 7.7 µm and 3.3 µm respectively.

9.6 Remote sensing specifications for detection of biogas

The specification of requirements relating to detection of biogas according to the review of the state-of-the-art of technologies for remote detection of natural gas was used as a guideline in the VOGUE project (Section 9.2), and was updated with information from end users in preparation for the current project in relation to landfill applications.

Table 9.1. Natural gas applications, user priorities for different categories and application, according to end users' evaluation and priorities of remote sensing of natural gas for applications 1-5. Based on assessment by delegates from an international reference and working group, Malmö, Sweden, 14-26 September 1998.

Priority					**1**		**3**		**2**		**4**	
↓	Specification categories and criteria	Range			Detection limit (A) (request/ limit)	Detection limit (A) (request/ limit)	Size of plume (m)		Survey criteria (B)		Detection of point-source emission (C) criterion	
	Application	H	M	A			B	NB	B	NB	B	NB
4	1. Production	10 m	100 m	100-500 m	2.2 points 0,1 - 2 %	1	-	5	-	5	-	0
2	2. HP Transmission	-	-	50-500 m	3.4 points 10 - 500 ppm	0.5 - 2	5	-	4	-	-2	-
1	3. LP Distribution	30 m	5-30 m	-	3.6 points 1 - 10 ppm	0.1 - 1	5	-	3	-	4	-
3	4. LNG Storage	10 m	100 m	100-500 m	2.6 points 0.1 - 2 %	1	-	3	-	3	-	0
3	5 Indoor air	5 m	--	-	2.6 points 0.06 - 5 l/h	0.1	-	-1	-	1	-	-5

(A) detection – able to detect gas leakage
(B) survey – scanning of surfaces to detect diffuse gas emissions and point sources
(B) pinpointing – localisation of point source emission
(C) measurement – measurement of gas leakage, concentration

B = buried pipes
NB = surface pipes

H = Hand-held instrument
M = Mobile, fitted on vehicle or 2-wheeled trolley
A = Airborne instrument

Table 9.2. Biogas and environmental applications – requirements and technical criteria from end users, according to end users' evaluation and priorities av remote sensing of natural gas for applications 1-5. Based on an assessment of landfills carried out by Jan-Erik Meijer 1999, and an assessment for environmental applications by Gretta Akopova, VNIIGAS, GASPROM, both of them delegates from an international reference and working group, Malmö, Sverige 14-26 September 1998.

Priority → ↓					1		3		2		4	
	Specification categories and criteria	Range			Detection limit (A) (request/ limit)	Size of plume (m)	Survey criteria (B)		Detection of point-source emission (C) criterion		Measurement criterion (D)	
	Application:	H	M	A			B	NB	B	NB	B	NB
1	1 Landfill	10 m	100-500 m	100-1 000 m	10-500 ppm	0.1-1	High	-	High	-	Low	-
3	3. Distribution pipelines, low pressure	30 m	5-30 m	-	10-500 ppm	0.1 - 1	5	-	3	-	4	-
2	5 Indoor use	5 m	--	-	2.6 points 0.06 - 5 l/h	0.1	-	-1	-	1	-	-5
	Application:											
1-2	7 Environment	5-30 m	5-100 m	100-1 500 m	10* -400* ppm	0.1-0.5		High		High	High	High

* Maximum permitted concentration CH_4 in residential area (Russia).
* Maximum permitted concentration CH_4 in industrial area (Russia).

B = buried pipes
NB = surface pipes

H = Hand-held instrument
M = Mobile, fitted on vehicle or 2-wheeled trolley
A = Airborne instrument

10. CHOICE OF METHODS

10.1 General

Field laboratory and field measurement methods, including the remote sensing technology described in Section 9, have been developed for detecting, mapping and visualising gas emissions from landfills.

The SIEMENS VOGUE laser system, AG, CT PS 8, which is a measurement instrument, was selected as it was considered to be the most suitable when developing methods to detect methane leakage, trace methane leakage sources, map gas emissions and measure the methane concentration in the surface layers of landfills.

The FLIR ThermaCAM™ GasFindIR LW, which is an image-producing instrument, was selected because it was the only IR system available on the market for detecting and visualising methane emissions and for studying the occurrence and diffusion pattern of gas emissions and gas clouds.

Supplementary field reference measurements were taken for a range of weather and radiation parameters considered important to record before, during and after measurement of laser and IR detection of methane emissions. Most of the measurements of field reference data were carried out near, or directly adjacent to, features and surfaces where the laser and IR measurements recorded methane emissions.

Figure 10.1 shows some of the measurement systems that were used for field reference measurements. At the start of the project, field reference data was noted manually on written recording sheets as shown in Figure 10.3. In a later phase of the project, these were supplemented with further field parameters, such as landfill pressure, atmospheric pressure, gas temperature, surface and ambient temperature, which were measured over long periods and were stored in real time in data logs adapted for use in the field (Figure 10.2.)

(a) (b) (c)

(a) (b) (c)

Figure 10.1. Reference measurement systems: (a) contact temperature gauge, (b) air temperature gauge, shielded from atmospheric radiation, (c) infrared radiation temperature gauge, with laser pointer for measuring atmospheric radiation temperature and for measuring the temperature of emitted gas and neighbouring features/surfaces, (d) rotating wind velocity gauge, (e) Variotec-6 gas sniffer, (f) examples of reference data collection in field laboratory experiments using the same measurement techniques and procedures as those used in the field measurements.

Figure 10.2. Logs with systems for measuring reference data, such as weather and radiation parameters, landfill pressure, gas temperature at the leakage source, wind speed, atmospheric pressure, etc.

Location: Forsbacka									**Signature: SÅL**
Place description: F1 S:.a slänten									
Forsbacka_F1_1-8_070712_02.xls									
Measurement		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Object		F1-01	F1-02	F1-03	F1-04	F1-05	F1-06	F1-07	F1-08
GPS, X-coord									
GPS, Y-coord									
GPS, Z-coord									
Date:		2007-07-12	2007-07-12	2007-07-12	2007-07-12	2007-07-12	2007-07-12	2007-07-12	2007-07-12
Time:		13,42	13,35	13,1	13,22	13,18	13	12,55	12,45
ppm x m	**	500-7000	<=500	<=1400	<=250	1500-2000	10-30	1500-2000	<=1100
FLIR, Fil nr									
$T_{surface}$		20,8	23,5	23,2	25,4	26,0	26,0	33,5	21,4
T_{gas}		23,5	21,3	22,2	24,6	26,0	26,2	26,5	21,4
$T_{y\text{-}g}$									
T_{air}		21,5	19,5	22,3	19,3	20,0	23,7	21,3	18,8
T_{panel}									
$T_{p\text{-}g}$									
T_{sky}	*	-3	-2	-3 -40	-3 -5	-4 -47	-2 -49	-2 -40	-3 -48
$T_{H\text{-}T}$									
T_{ref}									
Windspeed		0,5	1,5-2,2	0,5	0,5	0,5	0-0,5	0,5-1,0	1-1,5
Wind direction		NO	NO	NO	NO	NO	NO	NO	NO
Top surface	☐								
Crest	☐								
Slope	☐								
Slope toe	☐								
Gas well	☐								
Leachate well	☐								
Leachate pond	☐								
Leachate inlet	☐								
Gas pipe	☐								
Plastic liner	☐								
Covered surfacce	☐								
Final cover	☐								
Not cov. surface	☐								
SL	☐								

Comments:
*** Varying cloud cover gives greater variations in atmospheric radiation temperature (Ts).**
**** Gas from broken bottle, 500 ppm, see below (2 different ppm readings on the same occasion).**
**** 2 different ppm readings, 500 ppm at original marking/pole, ? 7000 ppm approx. 90 cm ESE of staking pole, between two stones.**

Figure 10.3. Examples of field variables, field data and field measuring sites. At the start of the project, data was recorded in writing on field recording sheets, and the same type of data, supplemented with data on landfill pressure, etc. was subsequently logged on data logs for comparative analysis with laser and IR data.

10.2 Measurement methods

The purpose of the field laboratory tests at the gas testing facility in Malmö was to, under controllable conditions, simulate and detect methane gas from piped gas distribution systems placed below ground in order to try to determine the detectability limits of the Siemens laser system in terms of flow and distance (range).

The purpose of the repeated field operative tests at Filborna was to produce data that could be used to develop operative methods for use in the field to detect and map gas emissions from landfills under realistic conditions.

As described in a previous section, a landfill usually comprises a large area with a large volume, varying topography and a varied composition of deposited material. In view of the size and complexity of landfills, it is important to test and develop straightforward and cost-effective techniques and methods for tracing, detecting and mapping methane emissions. It should be possible to use results from such field measurements as a basis for environmental evaluation of landfills, short- and long-term planning of emission-limiting measures, both urgent and preventative maintenance of recovery systems and leachate systems, and for instruction and training of landfill personnel. When selecting and developing methods, the ability to evaluate usability and limitations of the technology and field measurement methods selected should also be observed.

Taking into account observations and experiences from previous pilot studies and the field laboratory and field operative trials above, proposals for field operative methods were developed in discussion and consultation with the project's reference group. The following methods were chosen:

1. **For the six landfills in Sweden,** field measurements were concentrated to a selection of zones chosen in consultation with personnel at the respective landfill. The zones were to be typical for Swedish landfills, but measurement features/surfaces specific to a landfill could also be included. In addition to the method studies on these zones, methods were also to be developed for determining the status of gas recovery systems and leachate systems.

- The first stage involved field measurements using a laser. This was a general scan of methane emissions for the landfill surface in question. Detailed field measurements (pinpointing) were then carried out in order to trace, detect and measure the gas concentration, and to determine the positions of leakage sources. High-resolution GPS was used for positioning.
- Supplementary field measurements were made using the FLIR ThermaCAM™ GasFindIR LW for a selection of features/surfaces in order to detect, visualise and study the diffusion pattern of methane gas for different types of leakage source.
- Supplementary **field reference measurements** were carried out on each measurement occasion using the field measurement techniques and the field parameters described in Section 10.2.
- **Gas flows** were measured on a selection of sub-zones. Parallel with measurements using chambers, lasers were also used for measurements, directly before and directly after the chambers were placed on or removed from the measurement surface. Comparative laser measurements were carried out for the entire sub-zone and for the surfaces with chambers.

- In a later phase of the project, the field measurements described above were supplemented with **geoelectricity measurements** in order to map methane gas processes and water flows inside the landfill. Parallel with these measurements, comparative field measurements were carried out with the laser and chamber methods for the landfill surface in question.

2. **For the two landfills in France**, field measurements were taken on landfills, measurement features and surfaces unknown to the operator. The purpose was to, with no prior knowledge of these two landfills, and based on the observations and experiences from the field measurements at the six landfills in Sweden, measure gas emissions in the field and apply and test the usability and limitations of the field methods developed in Sweden.

Measurement method:

- In contrast to the landfills in Sweden, the field measurements in France included general scanning of the entire landfill surface, including the top surface (flat) and slopes. Field measurements were also taken on surfaces adjacent to the landfill surfaces in order to detect and identify sites/surfaces that can contribute to methane emissions, even though they lie outside the landfill area.
- Like the procedure at the Swedish landfills, a general scan was carried out according to a visually defined transect. Special attention was paid to the interface between crests and toes of slopes, as well as installations for gas recovery, leachate systems, gas wells, leachate wells, etc.
- Detailed field measurements, pinpointing, were carried out to trace, detect, measure the gas concentration, and to determine the positions of leakage sources. Positioning was established indirectly, with manual recording on the detailed landfill map. GPS was not available at the two French landfills.
- Like the Swedish landfills, supplementary measurements were made of field reference data and field measurements using the FLIR ThermaCAM™ GasFindIR LW for a selection of features/surfaces in order to detect, visualise and study the diffusion pattern of methane gas for different types of leakage source.
- Gas flows were measured with active and dynamic chambers for a selection of sub-zones. Parallel with measurements using chambers, lasers were used for field measurements, directly before and directly after the chambers were placed and removed from the measurement surface. Parallel with measurement using the chamber method, comparative laser measurements were taken from the entire sub-zone and for surfaces under the flow-measurement chambers.
- At Filborna a box for controlled diffuse emissions was used to calibrate the chamber method and the laser instrument. The box is referred to as a sand box in Table 13.3.

All locational data from the laser measurements, from field reference measurements and observations in the field, was documented on the landfill CAD map, which was also used as a recording sheet in the field. Other information noted included observations about point source emissions, diffuse gas emission from defined areas, gas emissions from fissures or from gas recovery systems and leachate systems, as well as gas emissions from holes or deficient connections/joints for plastic covered but not finally covered cells and sub-zones.

10.3 Use of field measurement equipment

Laser instrument
The rapid scan that can be carried out with the Siemens laser instrument makes it possible to detect methane emissions from landfills. The measurements show the concentration of methane in the air above the landfill surface, measured every tenth of a second along a laser beam. The concentration is shown in ppm x m. A simplified description is shown in Figure 10.4.

Dividing the recorded value in ppm x m by 2 x the length of the beam produces a mean figure for the methane concentration in the air along the beam, expressed in ppm.

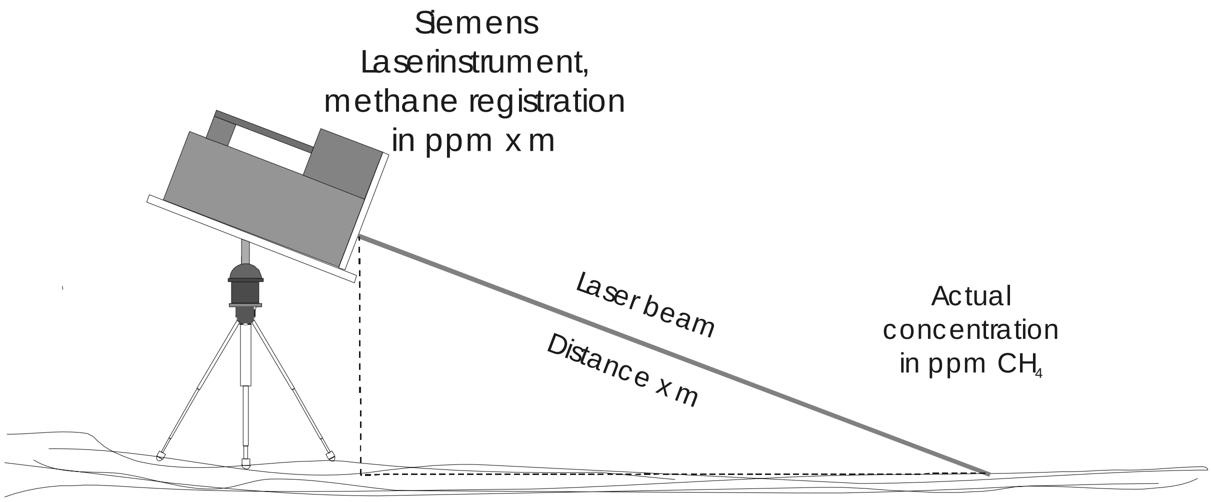


Figure 10.4 Measurements with the laser instrument.

After gathering information about size and quantities of waste, the first stage in the work was to conduct a complete scan of the surface of the study area using the laser instrument. The laser instrument was carried in a sweeping motion, back and forth, so that the beam hit the ground surface approximately 10 m in front of the operator. The operator had previously planned the transect so that the laser instrument would be moved in the sweeping motion and into the wind (see the principle in Figure 10.5). Where concentrations exceeded background levels, the sweeping motion was intensified in the direction of the higher concentrations, at the same time as the observer walked in the direction of the leakage source. The leakage point was marked with a pole for later detailed measurement.

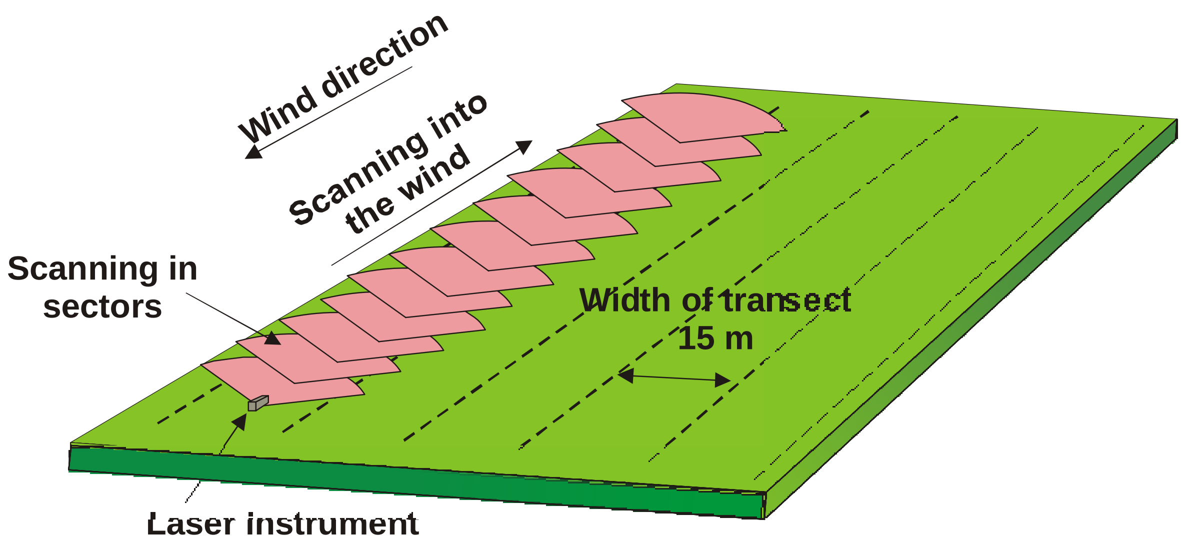


Figure 10.5. The method applied when scanning with the laser instrument. The operator walks slowly along the transect into the wind, sweeping the instrument from side to side.

The chamber method

The usual procedure is to survey an area of 100 m^2. One or more zones are used at each landfill. The procedure begins by placing a grid over a representative part of the surface for which the emission is to be determined. Then a number of sub-zones are chosen stochastically where the actual chamber measurements are carried out. A chamber is placed on every sub-zone and measurements are taken.

The chamber method as used in this project is illustrated in Figure 10.6.

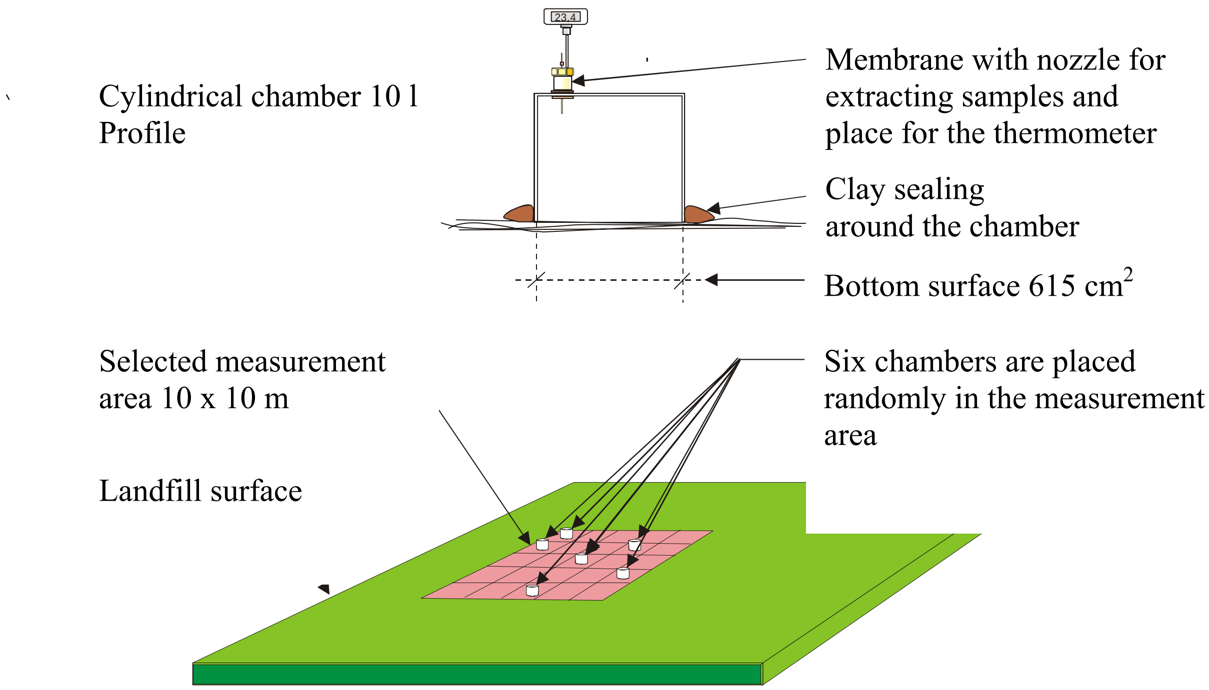


Figure 10.6. Cylindrical chamber with extraction points for gas samples, measurement surface on the landfill. Small gas samples were extracted at intervals of 2, 4, 8, 16 and 32 minutes after the chamber was placed and sealed on the landfill surface.

The method gives an indication of the gas emission from the specific surface under the chamber and at that particular time. In order to ensure accuracy in covering all emission, repeated measurements must be taken at different sites and under different weather conditions (Börjesson, Svensson, 1997).

Where emission is high, the static chamber is unreliable, since there is insufficient time to obtain a good indication of the linear increase in concentration in the chamber. A dynamic chamber is therefore better, but where convective outflows occur, the collection of the gas in a tight bag over a fixed period can be a good solution.

11. SELECTION OF MEASUREMENT FEATURES AND LANDFILL SURFACES

11.1 General

Measurements with the VOGUE laser and the FLIR GasFindIR instrument were carried out in Sweden at six landfill facilities with gas recovery systems, and a smaller landfill without gas recovery. The selected facilities vary in volume and scale, and differ in terms of gas generation and emission. The landfills were studied in different seasons and were located in different climatic regions of Sweden (see Figure 11.1). Four of the landfills were also examined using the chamber method in order to determine the size of the methane emission.

Measurements with laser and IR technology, as described in Section 10.3, were also carried out at two landfills in northern France. At these landfills, complete scanning, pinpointing of specific methane leakage sites, and chamber method measurements were carried out.

Figure 11.1. Swedish landfills studied in the project

All field measurements, including chamber measurements and geoelectricity measurements, were planned in consultation with proprietors of each landfill, and with fieldworkers carrying out the special measurements (chamber method, geoelectrical, etc.). The operators in the project planned, carried out and analysed field measurements and data, and these were discussed for consensus decisions during work meetings held at each landfill. The two landfills in France participated, with representatives for SITA France and SITA Sweden, at work group meetings in Sweden. Consequently, expertise from each landfill participated early in the project work.

Each individual landfill contributed specialist expertise and supplementary labour for field measurements throughout most of the project period. Where landfill questions arose that were important for planning and carrying out the field measurements, personnel from different levels in the organisation of the landfill participated in the project work. These could be simple questions about recovery levels for methane, or pressure in the gas recovery system, but also questions about operating personnel's observations about localisation of gas odours under different atmospheric conditions, melting of snow or occurrence of unvegetated areas as an indication of methane emission from the landfill, participation with special measurements of, for example, oxygen and gas emissions from leachate ponds, etc.

Supplementary measurements were also taken at various special features, such as measurement of methane emissions in conjunction with the move of old landfill masses from the old landfill at Ringstorp in Helsingborg, reference measurement of methane emissions from Högdala landfill with the flare operating, reference measurement of methane emissions from the leachate pond, LD1, with the aerators on, etc.

A detailed description of the landfills examined in this study is included in Appendix 4. The following section describes the landfills that were examined and their most important data.

11.2 Compilation of data from the landfill facilities

The following three tables show a compilation of the conditions relating to physical data (size, etc), surface properties of the landfills, gas formation and recovery. The information has been obtained from various sources. The geometric data used is primarily obtained from the surveys that each landfill proprietor has carried out. Description of the surface properties that can only be described in general terms is based on visual inspections carried out in conjunction with the measurements at the landfills and surveys. Information about gas recovery and emissions is based on the EPER national databases and, for Filborna, Löt and Hagby, the measurements the landfill proprietor carried out with the help of a consultant (Fluxosense). In certain cases, gas formation has been calculated using LANDGEM, a simple method of calculating gas formation at a landfill.

Table 11.1 describes the geometric conditions, particularly the size of the landfills, and it can be seen that the landfills vary greatly in size. At all landfills, both household and industrial waste has been deposited and, for many of them, over a very long time.

Table 11.1. Geometric conditions

Landfill	**Deposition period**	**Area ha**	**Height m**	**Volume m^3**
Spillepeng, 6 test cells	1988-1989	1	7	25 250
Filborna	1951-2008	35	45	11 000 000
Hagby, stages I and II	1989-1990	32	10 resp. 25	3 200 000
Löt, northern part	1995-2000	6	25	380 000
Forsbacka	1995-2008	12	17	1 500 000
Svenljunga	1975-2008	12	10	500 000
Högdala	1969-1999	30	20	2 000 000
French site 1, surveyed part	1975-	18.7	12	1 000 000
French site 2	1946-	18.5	30	3 000 000

Table 11.2. Surface conditions

Landfill	**Proportion**		**Covering material**	
	Slopes, %	Top surface, %	Slopes	Top surface
Spillepeng, 6 test cells	0	100	No slopes	Moraine clay 1.0-1.5 m, suppl. with new cover of slurry, earth
Filborna	36	64	Earth, varying greatly in thickness and quality	Finally covered area, varying quality of intermediate-cover 0.5-1.0 m
Hagby, stages I and II	0	100	Covering	Covering
Löt, northern part	86	14	Varying cover	Varying cover
Forsbacka	49	51	Varying cover	Varying cover
Svenljunga	39	61	Covered slopes	Covered top surface, slurry lagoon not covered
Högdala			Final cover	Final cover
French site 1, surveyed part	13	87	Relatively well covered slopes	Even, covered top layers
French site 2	51	49	From good coverage to very thinly covered sections	Mostly 1.0 m earth

Table 11.3. Landfill gas conditions, based on calculations and reported quantities, tons CH_4/year

Landfill	Gas generation, calculated	Recovered quantity	Emission	Gas recovery proportion
	Tons/year	Tons/year	Tons/year	%
Spillepeng, 6 test cells	0	0	0	0
Filborna, 2007	7 086	5 291	1 611	75
Hagby, stages I and II, 2007	1 025	210	666	20
Löt, 2007	1 034	385	613	37
Forsbacka, 2005			1 586	
Svenljunga	450	0	400	0
Högdala				
French site 1, 2005	2 720	2 385	331	88
French site 2, 2005	5 660	4 036	1 620	71

Table 11.2 shows general information about the surface conditions. Our observation is that, within the slope and top surface zones, the quality of the surface cover varies considerably. Various aspects of the quality and the materials used will be described in more detail in each part of the field investigations.

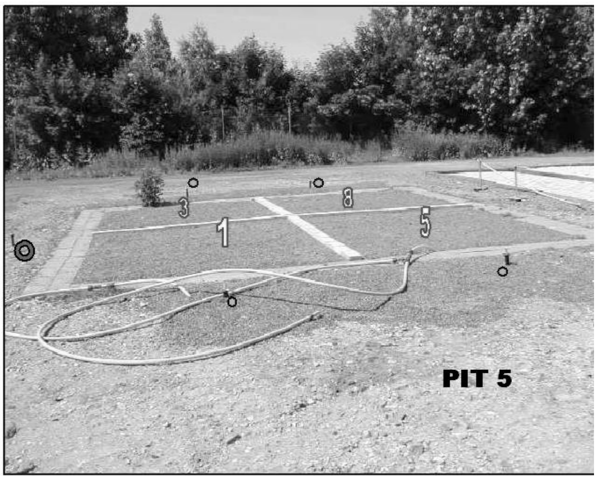
Finally, Table 11.3 shows general information about gas formation and gas recovery at the facilities. The quality of the figures varies, but they are the best that can be obtained without further surveys. There can be considerable differences within the landfills. There are probably sections where gas recovery is nearly 100 % yet, within the same landfill, areas where recovery is almost non-existent. Similarly, gas recovery varies very greatly over time, and the annual figures for recovery and emission are often based on a single measurement.

12. FIELD MEASUREMENTS USING THE LASER AND IR INSTRUMENTS

12.1 Results from the field laboratory measurements at Malmö Fire Service's gas testing facility

In order to examine the technical properties relating to measurement with the VOGUE Siemens AG, CT PS 8 laser system and the FLIR ThermaCAM™ GasFindIR system, field laboratory studies were carried out at the start of the project. Gas emissions from simulated methane gas leakage were measured under controllable conditions at Malmö Fire Service's gas testing facility (see also the report in Section 9.2). The field laboratory in Malmö was designed for simulation of gas emissions during pilot studies for ground-based and airborne gas detection and for use in the VOGUE project.

The field laboratory measurements were limited to a square area with four gas pipes placed 10 cm below the ground, with 1.3 and 8 mm holes, with coarse gravel as covering and surface material, and two rectangular areas with two gas pipes placed 80 cm below ground level, and with 3 and 5 mm holes. One of the rectangular culvert trenches has fine sand as filling material and cement blocks as surface material. The other culvert trench has earth as filling material and fine gravel as surface material (Figure 12.1, left and right). Culvert dimension DN63.



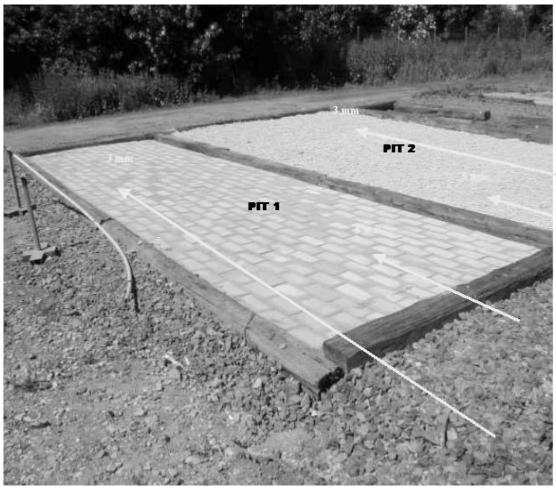


Figure 12.1. (*left*) Field measurement area consisting of 4 squares, a gas culvert with holes of 1, 3, 5 and 8 mm, placed 10 cm below the ground, surface material coarse gravel.

12.1. (*right*). Two field measurement areas, each containing 2 gas culverts placed 80 cm below the ground, with holes of 3 and 5 mm, fine sand and earth as filling material and cement blocks and fine gravel as surface material. Culvert dimension DN63

Field laboratory measurements were carried out in the period 16-18 July 2006 under favourable weather and radiation conditions, with a variable wind speed of 0.5-2 m/s, cloud-free skies and an atmospheric radiation temperature ranging from -40 to -50 °C, air temperature ≤ 30 °C, and with a gas temperature that varied between 32 and 45 °C. Delta T between the gas and background/backscatter surface was regulated using a temperature panel with computer-controlled regulation equipment (Figure 12.2, left, right).

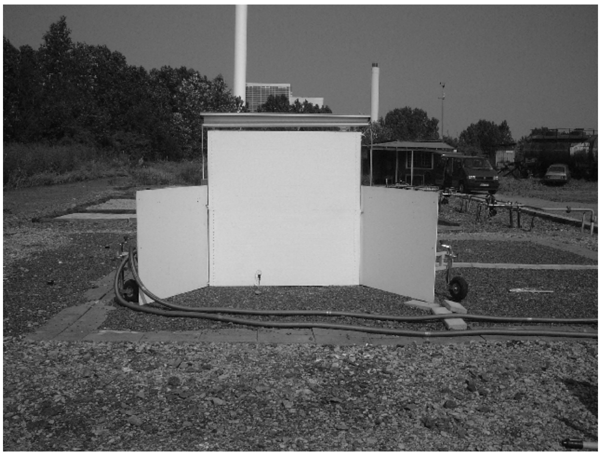


Figure 12.2. Reference temperature panel (*left*), connected to a temperature regulator (*right*).

The reference temperature system can be operated within the temperature range < 10 to 60 °C. The lower temperature level (<10 °C, etc.) can be regulated down to the temperature of the incoming piped water system. Where a temperature below freezing point is required, the temperature reference panel must be supplemented with a compressor.

Gas leakage is simulated through holes in gas pipes placed 10 cm under ground level. The gas flow is regulated with a computer-controlled mass flow regulator (Figure 12.3). Measurement of simulated gas emissions was carried out for four different gas pipes with holes of 1, 3, 5 and 8 mm as leakage sources. Repeated measurements were carried out with different gas flows for each leakage hole. Measurement started with a reference measurement with a flow of 0.l/min and then continued with 1, 5, 10, 15 and 20 l/min for leakage features with a 1-mm hole. The same measurement procedure was then repeated for leakage features with holes of 3 mm, 5 mm and 8 mm (Table 12.1).

Figure 12.3. Brooks Smart Mass Flow Meter, 5800 series, for regulating methane gas flows (*left*). Brook's microprocessor (0154 BC1B3) for selecting and controlling gas mass flow (*right*).

Before, during and after every field laboratory measurement with the laser and IR systems, supplementary measurements were made of field reference data. These were noted in the field recording sheet together with laser data measurements of specific points. The results from continual data from the laser were stored on logs for later analysis and interpretation.

Flow data was related to ppm data recorded with the Siemens laser system. The results from the field measurements indicated that wind speed and wind behaviour at microtopographic level affect the behaviour of the methane gas and thereby the measurement results. The results also vary according to the size of the leakage source, gas flow, and gas and atmospheric pressure. With repeated simulation of gas leakage from the 1-mm hole, large variations could be noted in the measured data from 200-2 000 ppm x m, recorded from a distance of approximately 2.5 m at the same flow of 1 l/min (see Table 12.1 below). It was also observed that the ppm values decreased when the flow was increased in stages up to 20 l/min. The decrease in the measured gas concentration at large flows and small/narrow leakage sources can be explained by the formation of a jet when a larger quantity of gas passes through the narrow leakage hole (1 mm in this case). The gas plume at the emission source is narrow, and broadens at a height of 1-2 m above the narrow leakage hole with the gas pipe placed approximately 10 cm below the ground surface. Similar observations have been made in simulations of biogas leakage at the Filborna field laboratory and for methane emissions from narrow, barely visible fissures in the surface layer of a landfill. Comparative measurements of simulated methane emissions from leakage features with larger holes, e.g. 8 mm, show ppm values that are low at low flows and increase as flow increases, 1 l/min = 20-600 ppm as opposed to 100-3 000 ppm for a flow of 20 l/min (Table 12.1). Note however that there is a wide range of measurement data /ppm values for both the 1 l/min flow and the 8 l/min flow. Here too, similar observations have been made in simulations of emissions of biogas at the field laboratory at Filborna.

Table 12.1. Passive & Active Gas Detection protocol

Field protocol: **Nr. 1.** BARBARA, VOGUE-laser and FLIR-GasFinder-IR, Methane gas. Object: Four buried gas pipes with gravel as surface cover, 1 hole for each pipe with different hole sizes. Date: 2006-07-16.

The Laser is directed towards the gas leak source at a distance of about 2,5 m, diagonally towards the wind direction.

Image no/disc	Time	Flow	Hole size	Surf. T	$\Delta T_{Y\text{-}G}$	GasT	$\Delta T_{G\text{-}A}$	Air T	PanelT	$\Delta T_{P\text{-}G}$	Sky-T	RefT 1	Laser	GasP	Wind speed	Wind direction	Rel. hum
Rec. no.												Ground					
		[l/min]	[mm]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	PPM-m		[m/s]		[%]
Ref. measure-ment/without gas	14^{00}	0	1	57,5	0				28,5		-42,0	47,0	200-2000		0,5-1,0	NW	
0-45	?	1	1	54	15	39			27,1		-45,0	31,5	200-2000		1	NW	
-2710		5	1	54	15	39			27,1		-45,0	31,5	200-2000		1	NW	
-22024	14^{55}	1	1	52	6	46			32,9		-44,0	36,0	50-500		2-2,5	NW	
-24823	14^{58}	5	1	50	16	34			32		-44,0	34,0	500-100		0-0,25	NW	
-32804	15^{03}	10	1	51	18	33			33,5		-44,5	34,6	10-800		1	NW	
-433324	15^{07}	15	1	52	9,9	42,1			30,6		-44,7	34,2	10-600		0,5-1	NW	
-153020?	15;12	20	1	52	12	40			30,0		-44,4	34,0	100-700		0,5	NW	
Ref. measure-ment *	15^{42}	0	3	50	-	-			35,6		-42,6	33,6	-		0,5	NW	
-63809?	15^{45}	1	3	51,6	5,9	45,7			36,8		-42,4	33,0	10-2000		0,5	NW	
-72620	15^{47}	5	3	53	6	47			35,5		-42,6	34,4	50-2900		1-2	NW	
-80113	15^{50}	10	3	50	3	47			36,2		-43,2	35,0	50-2000*		1-1,5	NW	
-85109	15^{54}	15	3	48	3	45			35,0		-43,0	33,7	50-3000*		1,5-2,0	NW	
-91807	$15,^{56}$	20	3	50	5	45			35,0		-42,8	34,2	50-3500*		1-1,5	NW	

Comments: Powerful insolation, variable wind, N-NW, wind turbulence at ground level, strong turbulence = $15^{07.}$ * reference measurement = sun directly on temperature reference panel. * -80113/15^{50}, laser directed 'downstream' of gas source.

Measurement for the test and determination of the detectability limit related to distance (range) between gas leakage and the laser system's position was carried out with gas leakage simulated without the gas flow regulator. Examples of results from measurements at different distances between laser and gas leakage source:

1-mm hole - 1 l/min - 10 m distance =	gas detectable
1-mm hole - 1 l/min - 20 m distance =	gas not detectable
1-mm hole - 5 l/min -10, 20, 30 m distance =	gas detectable
1-mm hole -10 l/min - 10 m distance =	gas detectable
1-mm hole -10 l/min – 20-30 m distance =	gas not detectable (powerful turbulence at ground level)

Laser data from the field laboratory experiments with simulated gas emissions was stored on field logs for later analysis and evaluation. Supplementary IR data from measurements with the FLIR IR GasFinder system was stored digitally, in real time, on a DVD unit.

IR detection with the IR GasFinder system

It is difficult to present gas-related IR data in a written report in a way that illustrates the GasFinder system's information potential and that shows the dynamics of thermal image data. One way of presenting IR data in a written document is to capture and freeze the image sequence from the digital video film that best shows the gas plume from a leakage feature at a specific time of measurement. However, the information potential of gas-related IR data is best illustrated through studies of the video film presented in an electronic report.

Figure 12.4 shows a still thermal image with methane emissions recorded with the FLIR IR GasFinder resulting from simulation of methane leakage carried out at the field laboratory at the Malmö Fire Service gas testing facility. When the temperature of the gas is lower than on the temperature reference panel, the gas plume is displayed in dark grey, and light grey when the gas temperature is higher. Figure 12.4 also shows examples of methane emission in a vertical direction caused by differences in pressure between methane and the atmosphere through forced convection. Where the pressure differences between methane gas and the atmosphere are large, and where the gas is emitted at high pressure, a jet is formed and, in the case with high atmospheric pressure and low gas pressure, the forced convection is dampened and the methane is emitted horizontally, depending on the prevailing wind conditions. Similar images have been generated from field measurements of gas emissions from different leakage features at landfills in both Sweden and France (see Figure 12.40 and 12.41), and from the pilot studies presented in Section 9.3 (e.g. Figure 9.5).

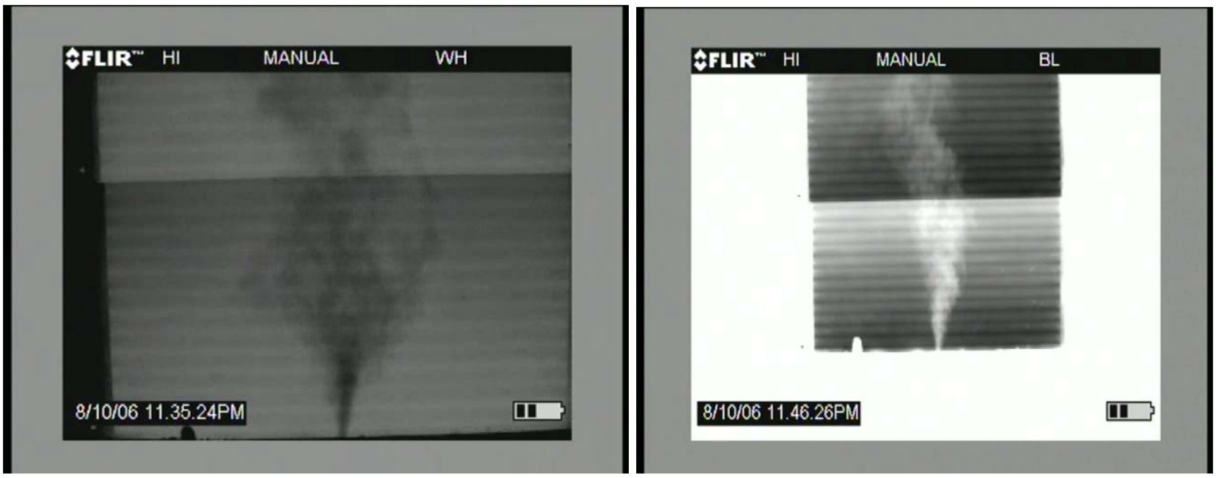


Figure 12.4. Thermal images from field laboratory measurements at the Malmö Fire Service's gas testing facility. The images illustrate the gas plume through differences in the grey shades indicating differences in temperature of the methane in relation to the ambient temperature, but they also illustrate a vertically-moving stream caused by pressure differences between the methane and the atmosphere. The gas plume in the left thermal image has a dark grey tone = lower temperature than the reference temperature panel, and the right thermal image shows a light grey tone = higher temperature than the reference temperature panel.

12.2 Conclusion from field laboratory tests at Malmö Fire Service's gas testing facility

The results from the field laboratory measurements indicate that methane is light and volatile in relation to surrounding air, so it is difficult to determine the relationship between ppm data and flow data using the laser system in question.

Results from passive detection of gas using the IR GasFinder confirm that methane is a volatile gas that is affected both by differences in temperature between the gas and the surroundings through natural convection, and by pressure differences between the methane and the atmosphere where high flows and narrow exits/small leakage holes give rise to a jet where the gas plume develops vertically through forced convection. Because methane is invisible to the human eye, the case of pressure differences means that the operator with the laser finds it harder to locate the leakage source than in the case with natural convection and horizontally developing gas plumes. Results from field laboratory measurements indicate that detection of methane emissions with the IR GasFinder is a good complement to laser measurements for visualising methane emissions and for showing the occurrence of gas emissions through natural and forced convection (jets).

12.3 Results from field measurements of methane emissions from landfills in Sweden and France

As shown in Section 8.2 and Chapter 9, the field measurements of methane emissions from landfills in Sweden using laser and IR systems were restricted to detailed measurements of a selection of landfill zones and gas and leachate systems, while the field measurements at the landfills in France included overview scanning of entire landfills and detailed measurements of a selection of zones and gas and leachate systems.

Using the definition applied by the UK Environment Agency, a zone is "an extensive area of the landfill site surface that is generally uniform and homogeneous in those factors that affect surface emissions (e.g. type of capping, slope, surface integrity)". The zones used in this project are surfaces whose properties differ from each other, and that are representative of the most common landfills in Sweden. Representative zones were chosen as they are assumed to produce gas emissions that differ from each other and because the total results from the different zones are expected to give an overall picture of gas emissions from landfills with similar zones, methane production and covering procedure.

The following section shows examples of results from representative zones from the different landfills in Sweden and from overview scanning and detailed field measurements for each landfill in France

12.4 Methane emissions from specific zones

The concept of zones includes top surface (level landfill surface), slope (gentle or steep), toe of slope, crest and terraced slope. A slope usually comprises a stepped sloping surface made up of lifts placed on top of one another in a terraced structure. Consequently, a slope can contain large or small terraces with a crest that is adjacent to a top surface and a slope toe that levels out towards the surrounding land, often separated by leachate ditches/drains. Field measurements indicate that settlement can occur, resulting in fissure formation and gas emissions at the interfaces between terraces and the lift surfaces along a slope. A slope can be gentle or steep.

12.4.1 Methane emissions from the top surface – measurement with laser and IR technology

Field measurement with scanning using the laser system and pinpointing has been carried out for top surfaces at all Swedish landfills examined in the project. Here, the results are shown from the field measurements for a selection of top surfaces that illustrate the results, usability and limitations of modern remote sensing techniques, such as the VOGUE Siemens AG, CT PS 8 laser system and the FLIR ThermaCAM™ GasFindIR system for detecting and mapping gas emissions from large, continuous and flat landfill surfaces:

a) Uncovered top surface,
b) Covered top surface,
c) Tipping face top surface,
d) Plastic-covered top surface

a) Forsbacka, F2 area (fissure zone) represents an **uncovered top surface** comprising approximately 1 200 m^2 m with mixed household waste and with a loose covering layer (25-30 cm) of mixed, treated contaminated earth. Most of the top surface is unvegetated. In the western part of the area, there are fissures caused by settlement in the landfill material. The area includes a visible fissure zone approximately 40 m long, 2-10 cm wide and 20-30 cm deep (Figure 12.5).

Figure 12.5. Forsbacka, F2 area, top surface of approximately 1 200 m^2 with mixed household waste, loose covering layer and fissure zone caused by settlement in the landfill. Measurement with laser and field equipment for measuring field reference data, with logs as storage media.

Gas emissions from the F2 area at the Forsbacka landfill were repeatedly recorded with the Siemens laser system in different seasons and under different weather and radiation conditions, with and without snow cover. Approximately ten complete sets of measurement were obtained, and supplementary synoptic measurements for a selection of surfaces and leakage sources, to examine detectability under especially unfavourable measurement conditions with rapid changes in pressure, precipitation and wind speed. The field measurements were carried out between 19 September 2006 and 8 November 2007.

After the scan, detailed measurements were carried out, pinpointing features and surfaces where the scan had indicated methane leakage. Laser data (ppm values) and supplementary weather and radiation data, and feature-related data and observations of the behaviour of the methane, fluctuations in ppm values, etc. were noted on a recording sheet.

During the field measurements in 2006, eight features and surfaces were detected with measurable gas emissions, and this figure had increased to 20 when measurements ended on 8 November 2007. During the same period as new leakage sources were detected, it was noted that a small number of leakage features/surfaces with previously high ppm values showed lower or no methane leakage and yet, on other measurement occasions, these gave measurable methane emissions. Observations during the measurement period indicated that methane emissions from the F2 area could vary during the same measurement occasion but also over longer periods. These observations were later confirmed through the results from repeated long-term measurements.

Results from repetitive detailed field measurements and long-term measurements show variations in ppm readings from 20 to 10 000 ppm x m. During the measurement periods in question, most leakage features in the F2 top surface gave emissions of 3 000-6 000 ppm x m. See examples of the results of the long-term measurements in Figure 12.6.

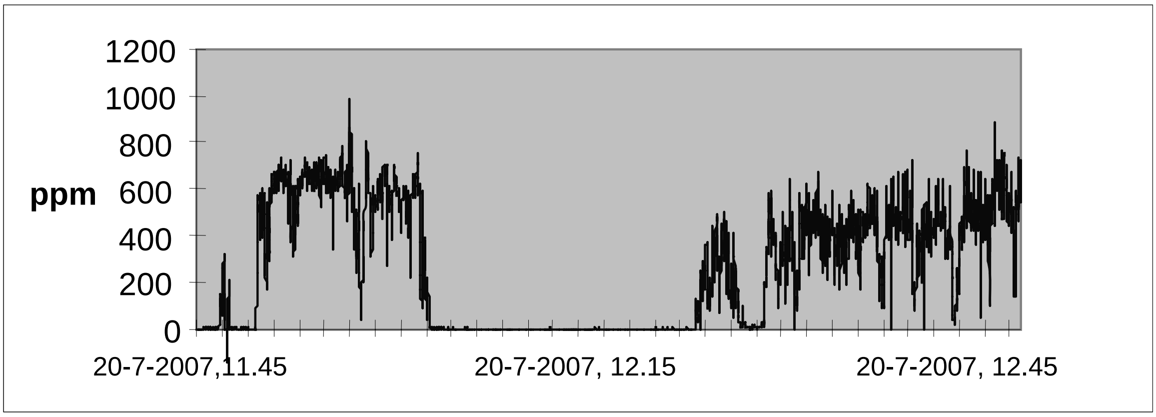


Figure 12.6. Examples of results from long-term measurements that show variations in gas emission, with periods of high to no pmm values, indicating fluctuations in methane production.

d) **Filborna Landfill Layer 2005** represents a plastic-covered top surface of approximately 2 600 m^2 (Figure 12.7). Covering with plastic to prevent infiltration of rainwater is a common method of covering in Sweden and internationally. The plastic covering also serves as a barrier against the infiltration of air when biogas is recovered. Normally, final permanent capping comprises placing selected material on top of the plastic. Where the plastic is not covered, protruding objects in the landfill mass, or birds, can perforate the plastic surface, water can infiltrate the landfill and biogas can escape. In the case of Landfill Layer 2005, seagulls have perforated the plastic surface, causing extensive leakage of biogas from a large number of holes in the surface layer.

Like other top surfaces, detection and mapping of gas emissions from Landfill Layer 2005 were first carried out with the scanning method in order to trace and map methane emissions from the entire top surface. This was followed by pinpointing for detailed measurement of gas emissions, and mapping and positioning of leakage features (see Figure 12.8).

In 2006-2007 repetitive measurements were taken with the Siemens laser system in order to map gas emissions from a selection of 127 leakage features. The results from the snapshot field measurements show a variation between 100 and 10 000 ppm x m. The diffusion pattern and behaviour of the methane was recorded with an IR Gas-Finder, documented as video sequences.

Figure 12.7. Filborna Landfill Layer 2005 represents a plastic-covered top surface of approximately 2 600 m^2, where birds have perforated the surface layer. Gas emission from a selection of 127 features/holes was detected with the Siemens laser system (100-10 000 ppm x m).

Figure 12.8. Recording gas emissions with IR and laser systems respectively. The right photo shows examples of gas emissions from holes in the plastic cover in the top surface, Landfill Layer 2005, where the holes were made by birds, 100-10 000 ppm.

e) F1, France, is another example of a landfill with a **plastic-covered top surface**, approximately 7,300 m^2 (Figure 12.9). Field measurements were taken using the Siemens laser system and the FLIR IR GasFinder over two days (17-18 September 2007), with supplementary field measurements on 27 September 2007. For data concerning F1 landfill, see Section 11, Table 11.1.

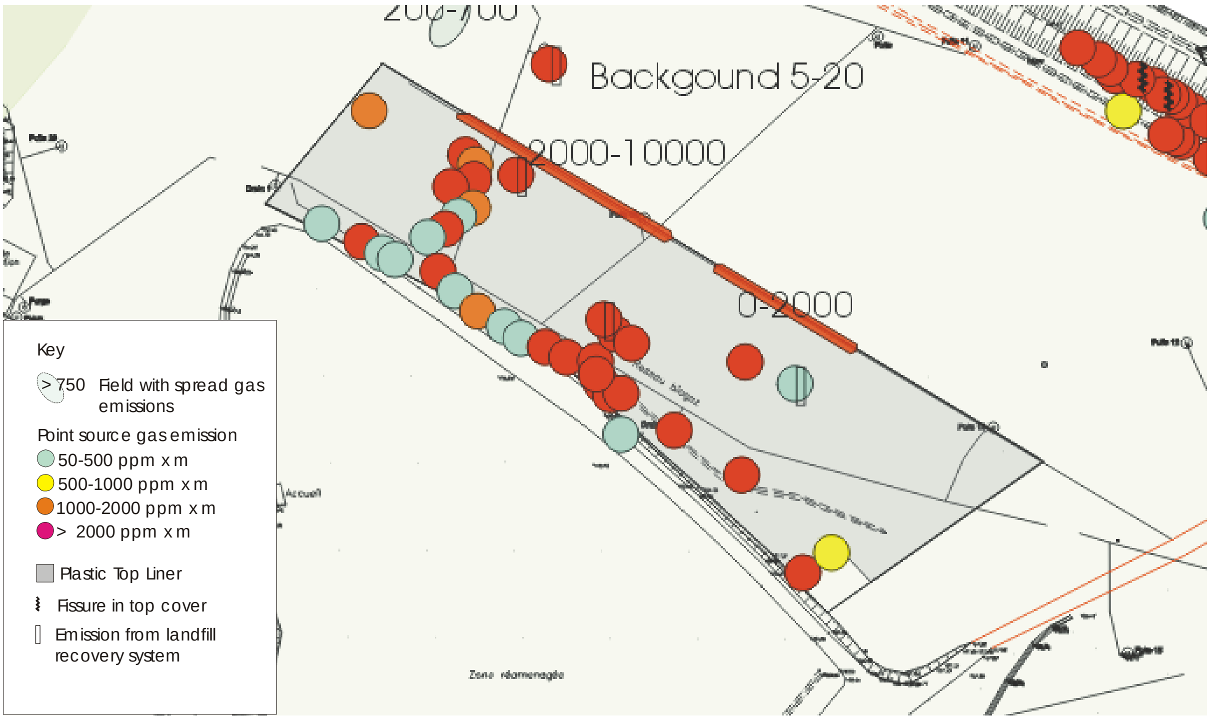


Figure 12.9. Plan of plastic-covered top surface at F1 comprising approximately 7 300 m^2, with gas emissions from 37 of approximately 100 potential leakage features, such as holes caused by protruding objects, deficient joints, and connections in corners, damage by birds, etc. There was also leakage from gas wells inside the plastic cover. The field measurements were taken using the Siemens laser system.

Weather and radiation conditions during the measurement period:

Air temperature: 9-16 °C
Varying cloud conditions, from cloud-free to full cloud cover
No precipitation during the day
N-NW wind, 1-4 m/s

Like the plastic surface at Filborna Landfill Layer 2005, the plastic-covered top surface at F1 shows perforations in the surface layer of covering plastic, caused by protruding objects from the landfill, deficient joints, deficiencies in connections in corners of the plastic cover, and also through the pecking of birds (see Figure 12.10 and 12.11). Visual inspection of the plastic surface revealed approximately 100 visible holes in the plastic surface, and deficiencies in joints in the plastic cover. Repeated field measurements gave gas emission of 100-8,000 ppm from 37 of the 100 visually examined and recorded potential leakage features.

Note that gas emissions from landfills occur at intervals and laser readings on one measuring occasion can differ from those on another occasion. Observations from measurement of gas emissions from the plastic-covered top surface at Filborna Landfill Layer 2005 above, indicate that different measurement occasions can show variations in where and how much methane gas is emitted from known potential leakage features. The potential leakage features in the plastic covered top surface at F1 showed no emissions on one measurement occasion yet can give detectable emissions on other measurement occasions, and vice versa.

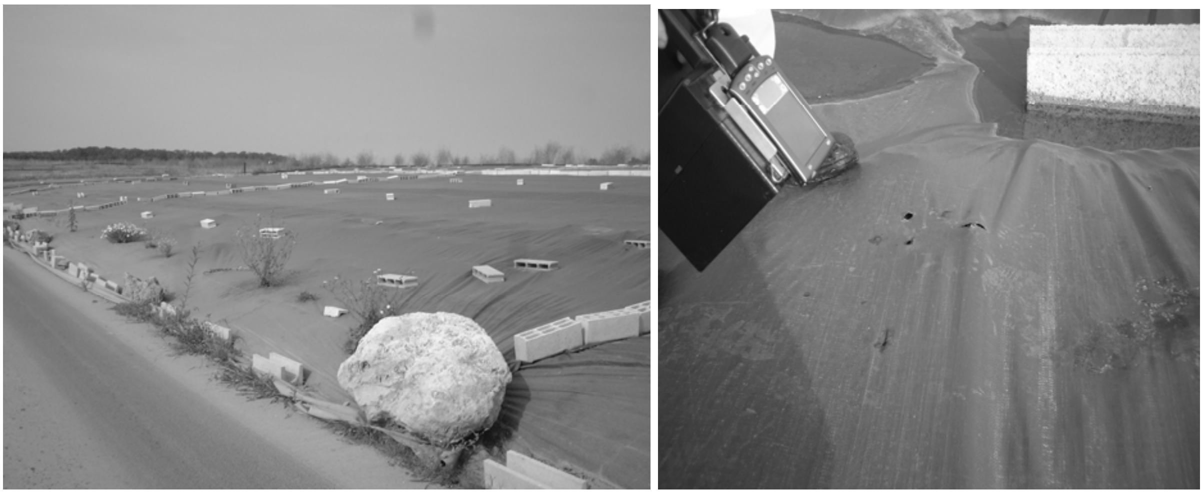


Figure 12.10-11. F1, *left*: part of plastic-covered top surface, and *right:* examples of perforation of the plastic surface. Results from field measurements using the Siemens laser system 100-8 000 ppm.

12.4.2 Methane emissions from slopes – measurement with lasers and IR technology

Preliminary results from the pilot study at Filborna and results from cited literature (Chanton et al., 2007) indicate that methane emissions from slopes, toes of slopes and crests are more frequent than from level landfill surfaces (top surface). Consequently, the project team decided to conduct more comprehensive studies of these types of landfill surfaces. The following section describes some examples of methane emissions from slopes at six landfills, followed by a corresponding presentation for the toes of slopes and crests.

a) Filborna, eastern slope, comprises mostly mixed household waste and industrial waste, approximately 10-30 years old. The slope has a gradient of approximately 1:3 and has an interim cover of 0.5-1.0 m mixed earth. The volumes inside the slope are connected to the gas recovery system at Filborna. The lower parts of the slope probably do not reach the gas recovery system. Field measurements were carried out as scanning, using the Siemens laser system along north-south transects, covering a total area of 40 x 300 m = 1,200 m^2. Five point source emissions were detected, and these were marked with poles (see Figure 12.12). The average readings over approximately 1 minute are shown in the table below.

Point	ppm	Observations
1	1,150	Hole in protruding metal dish
2	560	Small hole, incomplete covering
3	850	Small hole
4	2,780	Small hole by plank
5	290	Several holes

Figure 12.12. Overview picture of the eastern slope. As can be seen in the picture, all point source emissions detected lie at approximately the same height, and are relatively low down on the slope. Methane leakage was also discovered in the leachate wells below the slope and at a high-level connection well for gas.

b) SYSAV Spillepeng, western slope (Biocell 8/BC8) comprises household waste deposited in approximately 1990, with an overlying lift surface with industrial waste deposited since then. BC8 represents a slope with detectable gas emissions from relatively narrow, barely visible fissures along a horizontal stretch approximately 100 m long (Figure 12.13). Scanning and pinpointing with the Siemens laser system detected emission of methane gas from 22 leakage sources along the stretch in question, with methane emissions from 760-6 800 ppm. See Table 12.1, Appendix 6.

Figure 12.13. BC8, Spillepeng. Example of a long slope with gas emissions from 22 leakage sources with methane emissions in the range 760-6 800 ppm.

Like the observations on, for example, slope F3 at Forsbacka landfill below, a connection was indicated between the occurrence of a certain species of moss (Figure 12.14) and emission of methane gas. According to Professor Anders Lagerkvist (Lagerkvist A, 2007) the moss species in question has a short root system, so it is not exposed to as much methane as plants with deeper root systems. The phenomenon was noticed during field measurements at Forsbacka in 2006 and further observations in the field confirm that the moss species is the only plant species found where methane gas is emitted. Consequently, if the species is found on vegetation-free surfaces, this could be used as an indicator of methane gas emissions through the ground surface in that area.

Figure 12.14. Narrow, barely visible fissures that give measurable methane emissions, and a moss species with a short root system.

c) Löt, western slope. The Löt landfill has many interesting slopes with varying methane emissions. Here, the report is limited to field measurements carried out on the western slope. The slope comprises several lifts, with slope, crest and toe of slope. The lift surface has lower permeability because the landfill mass has been compressed by compactors, so methane gas is led horizontally out towards the sides, and is emitted mainly through the crest and the toe of the slope.

The western slope comprises a landfill section with industrial waste and small quantities of household waste deposited between 1995 and 2001. The slope comprises the outside of a number of visible lifts, defined by short terraces where the slope has not been treated (see Figure 12.15). At the bottom of the slope, an embankment forms the boundary for leachate collection and bottom drainage. The leachate is led northwards via two routes to wells at the northern edge of the landfill section. Figure 12.16 shows two adjacent overview pictures of the western slope, and Figure 12.17 shows a collage of pictures from different types of features/surfaces where methane emissions were detected using the Siemens laser system.

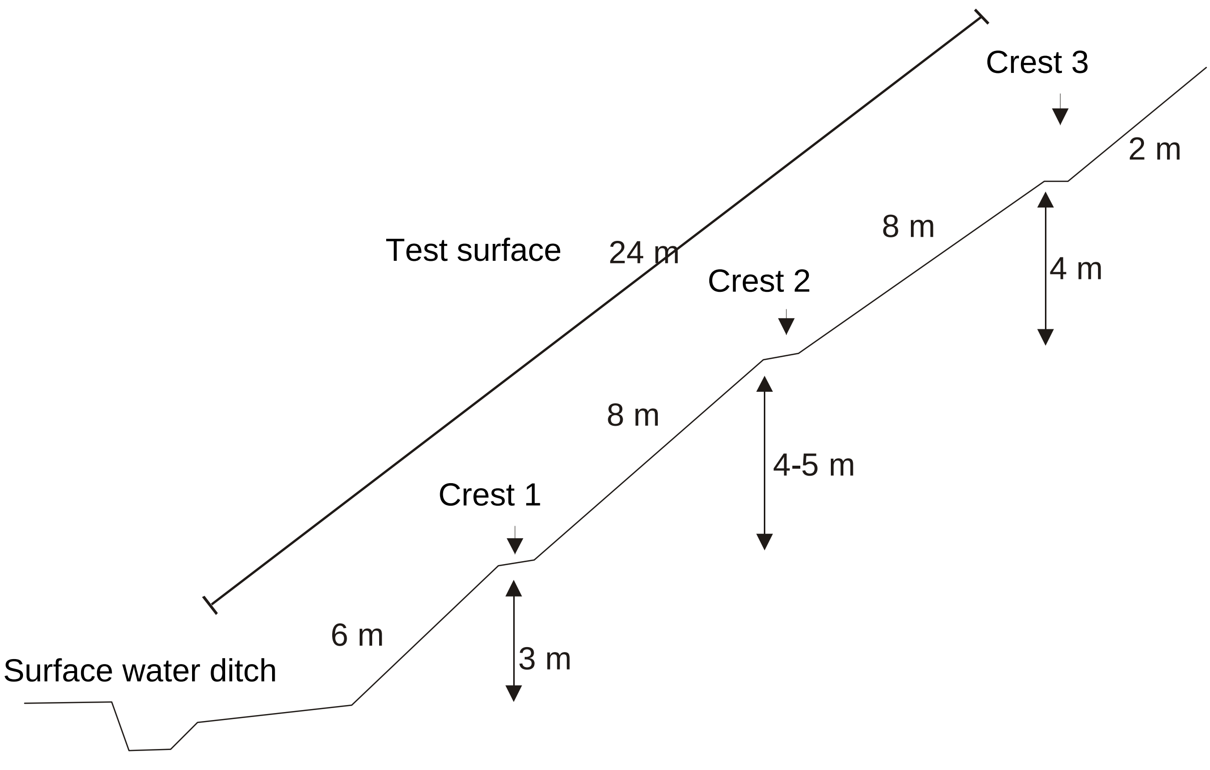


Figure 12.15. Lower part of the slope at Löt, profile, not to scale.

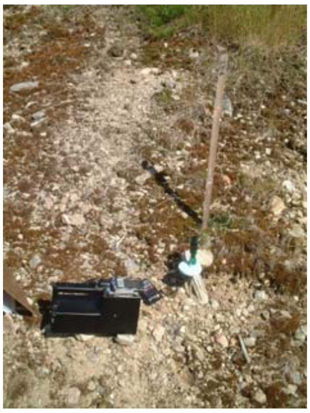
The diagram above shows the lower part of the slope at Löt. The waste lifts are 3-5 m high, and every lift surface is clearly visible. The upper part of the slope is flatter, and the surface has been designed so that the lift surface is not visible on the slope.

Repeated field measurements were carried out for the western slope in different seasons, with bare ground, snow cover and winter conditions, in 2006 and 2007. Supplementary detection and visualisation of gas emissions was carried out using the FLIR IR GasFinder on a selection of features and surfaces on the western slope.

Comparative ppm data from the field measurements in 2006 and 2007 are shown in Table 12.2, Appendix 6. Note that the table shows that ppm data indicating the size of the gas emission can vary considerably for the same leakage feature/surface on different measurement occasions, here illustrated with data from the measurement series carried out in 2006 and 2007. The same type of variation in methane emissions, but at microlevel, was observed in long-term measurements for the same feature/surface on the same measurement occasion (see examples from long-term measurements).

Figure 12.16. Adjacent overview photos, with zones from the western slope, Löt landfill, from field measurements carried out in 2006-2007.

L1-03, plastic feature ≥6 000 ppm



L1-06, moss species 2 000 ppm

L2-01-04, overview, 20-3 500 ppm

L2-05, ≥3 700 ppm

L3-1, ≤4 000 ppm

L4-1, ≤1 400 ppm

L5, 1 500-7 000 ppm

L6-04, 10 000 ppm

Figure 12.17. Collage of pictures from features/surfaces with gas emissions detected using the Siemens laser system, and visualised with the FLIR IR GasFinder. For comparison of ppm data from the field measurements in 2006-2007, see Table 12.2, Appendix 6.

In experiments with supplementary field measurements taken on other slopes L6 (southern slope) and L7 (northern slope), on 15 November 2007, it was noted that these slopes had been covered according to plan with a new 1-m thick layer of a clay/earth mixture, so comparisons with earlier measurement data were not possible (Figure 12.18). After covering, the southern slope (L6) showed methane emissions of 200-400 ppm compared with the previous 300-10 000 ppm. On the northern slope (L7) no measurable methane emissions could be noted after covering. However, airborne methane emissions were recorded on L6 and L7, transported from the western slope, L1-L5. The results from the supplementary measurements on 15 November 2007 indicate that covering reduced methane emission on the slopes in question. Figure 12.18 shows the southern slope (L6) before and after covering. The methane emissions after the covering were mainly from the deep wheel tracks caused by the dumper machines. According to operating personnel. it would be desirable to follow up with supplementary laser measurements to check the effect on methane emissions when the covering material has settled.

Figure 12.18. Löt, southern slope before covering (*left*), and after covering (*right*), 200-400 ppm compared with 300-10,000 ppm before covering.

d) Forsbacka, southern slope (F1) comprises the outer embankments of the cells in which the waste was deposited. The waste is a mixture of household and industrial waste. The slope is steep and not levelled.

The F1 slope is, together with the F3 slope (northern slope), the area where most field measurements were carried out. This is because these slopes show interesting variations in methane emissions and also because Forsbacka landfill is located so close to the University of Gävle. This means that the landfill, like the Filborna landfill in Helsingborg, was one of the base stations where it was easy and quick to visit the field area to take repetitive field measurements and to study the behaviour of the methane gas under different atmospheric pressure, weather and radiation conditions.

Repeated measurements were taken using the Siemens laser system in 2006 and 2007. Some of the field data from the laser measurements was recorded on the field recording sheets and some was stored in real time on a PC.

The photographs in Figure 12.19 show an overview of part of the F1 area. The moss species described earlier is found frequently in the F1 area as the only plant species found in sections with methane emissions. See example shown on the right picture of Figure 12.19 and the collage of photos, Figure 12.20.

Figure 12.19. *Left*: Overview of the F1 area. *Right*: examples of sections with large areas of the moss species on ground surfaces connected to sections/features and surfaces with methane emissions.

Methane emissions were recorded on the F1 slope, some from small fissures by the lift joints caused by settlement, some connected with protruding objects, and some at boundaries between stone sections, stone blocks and small open areas free of vegetation. Methane emissions were recorded for a total of 15 leakage features/surfaces, with a large range in methane emissions measured, 15-10 000 ppm. See examples in the photo collage, Figure 12.20.

a) Methane leakage in stone section, 500-7 000 ppm

b) moss section, 250 ppm

c) stone and moss section, 6 000 ppm

d) protruding object, 5 000 ppm

e) stone and moss section 10 000 ppm.

d) stone section on vegetated surface, 500 ppm

Figure 12.20. Photo collage of the F1 area with varying ppm data for different types of surfaces, from 250 to 10 000 ppm.

Methane emissions/ppm data from different leakage features/surfaces and zones show variations in most study surfaces lacking a final cover. Like, for example, the western slope at Löt, the F1 area at Forsbacka also shows variations in methane emissions/ppm data for the same measurement feature/surface on different measurement occasions, for example in the measurements carried out in September 2006 and July 2007. See Table 12.3, Appendix 6.

As described in the section on methods, Section 8.2, the field measurements were carried out using the Siemens laser system, first by scanning selected landfill areas/surfaces. The scanning procedure gives the operator an idea of whether there are methane emissions in the investigated area/surface. If measurable methane emission is indicated, detailed field measurements are carried out, pinpointing sites/surfaces with suspected gas emission in order to (1) detect and localise the source of the emission, and (2) measure and quantify the methane emission from the feature/surface in question, expressed in ppm. Consequently, the operator works in two stages, first by doing a general scan of an area and then by detecting methane emission and localising the source of the leakage. Operatively, scanning can be characterised as an indicator method, and pinpointing as a method for giving detailed information about the location of a leakage source and determining the size of gas emission.

Using infrared technology in the form of the FLIR IR GasFinder, the presence of gas emission can be detected and visually confirmed, and then the gas cloud's diffusion can be monitored and studied, as well as the gas's behaviour in relation to surrounding topography, weather and radiation conditions. However, as shown by the results above, and the observations presented in Figure 12.6, and in Tables 12.2 and 12.3 (Appendix 6), methane emission varies from the same feature/surface during the same measuring occasion, but also for the same features/ surfaces on different measuring occasions. See also Section 18, Analysis and evaluation.

The following section shows some examples of variations of gas emissions recorded with the Siemens laser system for the same features/surfaces, during a measurement period of ≤ 1 minute, measured in the Forsbacka F1 area, and where the laser data was stored on a PC. Figure 12.21 shows the results from field measurements of gas emissions using the Siemens laser system for measurement feature F1-01, file name Forsbacka-F1-01-07_060919_01.xls, for 2006. Figure 12.22 shows the same information for the same measurement feature in 2007, file name Forsbacka_070301F1_01. Note the large internal variation in methane emission expressed in ppm, recorded in less than 1 minute for each measurement series, 2006 and 2007. Note also the big difference in ppm readings for the same measurement feature recorded in the two measurement series in 2006 and 2007.

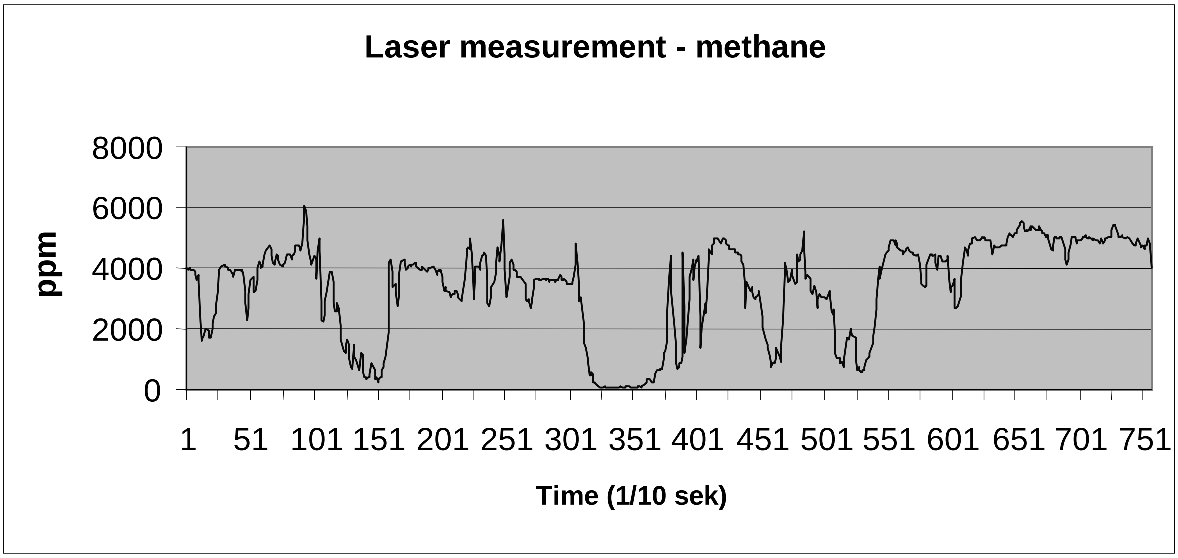


Figure 12.21. Variations in gas emissions in a measurement series of approximately ≤ 1 minute, recorded with the Siemens laser system, measurement feature F1-01, file name Forsbacka-F1-01-07_060919_01.xls, 2006.

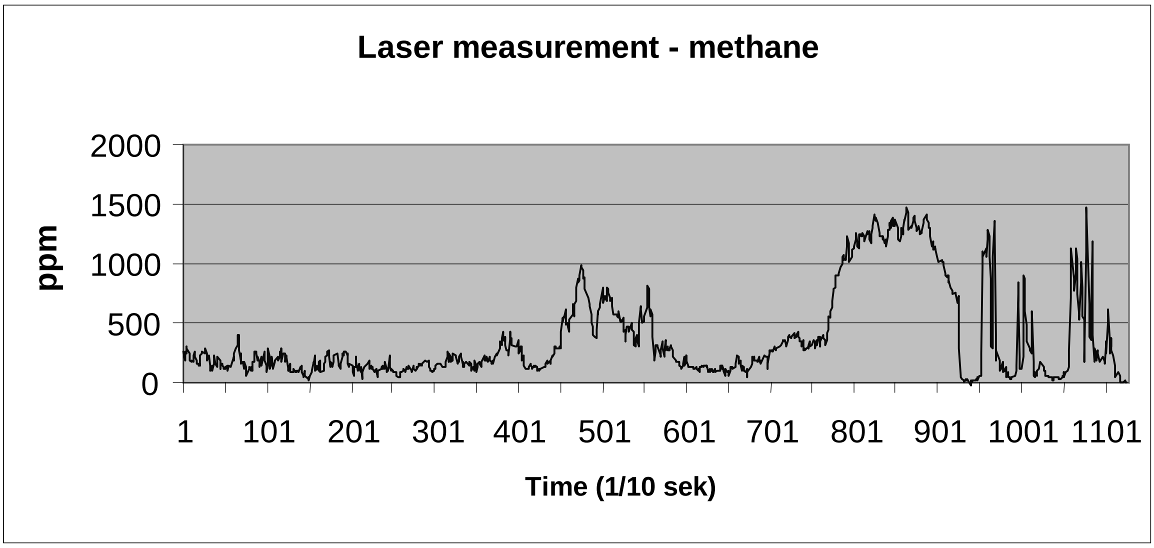


Figure 12.22. Variations in methane emissions for the same measurement feature as in Figure 12.21, but this time for 2007, file name Forsbacka_070301F1_01. Approx. 1.5-minutes measurement series, 10 readings/sec.

12.4.3 Methane emissions from lift crest (slope crest) – measurement with laser and IR technology

Results from the pilot study at Filborna (Section 6.3) indicate that gas emissions from crests and toes of slopes are more frequent than from lift surfaces/top surfaces and slopes. The crest on the northern slope, F3 area at Forsbacka landfill, was chosen as an example to illustrate gas emissions from crests.

The F3 area comprises one of the outer embankments of the landfill cells in the area. The lift surface can be discerned, as the slope has not been levelled. Field measurements for mapping gas emissions from the lift crest in the F3 area, Forsbacka landfill, were carried out using the Siemens laser system on ten different measurement occasions for 12 different leakage features/surfaces in 2006-2007. Supplementary field measurements were carried out with the FLIR IR GasFinder for detection and visualisation of methane emissions from selected features/surfaces. In addition to measurement of gas emissions from the crest in the F3 area, methane emission was also measured through line scanning of the entire northern slope in a horizontal direction, and chamber method measurements in a randomly chosen, vertically oriented rectangular measurement surface (see Section 13).

Field measurements at the slope crest in the F3 area show the presence of methane emissions from protruding objects, such as iron and plastic objects, from stone sections, small fissures in the surface layer of the covering material, on surfaces lacking vegetation, and from surfaces with the same type of moss vegetation as that described for landfills such as the Spillepeng landfill, Malmö (Figure 12.14), Löt, Stockholm (Figure 12.19/20), and for the F1 area, Forsbacka landfill (Figure 12.23/24).

Figure 12.23 is an overview picture of the crest, F3 area, northern slope, Forsbacka landfill. The lift crest in the F3 area consistently showed large variation in methane emissions, from low to very high ppm readings in the majority of field measurements, 100-15 000 ppm. Exceptions were on measurement occasions with rapidly changing weather and radiation conditions, in particular a switch from low to high pressure. On such occasions, no measurable methane emissions could be recorded with the Siemens laser system.

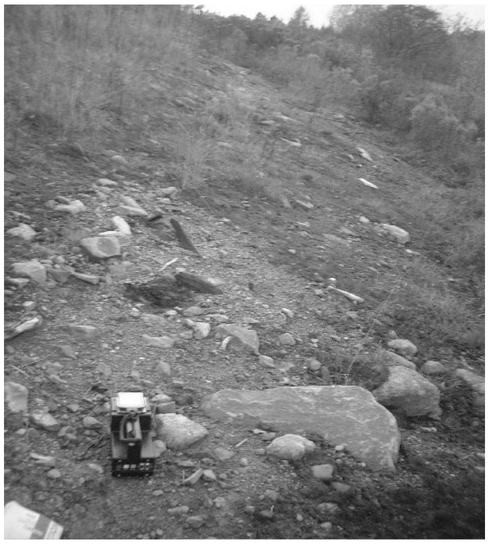


Figure 12.23. Overview photos of the lift crest, F3 area, Forsbacka landfill, from W=>E and E=>W, with protruding objects, vegetation-free surfaces, and moss species with short root systems found on surfaces with detectable methane gas.

Figure 12.24. Photo collage with features/surfaces representative of leakage sources for methane emissions on the lift crest in the F3 area. The long protruding plastic pipe (figure 12.23, left) has, in most of the measurement series, resulted in measurable methane emissions, even when the weather changed rapidly, when other surfaces and features showed ppm readings of around 0. The readings for the plastic pipe varied from ≤100 ppm to a maximum of 12 000 ppm. For a comparative analysis of readings from different measurement occasions and year, see Table 12.4, Appendix 6.


a) ≥12 000 ppm


b) ≥2 000 ppm


c) 4 000 ppm


d) 15 000 ppm


e) ≥ 1 000 ppm


f) ≥12 000 ppm


g) 4 000 ppm


h) 4 000 ppm

Figure 12.24. Photo collage with features/surfaces representative of leakage sources for methane emissions at the crest in the F3 area.

Like the previous diagrams of readings from laser measurement of methane emissions, Figure 12.27 shows great variations in ppm data over a measurement period of ≤ 1 minute. The project has not been able to establish whether these variations are caused by wind inducement, variations in micro topography or are caused by methane processes in the landfill, or a series of interacting factors.

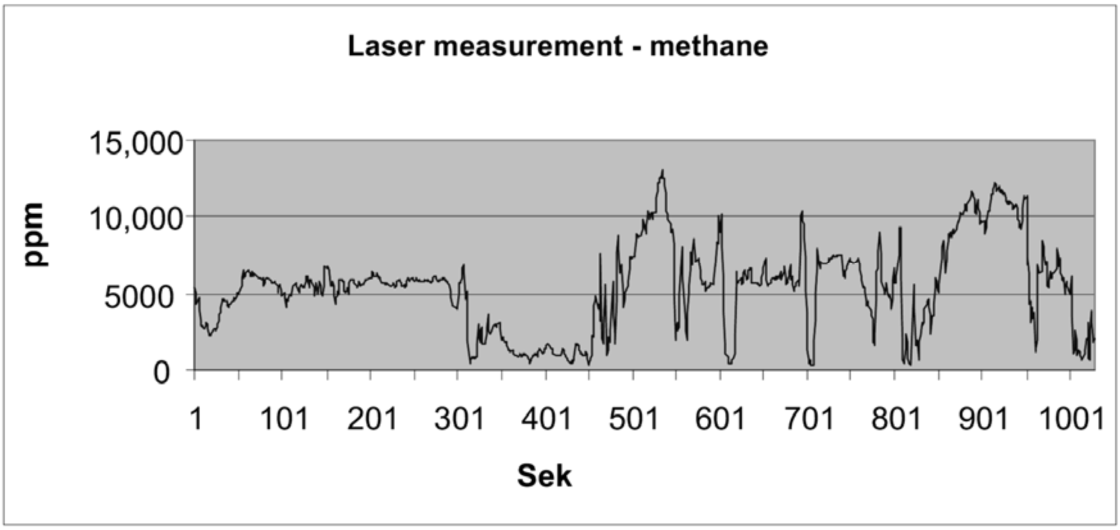


Figure 12.25. Diagram showing variations in measurement data in field measurements of gas emissions from one of the measurement features (F3-01) on the lift crest, F3 area, Forsbacka landfill, 100-12 000 ppm.

12.4.4 Methane emissions from toe of slope – measurement with laser and IR technology

The lift foot on the western slope of Löt landfill was selected to illustrate methane emissions from the toe of slope. See the sketch of the western slope, Figure 12.15. The lowest part of the toe of the slope (Löt_L5_1-5) includes 5 features/surfaces with varying methane emissions, 800-2 000 ppm, recorded with repeated field measurements in 2006-2007. The toe of the slope comprises an embankment, approximately 2 metres high, short slope and toe, and small flat surface and drainage layer. Figure 12.26 shows an overview of the toe of the slope, L5_1-5, with an approximately 10 cm fissure in the surface layer where methane is emitted and has killed the grass vegetation. Compare this with the luxuriant grass vegetation approximately 50 cm each side of the fissure.

Figure 12.26. Overview of the lowest toe of slope (Löt_L5_1-5), 800-2 000 ppm, 2006-2007.

Figure 12.27. Photo collage with ppm data for each leakage feature/surface. Note that, like the overview picture, Figure 10.26, the surfaces are unvegetated or have dead grass in sections with methane emissions, L2-1-5. In conjunction with chamber method measurements in 2007, a new surface, L2-4-1, was added as a reference surface.

L2-1 = 250 ppm

L2-2 ≤ 400 ppm

L2-3 = 6 000 ppm

L2-4 ≤ 5 000 ppm

L2-5 ≤ 1 000 ppm

L2-4-1 800 ppm

Figure 12.27. Löt photo collage.

There is no logged ppm data for the toe of slope L2-1-5, so no ppm diagrams can be shown. Table 12.5, Appendix 6, shows the variation in ppm data for toe of slope at Löt landfill L2-1-5, from field measurements with the Siemens laser system 2006-2007.

12.5 Methane emissions from Högdala landfill – final covering according to new EU norms

Högdala landfill is the only landfill in the project with final covering according to new EU norms (2001:512). Furthermore, it is a special case because it is also the only landfill in the project where the field measurement results with the Siemens laser system inequivocally indicate that a measure, in this case switching a gas flare on or off, gives a measurable result in the form of increased or reduced methane emission from the landfill. The results indicate the usefulness of laser technology for monitoring methane emissions from landfills of the same type, and same covering procedure, as Högdala landfill.

According to applicable EU norms that were incorporated in the Ordinance on the Landfill of Waste (2001:512), a landfill containing non-hazardous waste is to have a final cover. The technical requirement is that the final cover is to be so designed that the quantity of leachate that passes through the cover does not exceed or can be assumed to exceed 50 litres per square metre and year (Section 31 of the Ordinance). However, because there are protected sites from a water management perspective downstream from the landfill, it was decided that the standard of the final cover would exceed the technical requirement, 10 l/m^2 per år. The final cover consists of surface levelling, a sealing layer comprising a bentonite mat, a drainage layer of crushed glass, and more than 1 m of covering soil and vegetation soil.

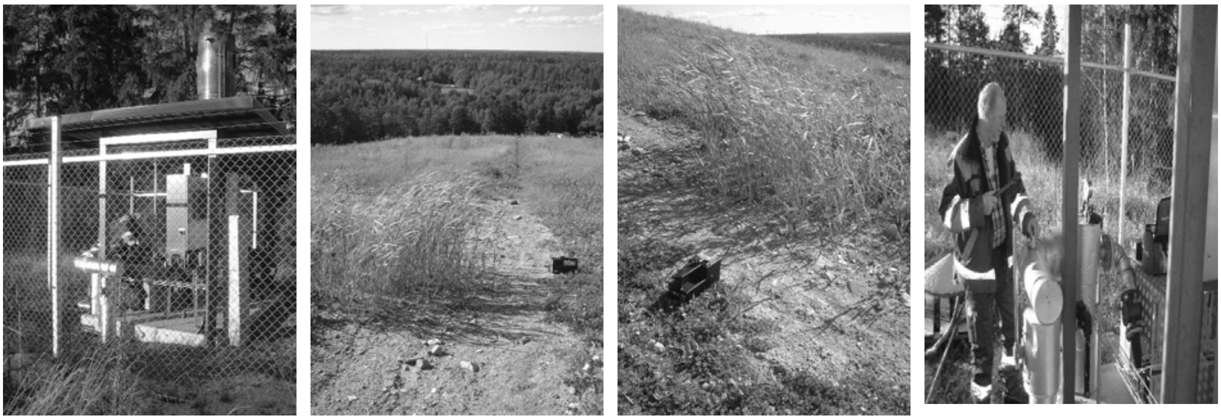
Participants at a reference group meeting proposed that Högdala landfill be included in a later phase of the project. Field measurements at Högdala landfill were limited to a series of snapshot measurements in the period 6 July 2007 – 28 November 2007. On the first measurement occasion, the gas turbine for the combustion of methane was out of action. On the three subsequent occasions, the gas flare was working but, on the fifth occasion, the flare was shut off for measurement and a study of whether and how methane emissions through the landfill surface were affected by the gas turbine being in operation or switched off.

The results from the field measurements at Högdala landfill are to be considered preliminary, and further measurements should be taken with the gas flare switched on and off, under different weather and radiation conditions. Wind velocity is the most important weather parameter because Högdala landfill is exposed to the wind on account of its size, geometric shape and location. Even initially relatively low wind velocity increases when the wind is forced up the high and abruptly steep slopes, which means that the wind velocity is normally higher on the plateau/top surface than at the toe of slope.

Figure 12.28. Aerial photo of Högdala landfill.

Field measurements were carried out during a season with strong vegetation growth on the slopes and during periods with less vegetation cover and unvegetated surfaces on the plateau/top surface (6-20 July 2007), and also during periods with winter conditions with sub-zero temperatures and light snow cover (11-15, 27, 28 Novemver 2007).

Figure 12.29 (a) shows the gas recovery system with a flare for combustion of landfill gas at Högdala landfill; (b) shows a sub-zone with gas emissions by the path with reeds, western slope, 1 500-2 000 ppm, with the gas flare not in operation; (c) close-up of the same section as (b) but in photo (c) the gas flare has been switched off in order to take measurements to compare methane emissions with and without flaring. When the gas flare was switched off, emission was up to 2 000 ppm at the reed area on the western slope using detailed laser measurement, and ≤ 1 000 ppm x m from fissures on the plateau/top surface, and 100-400 ppm x m generally for the W, N, E, and S slopes on scanning. When the measurements were repeated with the gas flare in operation, no measurable methane emissions were recorded for the section with reeds, western slope, plateau and the slopes gave 50-100 ppm x m. The results from these two comparative measurements indicate that, when the gas flare is switched off, the gas is transmitted through the landfill mass and is emitted through the surface layer, and when the gas flare is in operation, emission is only slightly higher than normal background emission from Högdala landfill. Note that the conclusions only apply in the measurement conditions prevailing at the time.



a) b) c) d)

Figure 12.29. a) gas recovery system; b-c) Western slope – 2 000 ppm, leakage; d) gas flare switched off at the flare by the reeds.

The reed area was such a clear leakage source because the thick reed stems, like thick stems through snow cover, are affected by wind movements and open up channels in the surface layer through which methane can escape. See also Section 10.5.

Weather and radiation conditions during field measurements at Högdala landfill, 15 November 2007,10.00:
T_s -50 °C
T_l -4 °C
SW in lee = 1 m/s, on the plateau = 3-4 m/s
Air pressure 1016 mb

Thin snow cover, broken by vegetation.
Hard frozen ground surface.
Continual flow of methane, particularly from the southern slope. Measurement with laser placed on the plateau, directed towards the southern slope = 100-400. Measurement directed towards the western slope = 150-300 ppm x m. See summary of readings in Table 12.6, Appendix 6.

Figure 12.30. Högdala landfill: laser, weather station and log system placed on the plateau, with laser directed along the plateau in a SE direction, 0-500 ppm x m.

Measurements of methane emissions and weather and radiation conditions were logged on one occasion (28 November 2007) with the gas flare switched off. The laser system, equipment for simultaneous measurement of weather and radiation conditions, and the logger system, were placed approximately 30 cm above ground level on the plateau/top surface (see Figure 12.30). The beam was approximately 30 m long. The diagram of methane emissions (Figure 12.31) shows increased emission from Högdala landfill when the gas flare was switched off. No comparative logger measurements were carried out when the gas flare was switched on, but there were snapshot field measurements (see table, 12.6, Appendix 6).

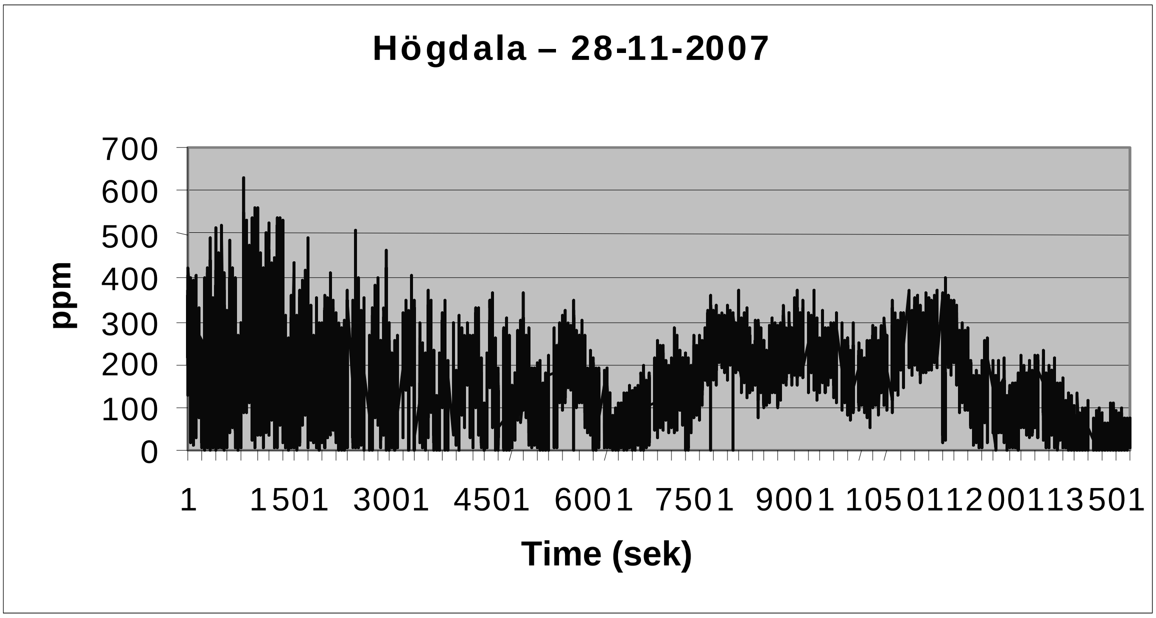


Figure 12.31. Diagram showing methane emissions when the gas flare was switched off.

12.6 Methane emissions under winter conditions with snow cover

The majority of the field measurements with the Siemens laser system and the FLIR IR GasFinder were carried out without snow cover, even during the winter season, with the exception of the Hagby and Löt landfills in the Stockholm region, and Forsbacka landfill in the Gävle region which, on account of its northerly location, has a thick snow cover on occasions in the winter. Field measurements with the Siemens laser system were carried out in all seasons at all landfills. Mapping of methane emissions for the most southerly located landfills, Spillepeng in Malmö and Filborna in Helsingborg, were carried out under winter conditions with low temperatures and no snow cover.

The report below is restricted to a selection of field measurements at Hagby and Löt to illustrate how remote sensing, in the form of the Siemens laser system and the FLIR IR GasFinder system, can detect and map methane emissions from landfills during the winter season with snow cover.

Field laboratory experiments with controlled simulation of methane emission from gas pipes placed under a 20-50-cm thick layer of snow were carried out in the VOGUE project

(VOGUE-project, NNE5-1999-20031). Results from these experiments indicate that snow serves as an effective insulation layer that prevents or reduces methane emission/distribution from the ground surface. But the results also show that the gas seeks the easiest route out through the insulating and barrier-like snow cover. On the occasions when the surface layer had frozen to a crust, the gas is prevented from emission through the snow layer, pressure builds up under the surface and landfill gas pressure is increased. Finally, pressure increases so much that the methane breaks through and is emitted through the surface layer of the snow cover, or finds its way out at the edges of the snow cover, or through channels that are formed by high, stiff grass stems or other high ground vegetation that protrudes from the snow cover and whose movements are affected by wind. This is illustrated in, for example, Figure 12.32.

Field measurements using remote sensing techniques, such as the Siemens laser system and the FLIR IR GasFinder, at Hagby landfill (cell 89) confirm the results about how methane behaves under winter conditions and snow cover, as indicated in the VOGUE project. The results also confirm the assertion that it is possible to detect and visualise methane emissions from snow-covered landfills under difficult winter conditions with low temperatures and thick snow.

Figure 12.32 shows a snow-covered section of landfill, cell 89, Hagby, where field measurements during the autumn recorded methane emissions from located features/surfaces (h9, h10, h11, h12) with ppm readings that varied from 1 000-3 000 ppm. When the field measurements were repeated under conditions of snow cover, no methane emission could be detected with the laser system at the identified features/surfaces where methane emissions had previously been measurable. One of the marking poles was pulled up, and this resulted in methane gas escaping through the hole made by the pole. When the marking pole was replaced in the same hole, the gas flow stopped. It was noted that the surface of the snow had a thin but hard crust. Scanning of the area in question revealed that methane was leaking out where hard grass stems protruded through the snow surface. The wind set the grass stems in motion, opening up channels through the snow layer from the landfill surface up to the top of the snow cover. The measurement area was 10-15 m^2 and included the identified features/surfaces marked with poles. Methane emission from the new snow-covered measurement features was ≥ 1 000-3 000 ppm, i.e. similar results to those obtained in the field measurements in the autumn. The field measurements under winter conditions at Hagby, cell 89, were carried out on 29 January 2007, 15.00-17.00, at an air temperature of $-5\ ^{\circ}C$, NW wind, 1m/s, cloud-free skies, with a snow cover of 20-30 cm.

Figure 12.32. Energy cell 89, Hagby. Methane emissions via channels formed when the wind set stiff grass stems in motion were 1 000-3 000 ppm, recorded with the Siemens laser system. Snow cover, 20-30 cm.

Conclusions: A snow layer forms a barrier that prevents the emission of methane through previously located leakage sources. Pressure builds up under the snow cover and the methane finds its way to the root system of the thick grass stems. The wind above the snow surface moves the thick, rigid grass stems, and channels are formed that give the gas free passage through and around the grass stems from the landfill surface up to the surface layer of the snow cover. Similar conclusions also apply for bushes, etc. that stick up through the snow cover.

The example presented, Figure 12.32, illustrates a case with a snow cover with a crusty surface. The next example, Figure 12.33, illustrates a condition with deep porous snow where the methane has free passage for emission through the snow cover up to the surface.

Figure 12.33 shows a) an overview of the slope, L1-6 – L1-1, and (b) a close-up picture from L1-3) as examples of gas emission through a snow cover without grass stems or other protruding vegetation, and where there were no visual signs of gas emission. Field measurements with the Siemens laser system and the FLIR IR GasFinder were carried out at Löt landfill on 30 January 2007, 15.00-17.00, with air temperature ranging from -2 to -5 C, NW wind, 1 m/s, cloud-free skies, 20-30 cm snow depth. Measurement with the laser system gave a ppm reading of ≥5 000 ppm, which can be compared with the previous reading of ≥6 000 ppm when the same site (L1-3) was measured under conditions with no snow cover on

19 September 2007 (Figure 12.17 (L1-03), Section 12). Figure 12.33 c) shows Löt, western slope.

The specific part of the western slope, Löt L1_1-8, includes 8 features/surfaces with methane emissions that vary from 500 ≥5 000 ppm, when there is snow cover. In comparison with field measurements of snow-covered features/surfaces at Hagby landfill, shown in Figure 10.36, methane emissions could be detected from all located features/surfaces at Löt landfill both under winter conditions with snow and under conditions with no snow cover/bare ground. Note that there was no crust on the surface layer during the field measurements at Löt, western slope. Here, too, a crust would have prevented the methane from penetration, and prevented emission through the snow cover, so there would probably be no measurable methane emissions, especially as there was no vegetation that could form channels through the snow cover up to the surface layer.

Measurement feature L-3 comprises a plastic object that protrudes from the landfill surface and provides a channel for methane emission under both bare ground and snow cover conditions. It is not known how large the plastic object is, or how far it extends down into the landfill. However, it is clear that methane flows along the edges of the plastic give emissions that are detectable with both the Siemens laser system and the FLIR IR GasFinder. The western slope of Löt landfill represents a slope with many leakage features with relatively sizeable gas emissions. When the wind is westerly and north-westerly, a gas smell is evident, and airborne emissions of 200-400 ppm can be recorded on the adjacent plateau, and on the southern and northern slopes.

Figure 12.33. a) overview picture of feature L1-6 – L1-1, western slope, Löt landfill; b) feature L1-3, gas leakage through untouched porous snow cover (20-30 cm), ≥5 000 ppm.

Figure 12.33b (c) L1-03, plastic feature ≥6 000 ppm = same object as Figure 12.33 (b)

12.7 Methane emissions from leakage systems and gas recovery systems

Literature relating to landfills shows that methane emissions from gas recovery systems and leachate systems can be extensive because the pipe systems for gas distribution and leachate distribution can serve as transport routes for methane (Chanton, J. et al., 2007, Scheutz, C. et al., 2007). Similar observations have been made in the current project, where measurements of both distribution systems, gas wells, leachate wells and leachate ponds indicate the occurrence of methane emissions, some of which are relatively strong indications from certain features. The following section reports on a selection of features that illustrate the usability and limitations of remote sensing for determining the status of pipeline systems for distribution of gas and leachate.

12.7.1 Methane emissions from leachate systems

Design and function of leachate collection systems vary for the different landfills in the project. This section describes a selection of leachate systems that we were able to measure in the field using the laser and IR systems for detecting methane, and that contribute results of general interest for the project, such as the leachate systems at Forsbacka and parts of the Hagby and Löt landfills.

Forsbacka has a leachate system in which untreated leachate from the landfill is led via a pipe system to a leachate well (LAK 1) from where it is pumped to an aerated leachate pond (LD1) that comprises the first cleaning stage. The leachate is then led to a ground bed comprising a sand filter (PP4, stage2), connected to a leachate pond. From cleaning stage 2, the treated leachate is led to a wetland with partly open water, cleaning stage 3, and then released through an outlet to an open ditch (PP6). Field measurements with laser indicate higher methane emissions from the final stage (PP5) in the cleaning process, 200-800 ppm x m, compared with 50-200 ppm x m in the first cleaning stage, the aerated leachate pond, LD1. The leachate at the outlet (PP5) should show considerably lower ppm readings than the leachate pond with untreated leachate (LD1). For more detailed measurement data, see Table 12.7. Appendix 6. Figure 12.39 shows (a) the leachate pond LD1 with untreated leachate, and (b) the final stage, PP5, which should have clean water.

Figure 12.34 **(a)** LD1, first cleaning stage of the leachate, Forsbacka, 50-200 ppm x m

(b) PP5, final cleaning stage, 200-800 ppm x m

The results from field measurements of methane emissions from leachate ponds at Forsbacka landfill cannot be used to draw general conclusions about methane emissions from leachate ponds, because measurement errors caused by windborne emission contributions from other adjacent emission sources cannot be excluded. Furthermore, methane emissions from leachate ponds should be measured using reflector surfaces such as a backscatter surface, which allows the conversion of ppm x m data to ppm data and correction of the calculation of the net contribution of the methane emission from the leachate pond in question. Laser measurements against reflector surfaces were not introduced until the majority of the field measurements had been completed in the project. However, results from repeated snapshot laser measurements and long-term measurements with laser data stored on logs from leachate pond LD 1 and for other leachate systems in the project (Hagby, Löt, Filborna) indicate that leachate systems with open ponds, open leachate drains, etc. produce a constant and continuous flow of methane to the atmosphere, regardless of the oxygen content in the water and weather and radiation conditions. Supplementary field measurements should be carried out to identify the contribution of leachate ponds to methane emissions. However, it is worth noting that leachate systems consist of more than leachate ponds; both open and closed distribution systems, and leachate wells, can emit methane. See the presentation below.

Hagby. An example of emissions from the leachate system is the open system for collecting leachate at Hagby landfill, related to Cell 89 and Cell 90. Here, the leachate is pumped to a pond for treatment/purification situated at the top of the landfill, and is then transported along the landfill slope in an open stone channel to the next treatment stage, Figure 12.35. At the end of the open stone channel, there is usually a large stone store from which water is forwarded to a leachate pond. The purpose of the open stone channel is to oxygenate the leachate as the mechanical aeration system in, for example, the leachate system, LD1, etc. at Forsbacka landfill, shown in Figure 12.39, 12.40 above.

Results from repeated laser and IR measurements under similar measurement, weather and radiation conditions indicate that open stone channels and special infiltration stores of stone, like the structure at Hagby landfill, result in continuous and relatively high gas emissions to the atmosphere in all seasons, 2 000-8 000 ppm.

Figure 12.35. (a) Leachate-stone channel with infiltration store of stone, methane emission summer=>winter, 2 000-8 000 ppm.

b) Same feature, winter

Figure 12.35 (c). Overview picture, winter, same feature as in Figure 12.35 (a-b).

Figure 12.36 (a-b) shows thermal images from the IR GasFinder measurement of the same object as in Figure 12.35 (a-b), wintertime. The photo pair Figure 12.36 a-b, shows elevated radiation temperature and a deviating radiation temperature pattern from the stones in the stone culvert as a secondary effect of emission of methane through the stone culvert in the open leachate drainage. A continuous, light, slightly deviating grey toning pattern can be discerned from the middle and down towards the date caption in the image, indicating a gas cloud. The right thermal image (picture b) is an inverted grey tone image. The picture pair is selected from a video sequence. In the video film, the gas emission is visualised clearly as a pulsating gas cloud that flows out along the landfill surface.

Figure 12.36 (a-b) shows thermal images from recordings under winter conditions using the IR GasFinder system for the same feature, the leachate culvert, as in Figure 12.35 (a-b). A gas cloud can just be distinguished through the light grey and dark grey radiation temperature pattern in the thermal images, pictures (a) and (b). The video film from which the frames were taken visualises the emission of a clear gas cloud from the stone culvert.

12.7.2 Gas emission from gas recovery systems

The condition of the gas recovery systems varies between the different landfills in the project, and can also vary locally within each landfill. Figure 12.37 and Figure 12.38 illustrate parts of a gas recovery system where both the Siemens laser system and the FLIR IR GasFinder indicated the occurrence of large gas emissions comparable with the gas flows simulated in the earlier VOGUE project, here in a range of 5 000-20 000 ppm, mainly from gas wells. Similar results were documented from field measurements carried out at the two French landfills in the project.

Figure 12.37. Gas control well, Hagby, summer conditions, 6 000-10 000 ppm.

Figure 12.38. Gas control well, Hagby, winter conditions, 6 000-10 000 ppm.

Laser measurement

Figure 12.39 shows a gas concentration profile with readings from field measurements carried out using the Siemens laser system. Note the large variation in measurement data over the measurement sequence (2 000-15 000 ppm x m). The measurements were taken with a distance of approximately 5 m between the laser system and the leakage source. Similar variations were found for the majority of short- and long-term measurements carried out for different types of gas control wells in the project.

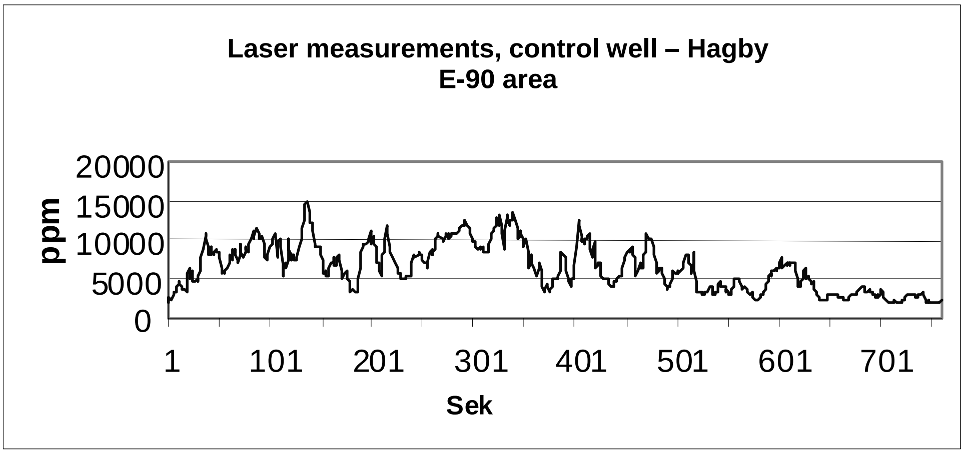


Figure 12.39. Gas concentration profile for gas control well, situated in the E-90 area, Hagby landfill (2 000-15 000 ppm), Hagby_060912_02.

Measurement with IR GasFinder system

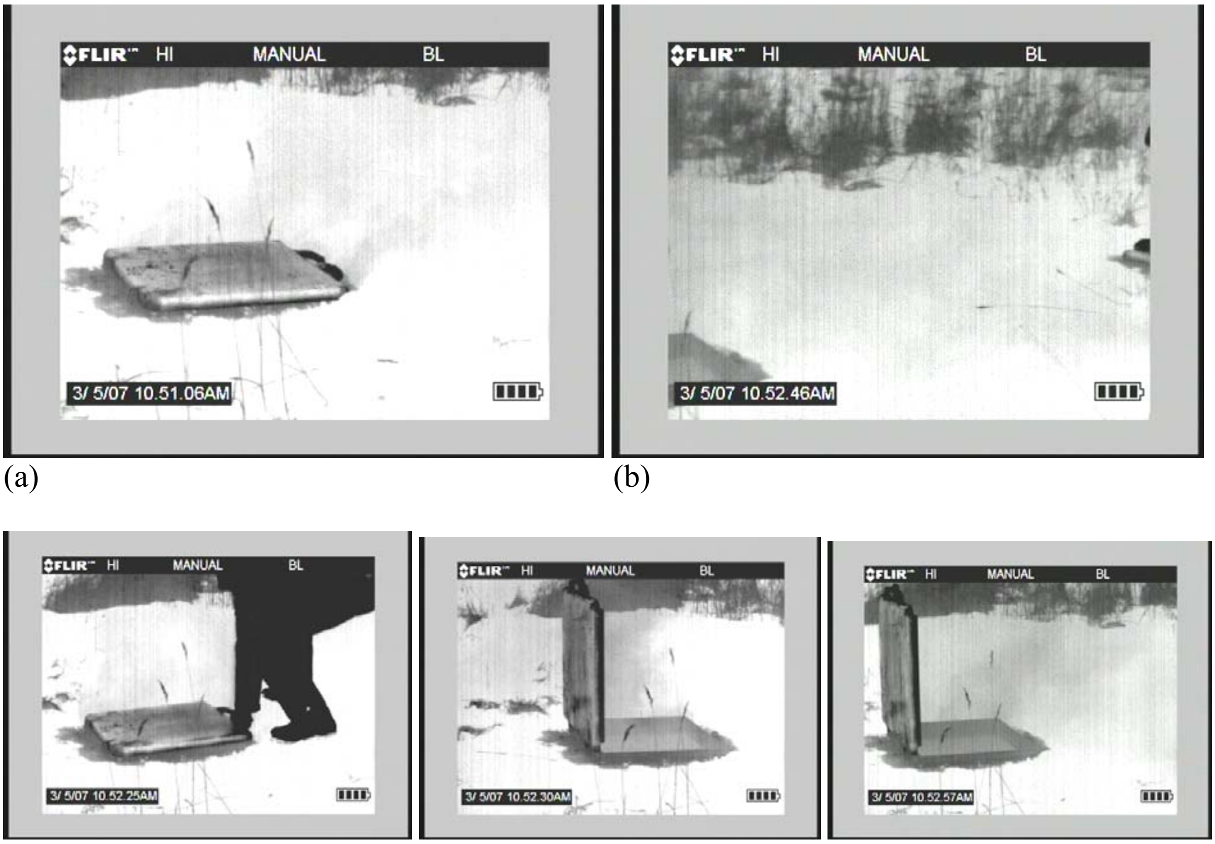
The FLIR IR GasFinder is a supplementary method for detection and to visually form an impression of the scale and diffusion pattern of gas emissions from gas recovery systems. The results from simulated and controllable gas leakage at Malmö Fire Service's gas testing facility, BARBARA, show that it is difficult to present gas-related IR data in a way that shows a true picture of the information potential of the GasFinder system and the dynamics in thermal image data (see Section 12.2). In terms of gas emission from gas recovery systems and leachate systems, it has proved possible to capture and freeze the gas plume in a still-frame from the video film and produce an IR image that shows the gas emission at a specific measurement time, usable for indicating the information content in the thermal image data. However, analysis of the gas emission based on a digital IR video film is to be recommended if the aim is to visualise the methane emission and to study the diffusion pattern of the methane.

Figure 12.40 shows two thermal images selected from a series of thermal images that illustrate different diffusion patterns in a still frame of a gas plume, and that confirm gas leakage from the gas control well shown in Figure 12.37 above. The left image shows an upward-moving stream of methane in the form of a light grey gas plume, and the right image shows the same feature with a horizontal-moving gas plume that is shown as a continuous light grey gas cloud against the light snow. Both thermal images are taken from an IR GasFinder video sequence. The left picture was taken approximately 1 minute after the cover of the gas well was removed, and the right picture about 2 minutes after the cover was removed. The powerful upwardly-moving gas stream in the left picture is caused by methane leaking from the gas pipe in the well, giving elevated methane concentration that has free passage to the atmosphere once the cover is removed. The right thermal image shows a horizontal stream of methane from the same feature, approximately 2 minutes after the cover was removed, caused by a temperature difference between the methane (+3.7 °C) and the surrounding air (0 °C), natural convection, 2 000-15 000 ppm measured by laser.

Figure 12.40. Two still-frame thermal images from an IR GasFinder video sequence of gas emission from a gas control well in Cell E90, Hagby, corresponding to Figure 12.37.

Similar behaviour in methane emissions from gas recovery systems is illustrated in Figure 12.41 from another gas control well at Hagby landfill. Thermal image (a) shows methane leakage from the control well with the cover closed, and thermal image (b) shows how the gas cloud formed at the well cover moves away from the gas well and is mixed with surrounding air. Thermal images (c) and (d) show gas emissions from the same gas control well with the well cover closed (c) and open (d). Like the thermal images in Figure 12.40, thermal image (d) shows a vertical stream of methane approximately 1 minute after the well cover was removed, caused by temperature differences between the methane (+2.8 °C) and the surrounding air (0 °C), natural convection and (e) shows a horizontal gas stream about 2 minutes later. As the methane concentration in the gas well decreases, the gas will be emitted through natural convection in a vertical stream, thermal image (e), 9 000-10 000 ppm measured by laser.

Like Figure 12.40, the thermal images in Figure 12.41 a-e illustrate the information potential of IR GasFinder technology for detecting and visualising gas emissions from gas recovery systems. Note that the thermal image data analysed as continual pictures in a video sequence gives much stronger and more dynamic information about the movements and diffusion pattern of methane than still thermal images in a written document.



(a) (b)

(c) (d) (e)

Figure 12.41. Collage of thermal images from an IR Gasfinder video sequence recorded at Cell E90, Hagby landfill. Thermal images a-b show methane emissions and the diffusion pattern of gas emitted from a gas control well with the cover closed; (c) the moment of removing the well cover; (d) vertical movement of gas caused by a temperature difference between the methane (+2.8 °C) and surrounding air (0 °C), natural convection; (e) a change in the direction and pattern of diffusion, 9 000-10 000 ppm measured by laser.

It is difficult to present gas-related IR data in a written report in a way that illustrates the GasFinder system's information potential and that shows the dynamism in the thermal image data. One way of presenting IR data in a written document is to capture and freeze the image sequence from the digital video film that best shows the gas plume for a leakage feature at a specific measurement time. However, as pointed out earlier in this section, the information potential of gas-related IR data is best shown through a video film presented in an electronic report.

12.8 Detection of methane emissions from a landfill without a landfill gas recovery system

The Änglarp Waste facility contains a landfill where waste has been landfilled since 1968. The reception of waste is since 2002 very small compared with the reception during the 1990-decade when 12 000 tons of waste was landfilled every year. Large quantities of sludge have been provided in lagoons on the landfill. All lagoons are now covered except for the last large lagoon. The older landfill part is not finally covered, but has a soil cover. The newer part is not covered.

The landfill parts have no landfill gas recovery system. Produced landfill gas will emit to the atmosphere, except for the methane that can be oxidized in the surface layer of the landfill.

The landfills have been investigated on two occasions, in December 2006 and in June 2008. Results of the measurements are shown in Figure 12.42. The measurement in December 2006 showed no point source emissions. Methane was instead detected in the air above the landfill surface at low levels. There were some difficulties to find which other areas emitted the methane, when wind transported the methane from the open lagoon, which was the largest source of methane emission.

In the summer 2008 the methane content in the air above the landfill surface was lower, and methane could only be discovered at point sources in the old landfill part with no vegetation layer and in slopes on the newer landfill. Over the area with no vegetation on the old part there was a concentration of 5 ppm, with lower concentrations in the other areas. This should be compared with the concentrations of 5-10 ppm measurent in a number of places in 2006.

The measurements first of all show that methane oxidation is significant in the summer and the emissions of methane from areas with a vegetation layer low. The methane found in the summer 2008 came from an area covered with gravel in the old landfill part. The lagoon that showed a leakage of methane in 2006 had no leakage in 2008. The degradation of the sludge was now low, when no new sludge has been landfilled since 2005.

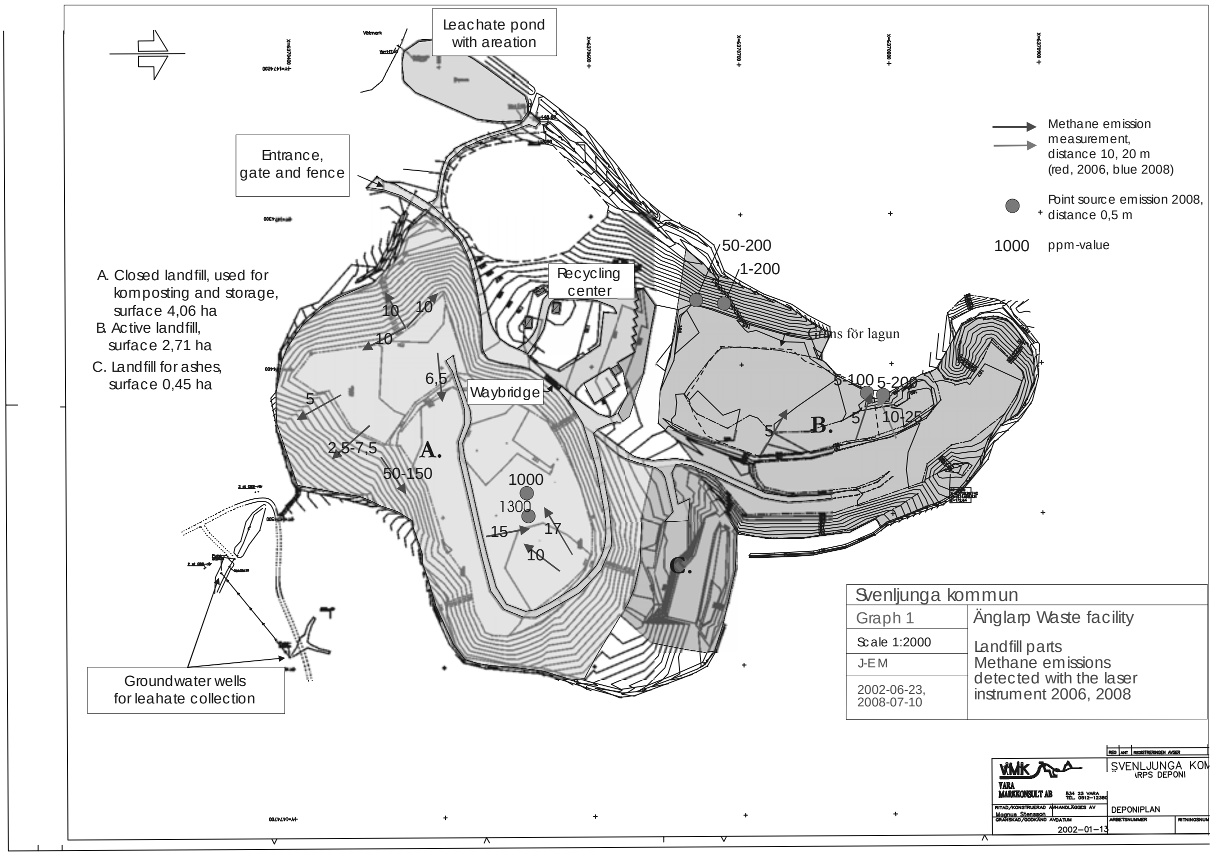


Figure 12.42. Results from measurements with the laser instrument 2006 and 2008 at the Änglarp landfill. Not in mentioned scale.

13. MEASUREMENTS WITH THE LASER INSTRUMENT AND THE CHAMBER METHOD

13.1 Chamber method and measurement of concentration with laser instrument, controlled flow

As an introduction to simultaneous measurements of flow using the chamber method and measurements of concentration with the laser instrument, a box filled with sand was used to simulate landfill gas emissions and test for a reliable and usable correlation. The design of the box is shown in Figure 13.1.

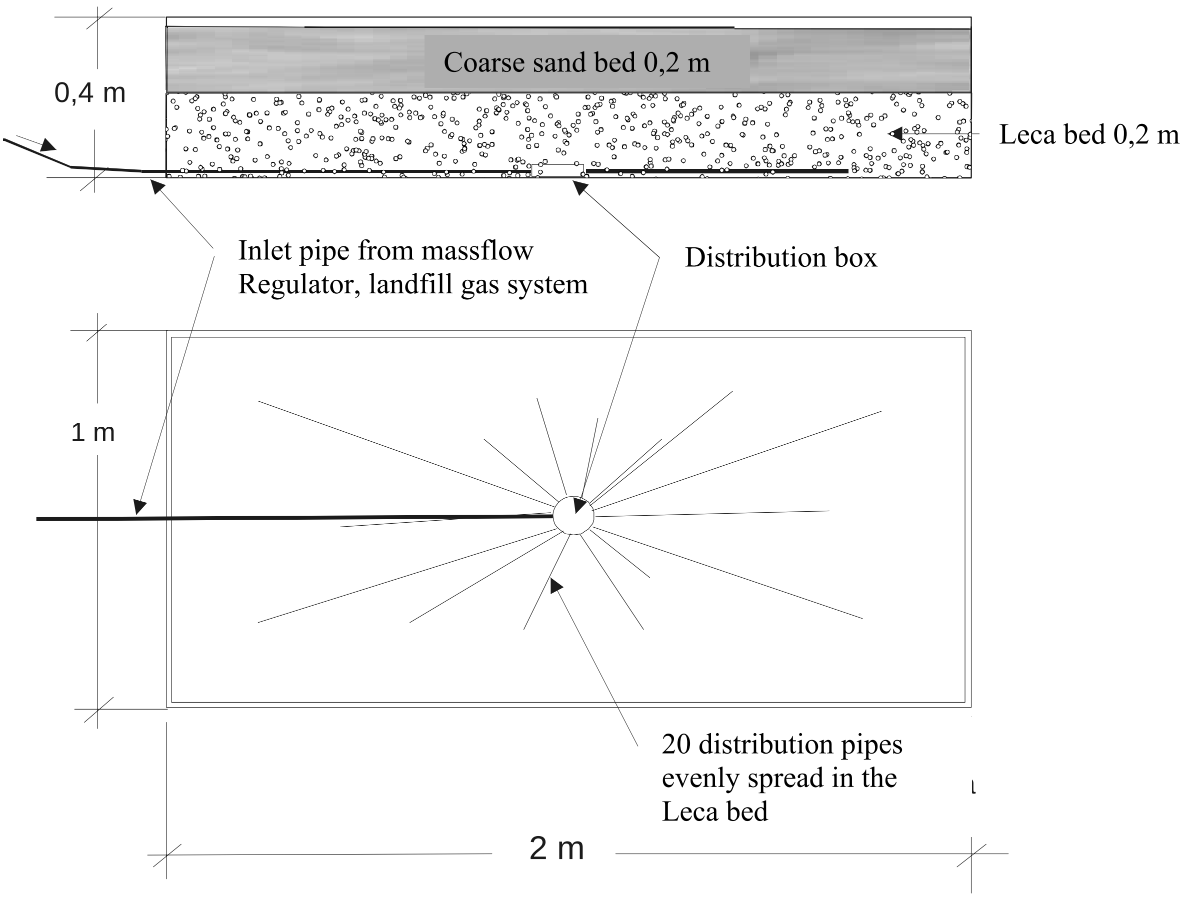


Figure 13.1. Box with sand for flow measurements. Landfill gas from the Filborna gas recovery system is fed into the Leca bed from below and is distributed via pipes. The landfill gas flows through the sand uniformly, and the concentration and flow can be measured on and above the sand surface. A mass flow gas regulator, where the flow can be regulated between 0.2 and 20 l/min, controls the inflow to the box.

Simulated methane gas emission from the sand bed was measured using the laser instrument for concentration data and the chamber method for flow data. The landfill gas flow varied from 0.2 l/min to 10 l/min. The results are shown in Table 13.1.

Table 13.1. Simulation of methane gas emission through sand, measurement with the chamber method.

Gas flow through mass flow gas regulator, biogas l/min	Flow through sand bed, CH_4 l/ m^2, year Q1	Measured flow using chamber method, CH_4 l/ m^2, year Q2	Ratio Q2/Q1	Laser instrument, concentration ppm x m (Mean value, measurement 2 minutes)
0.2	26 280	164 308	6.25	24
1	131 400	95 397	0.72	27
5	657 000	147 825	0.22	38
10	1 314 000	333 344	0.25	147

It is clear that there is a poor relationship between the controlled flow and the measured flow. The selected emissions from the sand bed are relatively high, and the chamber method's measurement range is relatively low. According to this investigation, the measured value that best corresponds with the flow out of the sand bed is at 1 l/min, the equivalent of 131 400 l/ m^2 per year. At higher emissions, the chamber method gives values that are too low and, conversely, at low outflows, the values are too high.

According to the table, there is a relationship between concentration values measured with the laser instrument, and the actual emission from the sand bed.

In a special study, the relationship was studied in flow intervals from 1.0 l/min to 10 l/min biogas from the sand bed. The flow is the equivalent of 131-1 310 m^3/m^2 per year of methane (see Figure 13.2).

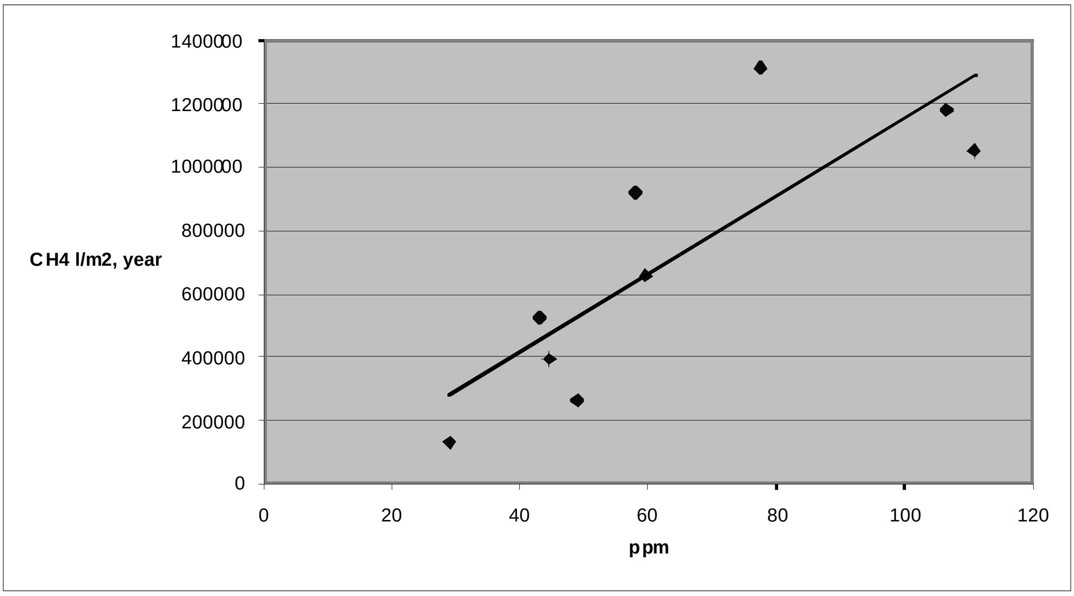


Figure 13.2. Relationship between emission of methane from the sand bed and the concentration above the sand bed, measured with the laser instrument

There is a clear relationship between emission and the readings shown by the laser instrument. At higher flows, the range is bigger, i.e. each measurement is less reliable.

A field experiment to examine emission of landfill gas from a point source was carried out under controlled conditions at Filborna. A tube connected to a mass flow gas regulator was buried in the ground and concentration was measured with the laser instrument at a distance of 1 metre from the point of emission. The results are shown in Figure 13.3.

The experiment obtained a reverse proportionality to the landfill gas flow. At low emissions, higher concentration values were obtained than at higher flows (see Figure 13.4). At point source emission from, in this case, a tube, the emission was so concentrated and the rate so high at the higher flows that the laser instrument, which was fixed in position on a camera tripod, failed to capture the gas plume. The range at low flows could depend on wind, although the wind speed throughout the measurement period was less than 3 m/s.

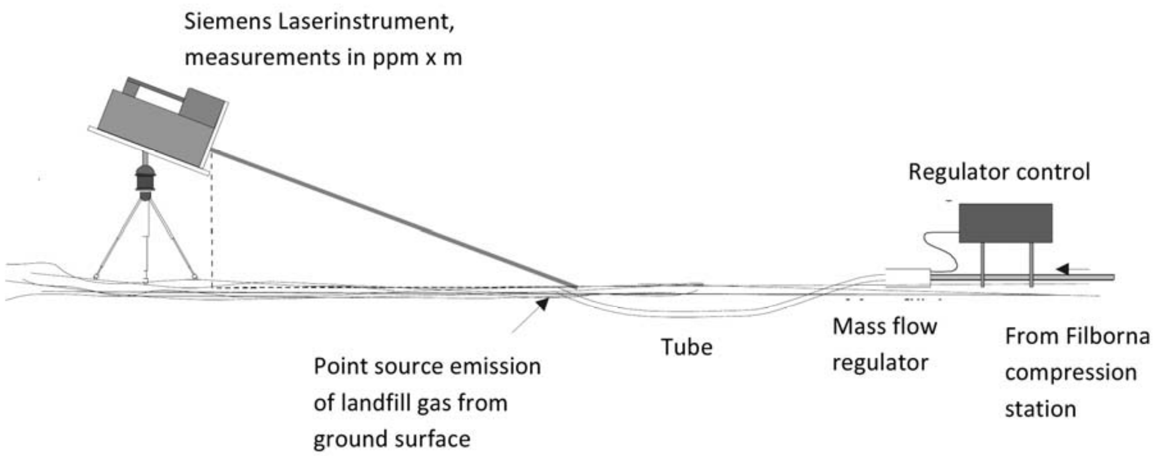


Figure 13.3. Experiment to measure the methane concentration from a controlled point source emission, Filborna 2007

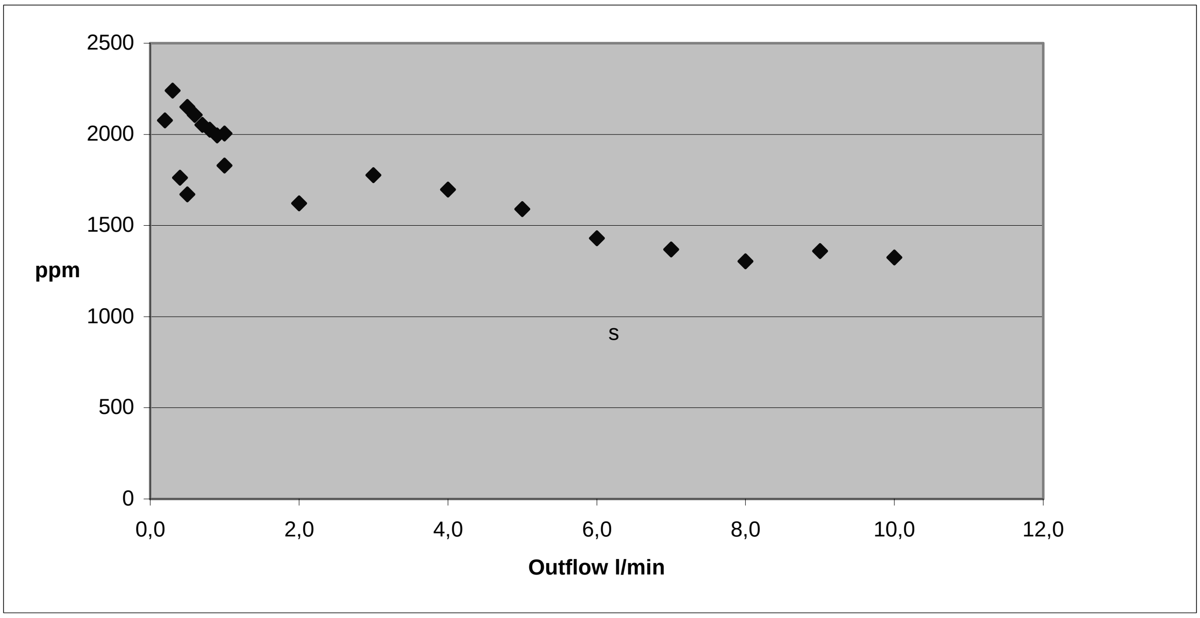


Figure 13.4. Concentration measured with the laser instrument above a point source emission of landfill gas.

According to observations from, for example, the pilot studies at the field laboratory at the BARBARA gas testing facility in Malmö, large flows through narrow outlets give rise to a jet with a thin gas stream closest to the ground surface and a broadened gas plume 1-1.5 m above the leakage source. The jet is caused by a high gas outflow velocity. When gas emissions are measured with pinpointing, attempts are made to measure the gas emission as close to the leakage source as possible. Where there is a jet, the operator tries to hit the thin gas stream close to the ground surface, thereby missing the broader gas plume above the leakage source. In field laboratory studies, measurements can be taken vertically at different heights simultaneously with several laser systems, thereby obtaining a gas concentration gradient that gives a picture of the gas concentration at different levels in the gas emission plume, including the narrower gas stream at ground level and the broader cloud higher up in the gas plume. The jet phenomenon can arise at a landfill, but is primarily related to gas emissions from gas recovery and leachate systems but, in exceptional cases, also from narrow exit channels where an object protrudes through a landfill surface.

13.2 Field measurements using the chamber method and laser instrument

In spring, summer and autumn 2007 a large number of combined laser and chamber method measurements were taken under different conditions at seven landfills. The dates and the scope of the measurements are shown in Table 13.3. A total of 20 surfaces were studied, and 690 gas samples analysed.

In our preliminary studies, we were able to identify zones, parts of the landfill surface that could be considered typical in terms of methane emission. The different parts are shown in Figure 13.5.

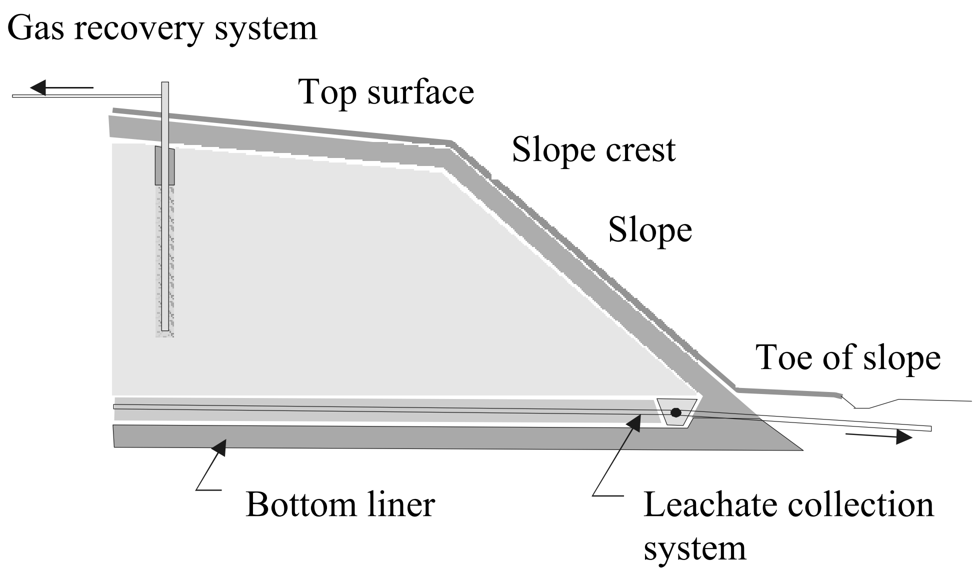


Figure 13.5. Structural components of a landfill that are important for emission

We discovered that the components shown in the diagram should be systematically and individually studied. The different zones differ in their effects on emission. We therefore divided up the study so that the different zones were the subjects of special study at the selected landfills. The importance of the zones for emission, and the areas that were investigated at the different landfills, are shown in Table 13.2.

Table 13.2: Different components in the landfill surfaces and classification

	Filborna	Spille-peng	Hagby	Löt	Fors-backa	French site 1	French site 2
Top surface Final cover EU standard	X						
Slope Final cover EU standard							
Covered top surface		X		X	X	X	X
Covered slope	X			X	X	X	X
Top surface without cover					X		
Slope without cover		X		X	X	X	X
Leakage, gas recovery system			X				X
Leakage, leachate collection system	X	X	X				
Final cover, old landfills		X	X			X	X
Tipping face	X						X
Landfill with plastic sheet cover	X					X	

Surfaces with mostly low emission of methane

Surfaces and installations with risk of high emission

Surfaces with risk of partially high emission

The different risk categories for emission were divided up on the basis of the observations made in the project. The concept ‘covered top surface’ means that another covering measure was carried out in addition to the normal covering with earth when a stage or a cell is completed. This additional measure commonly involves surface planning and addition of more earth masses, to a thickness of 0.5-1.0 m.

Surfaces or installations with risk of high emission of landfill gas comprise slopes without cover, active tipping faces, and systems for leachate collection and gas recovery. ‘High risk’ means that the surface or installation had high emissions of landfill gas during the project. Tipping faces show constantly substantial emission. It is perhaps surprising that gas installations, particularly vertical gas wells and the areas closest to a well, are at risk of high emissions of landfill gas because a gas recovery system often has negative pressure applied in the parts that are within the landfill surface. However, our early investigations gave the impression that parts of the recovery system for landfill gas did not work in the intended manner.

Based on the classification of surfaces, surfaces were selected for combined laser and chamber method measurements. The measurements, and the landfills at which they were carried out, are shown in Table 13.3.

In addition to surface factors, methane emission also depends on the amount of waste, the composition of the waste, and the age of the landfill.

Table 13.3. Measurement programme for chamber method measurements, and division into different zones. Colour coding in accordance with Table 13.2.

Landfill	**Time**	**Zone**	**Grid, m**	**Conditions**
Spillepeng	31-5-2007	Covered top surface	10 x 10	Covering of test cells
Spillepeng	31-5-2007	Final cover on top surface	10 x 10	Covering, old landfill
Filborna	1-6-2007	Final cover on top surface	10 x 10	Final cover according to EU norms
Filborna	1-6-2007	Covered slope	24 x 4	Covering before final cover
Filborna	1-6-2007	Sand	2 x 1	Box for calibration
Hagby	11-6-2007	Covered top surface	10 x 10	Covering, old landfill
Hagby	11-6-2007	Final cover on top surface	24 x 4	Covering of test cells
Löt	12-6-2007	Covered top surface	10 x 10	Covering before final cover
Löt	12-6-2007	Slope	24 x 4	No treatment, slope
Forsbacka	13-6-2007	Top surface	10 x 10	Covering
Forsbacka	13-6-2007	Slope	24 x 4	No treatment, slope
French site 2	25-9-2007	Top surface	10 x 10	Covering
French site 2	25-9-2007	Slope	6 x 1	No treatment, slope
French site 2	25-9-2007	Slope	18 x 6	Treated slope
French site 1	26-9-2007	Top surface	10 x 10	Covering
French site 1	26-9-2007	Slope	24 x 4	No treatment, slope
French site 1	27-9-2007	Top surface	50 x 2	Covering near slope crest
French site 1	27-9-2007	Top surface	10 x 10	Covering
Filborna	4-12-2007	Slope	10 x 10	Covering, surface for geoelectr. measurement
Filborna	4-12-2007	Slope	10 x 10	Covering, surface for geoelectr. measurement
Filborna	5-12-2007	Slope Same Test area	10 x 10	Covering, surface for geoelectr. measurement
Filborna	12-12-2007	Slope	10 x 10	Covering, surface for geoelectr. measurement
Filborna	12-12-2007	Slope	10 x 10	Covering, surface for geoelectr. measurement

Surfaces with mostly low emission of methane

Surfaces and installations with risk of high emission

Surfaces with risk of partially high emission

The slope surfaces at Löt and Forsbacka were considered to be at greater risk than the surfaces at F2 and F1. At Filborna, repeated measurements were carried out on the same slope surface in December 2007 together with the geoelectricity measurements.

All sites where the chamber method was used were also investigated with the laser instrument, and a figure for the methane concentration in the air above the measuring point was recorded. At all sites, the laser instrument was held approximately 0.3 m from the surface. When measurements were recorded, extreme values were excluded. If a relatively constant value was obtained, this was recorded. If there were variations, an interval was recorded that was later used for simple calculations of means.

If the pairs of values for flow according to the chamber method and concentration according to the laser instrument, for all sites regardless of the landfill and the nature of the site, are plotted on the same graph, a pattern is shown like that in Figure 13.6. (All measurement results, see Appendix 7). Four of the points come from the same surface (the geoelectricity surface). On this surface, measurements were taken with the chamber method and the laser instrument at the same points for three days (see Table 13.3).

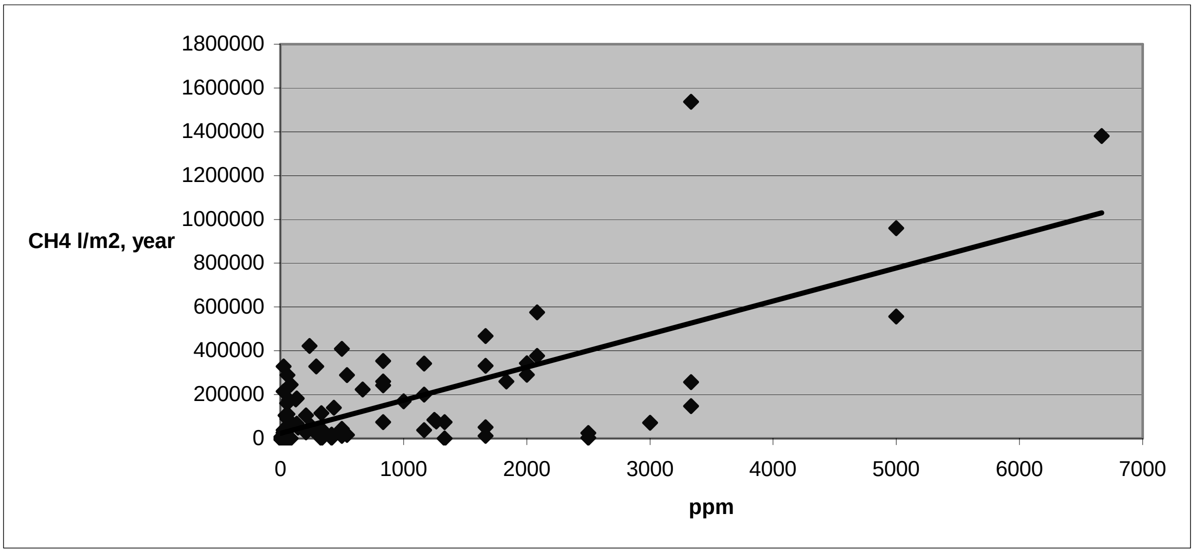


Figure 13.6. All pairs of values, methane flow from chamber method measurement, methane concentrations from laser instrument. A trend line has been inserted in the diagram.

Figure 13.6 shows a clear relationship between data from the chamber method and the laser measurements. The number of pairs of values is small, but it was not possible to carry out more measurements in the project. The measurements that were taken may be taken as a good indication that the chamber method can be used to calibrate the laser instrument, and obtain flow readings from point source emissions measured with the laser instrument. The distribution of the pairs of values is caused by several factors. The most important were:

- Wind that affects the concentration readings;
- Import of airborne methane from other parts of the landfill;
- Time lag between the laser measurement and the chamber method measurement.

According to the approach shown in Table 13.3, different zones should give rise to different degrees of methane emission that stem from the release of biogas from inside the landfill. If an initial division is made so that all pairs of values from the top surfaces and slopes are divided according to the relative risk valuation in Table 13.3, a more accurate picture is obtained (see Section 13.5 and 13.6).

13.3 Top surfaces

Top surfaces were investigated with the chamber method in combination with laser measurement at all the landfills included in the study. However, these top surfaces have very different characteristics and very different emissions. This evaluation did not take into account the efficiency of gas recovery.

The results below are based on mean values of measurements made with the chamber method and the laser instrument within the chosen 100 m^2 surfaces.

Chamber method measurements were carried out on ten top surfaces, including the landfills in France. A more detailed description of the surfaces and conditions of measurements is shown in Table 13.4.

Table 13.4. Characteristics of the top surfaces investigated.

Landfill	**Type of cover**	**Temp. °C, 1 m**	**Wind speed m/s**	**Wind direction**	**Surface temp. °C**	**Moisture condit.**
Spillepeng, test cells, 31-5-2007	Thick earth cover (> 1 m, fissures at cell edges)	19.7	2.1	NNW	23.2	Dry
Spillepeng, older landfill, 31-5-2007	Earth cover 1.0 m thick	19.7	2.1	NNW	23.2	Dry
Filborna, final cover surface, 30-5-2007	Final cover in accordance with EU standard	21.2	2.4	NW	22.3	Dry
Hagby, test cell E-89	1.0 m peat, plastic sheet, earth masses	27.9	1.2	E	31.3	Very dry
Hagby, test cell E-90	Old final cover, earth and slurry 0.5-2.0 m	25.2	2.7	SE	29.6	Very dry
Löt, northern part	Interim cover, 1 m earth masses	21.7	2.7	SE	38.7	Dry
Forsbacka, cell surface	Interim cover 0.5-1.0 m	15.7	1.7	SW	30.5	Dry
French site 2, covered surface	Cover of clay earth	15	3	SW	15	Slightly damp
French site 1, southwest corner	Cover of clay earth	11.6	2.1	NW	10.9	Slightly damp
French site 1, bare surface at gas well	Cover of clay earth	9.6	3-4	W	10.7	Damp

The readings for methane concentration (ppm) varied greatly between the investigated top surfaces on the measurement occasions, as shown in Figure 13.7.

The chamber method measurements in the studies were carried out as described in Section 10. The laser measurements were carried out after the chamber method measurements by aiming the instrument at the ground from a distance of 0.3 m inside the sub-zone where the chamber measurements were taken. The pairs of values were produced by calculating the mean value for methane emission at the different sites, measured with the chamber method and the mean of measurements from the laser instrument at the same site.

It should be emphasised that the measurement results only applied at the time of measurement. A number of variables that affect methane emission can change quickly, which results in different concentrations measured by laser above the landfill surface and other flows in measurements with the chamber method.

There is a clear relationship between the flow measurements produced by the chamber method, and the recordings from the laser instrument. The correlation was good (R^2 = 0.91).

Emission of 25 000 l/m^2 per year, i.e. approximately 50 m^3/m^2 per year of landfill gas (50 % methane) is the equivalent of 0.5 Mm^3/ha per year of landfill gas. This scale of emission is perfectly reasonable in most cases, assuming that the recovery system is not optimised. The lower emissions probably indicated that the gas recovery system is better or that the waste is almost completely degraded.

The diagram also shows the characterisation of the surface, its cover. No conclusions can be drawn on the basis of this characterisation. However, it can be observed that surfaces over older waste generally show a lower emission of methane.

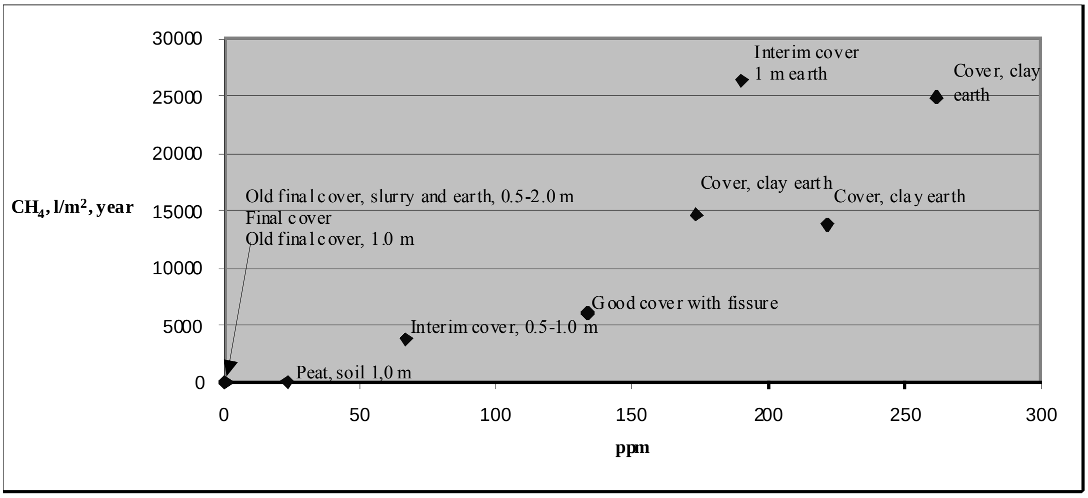


Figure 13.7. Methane emissions at the investigated top surfaces, summer 2007, converted to pairs of values for methane emissions recorded by the chamber method and the laser instrument respectively.

Two of the points deviate from the general trend, as can be seen in the diagram (Figure 13.7). A mean higher than the general trend for the measurements with the laser instrument was obtained at French site 2, which can be because the measurements were carried out close to active tipping faces with high emissions of methane. The background level at the site can therefore have raised the mean. There is also a pair of values where the mean recorded by the laser instrument is lower than the general trend, which may be because the site was very exposed to the wind (Löt). At the time of the measurements, the wind was not particularly strong, but wind exposure was at a maximum, at the highest part of the landfill.

13.4 Slopes and crests

In the same way as for top surfaces, slopes at five landfills were studied on seven sites. The properties of the slopes and the measurement conditions are shown in Table 13.5. The measurements with the laser instrument and the chamber method have been performed in accordance with the description in section 10. The results are based on mean values of measurements made with the chamber method and the laser instrument within the chosen 100 m^2 surfaces.

Table 13.5. Slope surfaces investigated

Landfill	**Type of cover**	**Temp. °C, 1 m**	**Wind speed m/s**	**Wind direction**	**Surface temp. °C**	**Moisture condit.**
Filborna, eastern slope, 1-6-2007	Cover with unspecified inorganic mass, 0.5-2.0 m	20	0.5-1.5	NW	20	Dry
Löt, northern part, 12-6-2007	Cover, inorganic mass, great variation in thickness	18.9	0.6	W	28.2	Dry
Forsbacka, slope in north, 13-6-2007	Cover, inorganic mass, great variation in thickness	16.7	1.4	SW	23.9	Dry
French site 2, covered slope	Good cover, earth mass	15	4	SW	17	Moist surface
French site 2, crest	Cover, but steep slope has thin cover in places	15	3	SW	16	Moist surface
French site 1, northern corner	Cover with inorganic mass, steep slope	11.7	3.4	NW	14.9	Dry
French site 1, crest against road	Cover with earth mass, fissures	13.4	2.7	E	12.0	Dry

A trend can also be seen for slopes, i.e. higher means in terms of emission measured with the chamber method gives higher means with the laser instrument. The correlation can be seen in Figure 13.8.

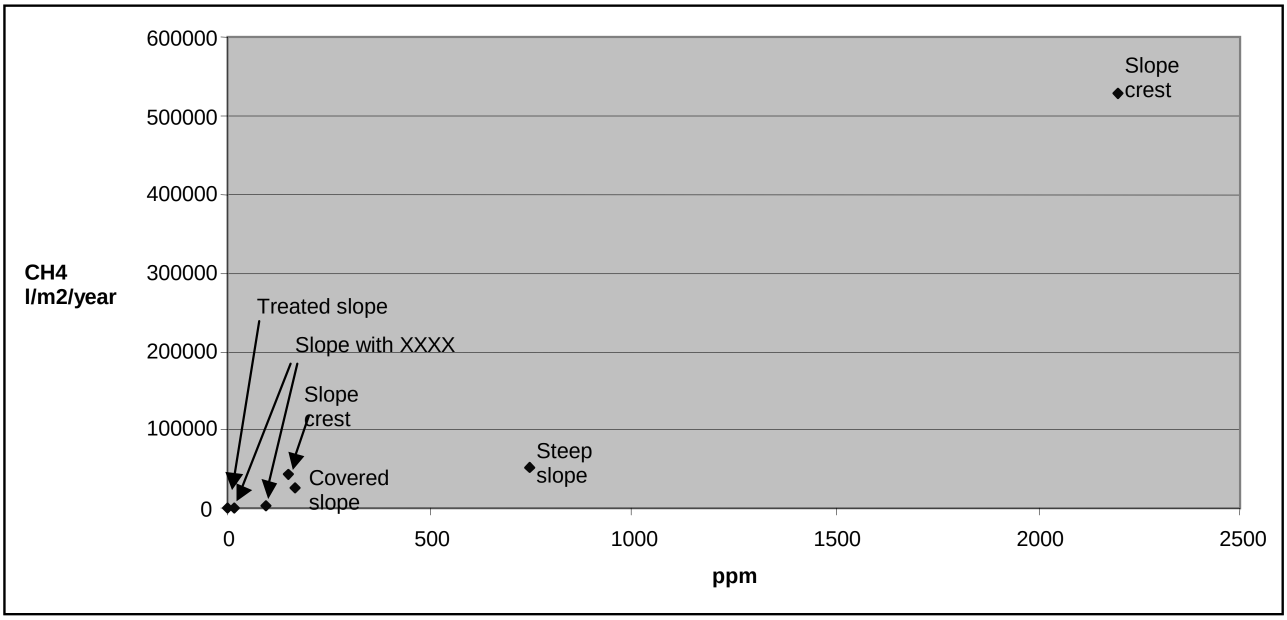


Figure 13.8. Pairs of values created from test surfaces on slopes and crests.

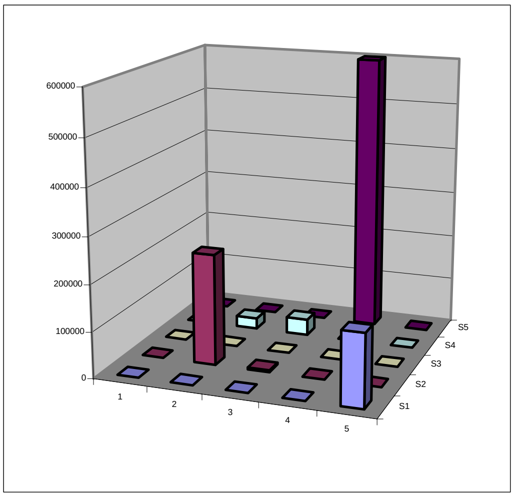
As can be seen in diagram 13.8 there is a clear relationship between the measurements with the laser instrument and the flow determinations produced by the chamber method. The pairs of values shown in the diagram show good correlation (R^2 = 0.97).

Two test surfaces consisted of crests, i.e. the transition between slope and top surface. At one of these, point source emission was measured directly using the laser instrument and the chamber method, and pairs of values were obtained. The site can be seen as an example of an area where frequent point source emission occurs, and one that forms a representative surface for crests with poor covering. This surface has been included in the diagram, along with another test surface that also comprised a crest, but with lower emission levels.

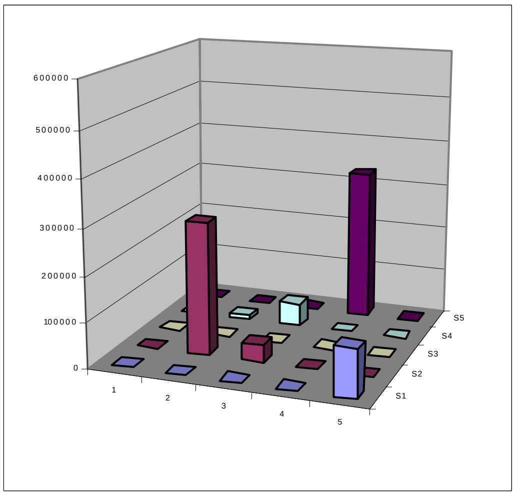
Review of the data from chamber method measurements showed that slopes give higher emission per surface unit than top surfaces. This is also confirmed by the results from surface scanning and from detection of point source emission.

13.5 Sample surfaces on slopes, repeated measurements

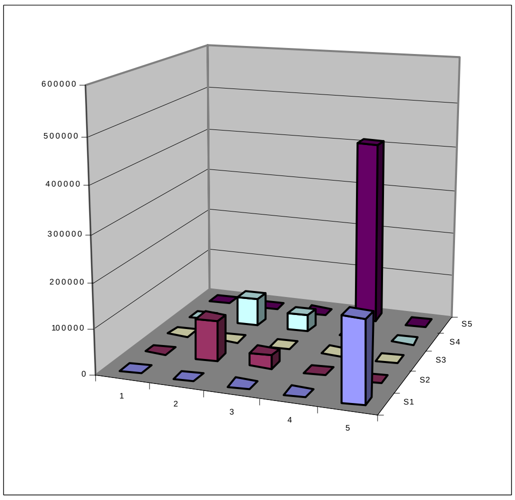
In conjunction with the resistivity measurements, five measurements were taken with the chamber method on a slope at Filborna in December 2007. The results are significant for interpreting the geoelectricity measurements, and are shown in Figure 13.9 in the form of bar graphs. The measurements were taken on a square surface, 10 x 10 m.



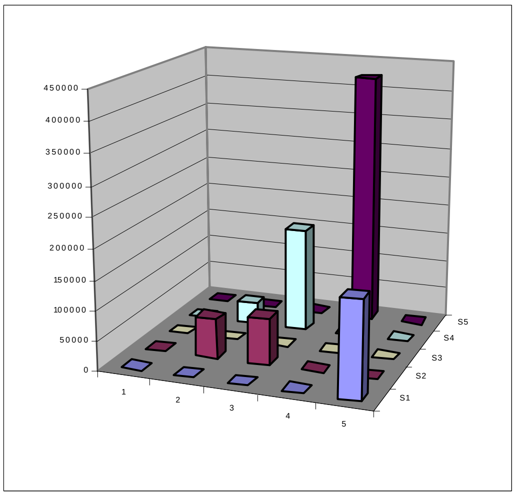
4 Dec 2007, 12:22, 1002 hPa, rising



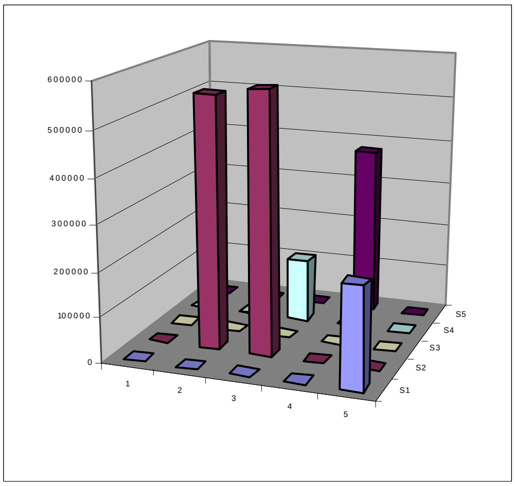
4 Dec 2007 16:20, 1006 hPa, rising



5 Dec 2007, 12:55, 1005 hPa, falling



5 Dec 2007, 15:30, 1004 hPa, falling



12 Dec 2007, 10:30, 1020 hPa, rising

Figure 13.9. Results from chamber method measurements on a 10 x 10 m surface. Emission of methane for the different sub-zones at different times, l/m^2 per year.

The results from the chamber method measurements on the ‘geoelectricity surface’ showed that:

- Each sub-zone can show emission that is virtually zero, and a week later give the highest reading of all, indicating that emission can vary greatly over time.
- Another sub-zone may show constant emission figures all the time, even though the point is only 5-6 m from the other measuring point that showed such great variation.
- The first four measurements each gave a mean figure in the interval 32 032 – 44 152 l/m^2 per year, while the measurement taken a week later gave a mean figure of 74 936 l/m^2 per year, i.e. virtually double the emission. On this later measuring occasion, the air pressure was higher than for the first four measurements (1006 hPa 5th December 2007, 1037 hPa 12th December 2007).

The large variation in both time and space raises doubts about the suitability of using the chamber method on landfills, which is also supported by the results from other studies (Börjesson et al, 2000). A method that can measure the flow directly over the surface is necessary in order to attain sufficient reliability. One problem remains: if the flow can successfully be measured quickly on a surface, how can the individual value at a point be interpreted, and also how many measurements are needed to give a reliable figure usable for a calculation of methane flow on a yearly basis?

13.6 Conversion of combined results from laser and chamber method measurements to emission calculations

The measurements with the laser instrument were carried out on the sub-zones where the chamber was placed for flow measurements, so the real pairs of values involve very small landfill areas. Furthermore, they represent the emissions where the laser instrument recorded a leakage, and a low emission (less than 0.1 l/min at a point source emission) was only detected using the chamber method when the laser instrument showed zero.

Point source emission
The methane emission from landfill surfaces can be divided up into point source leakage and diffuse emission from the different parts of a landfill. By combining the laser measurements and the measurements using the chamber method, the total size of the point source emission can be calculated. The examples of complete measurements of landfills comprise principally the landfills in France. Point source emissions at French sites 1 and 2 were 102 and 75 respectively.

When calculating the total emission at the landfills, the following relationship was used:

CH_4 l/m^2 per year = 151.1 * ppm + 23 058

The relationship must be regarded as relatively unreliable as only a few measurements were taken. But it nevertheless shows that there is a relationship, and that this relationship could probably be made more reliable if a greater number of pairs of values were used.

If the above relationship is used on all point source emissions found at the French landfills, the landfill gas emissions are as shown in Table 13.6. The total emissions are from year 2005, it is estimated that the landfill areas in 2005 and the scanned areas in 2007 are approximately the same.

Table 13.6. Total emission from point source emission, and comparisons with previously estimated methane emission from the French landfills.

Landfill	Emission from point sources, detected and measured with the laser instrument (tons/year)	Emission of methane in tons/year (from Table 11.3)	Proportion of point source emissions in relation to total emission %
F1	41	331	12
F2	30	1 620	2

Methane leakage from landfill surfaces

The methane emissions from characteristic surfaces at each landfill can be used to estimate the total emission from a landfill. As above, the examples of the French sites were used for the calculations. In the calculations, the results from both these landfills were used as far as possible. The results of the calculations are shown in Table 13.7.

Table 13.7. Calculation of methane emission from surfaces, divided into characteristic sub-zones, for the French sites landfills.

Part of landfill	F1			F2		
	Area, ha	l/m^2 per year	Emission CH_4 m^3 per year	Area, ha	L/m^2 per year	Emission CH_4 m^3 per year
Top surface, old part of landfill, good cover, waste >10 years	9.1	0	0	5	0	0
Top surface, newer part of landfill, waste 5-10 years	5	14 000	700 000	2.3	14 000	322 000
Top surface, new part of landfill, waste < 5 years	0	0	0	1.2	26 000	312 000
Treated slope, old waste tip	1.8	0	0	2.5	0	0
Slope, newer part	0.3	200 000	600 000	2	26 000	520 000
Total:			1 300 000	13		1 154 000

French site 1

Emission from the landfill surfaces at F1 was calculated as 1 300 000 m^3 CH_4 per year, which is more than the figure given by SITA (466 000 m^3).

French site 2

The calculation according to Table 13.7 is lower than the figure given by SITA in 2005 (2 280 000 m^3 CH_4). Point source emission of 30 tons is to be added, which is small in relation to the emission from the landfill surfaces. Leakage from the active surface, which consists of two cells with fresh waste, is probably greater, but measurements are lacking that could give more reliable figures. At F2 there were also a number of points with very large amounts of leakage from landfill gas installations whose flow could not be determined.

It can be argued that the calculations are based on insufficient figures from the chamber method. The important thing is that a division is carried out in the way shown in Table 13.7 where the zones are given and specific emission can then be assumed. It is the measurements with the laser instrument that form the basis of the surface division.

14 RESISTIVITY MEASUREMENTS COMBINED WITH LASER AND STATIC CHAMBER MEASUREMENTS FOR DETECTION OF LANDFILL GAS MIGRATION

14.1 Background and objectives

Geoelectrical imaging techniques are considered to have several applications in connection with waste management facilities, in particular groundwater contamination around landfills. Leakage from municipal and mining waste deposits is generally associated with high ion concentrations and hence very low resistivities and therefore, geoelectrical imaging techniques particularly interesting for leachate migration at landfills.

Furthermore, the use of geoelectrical imaging techniques is an established practice for environmental investigations and monitoring of various landfill processes (e.g., Bernstone and Dahlin, 1997, Rosqvist et al, 2003, Cardelli and Di Filippo, 2004), and in recent years also the internal processes in landfills have been emphasised (Guerin et al, 2004, Moreau, et al., 2004, Rosqvist et al, 2005, Rosqvist et al, 2007). In these studies, the emphasis was on the use of electrical resistivity technique for changes in moisture content, but also other processes including, for example gas migration, temperature and ionic content was studied.

The main objective in this study was to investigate the possibility to use resistivity for detection of gas migration. To develop the technique, a three dimensional (3D) experimental set up was used. 3D-measurements provide an opportunity to develop a better understanding for the subsurface three dimensional conditions, since the results are influenced by the volume of the porous media. Previous investigations have relayed on two dimensional (2D) measurements, which is enough if the sub surface structure can be estimated to be homogenous in a direction perpendicular to the direction of the measurements. However, solid waste landfills are highly heterogeneous formations and therefore 3D-investigations are more appropriate. In recent years the development of the 3D-technique has made it possible to perform 3D-investigations in the filed.

An additional objective was to investigate the possibilities to compare and correlate the resistivity measurements with gas measurements above the surface using laser technique and the static chamber method.

14.2 *Materials and methods*

14.2.1 The area for the field experiments

The resistivity measurements were carried out in an area where a bioreactor landfill is connected to the slope of a large landfill (see Figure 14.1 and 14.2). In the bioreactor landfill the waste has a high organic content leading to high production of landfill gas (LFG). To provide good conditions for the measurements a field plot was chosen based on the experience that the gas was leaking through the soil cover in the area. Odour observation and measurements with a laser instrument had clearly indicated a high gas leakage through the soil cover.

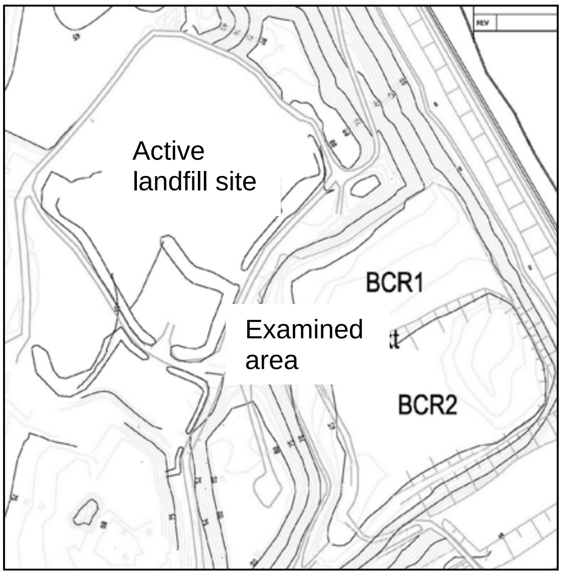


Figure 14.1. Location of the area for the field experiments

The resistivity measurements were carried out in an area, 10 by 10 metre, where the bioreactor landfill is connected to the slope of a large landfill (Fig. 14.2). The measurements were performed at eleven parallel lines with a distance of one meter, see Figure 14.3 and 14.4.

Figure 14.2. The area for the field experiments. The yellow stripes show the location of the eleven lines where the resistivity measurements were performed.

Figure. 14.3. The area for field experiments showing the resistivity set up and some static chambers. Line A is to the right (compare with figure 14.4).

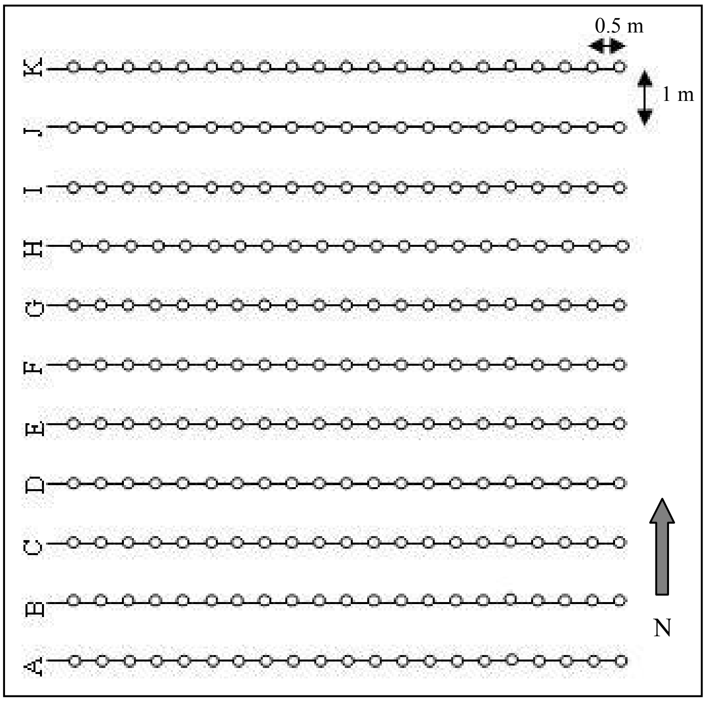


Figure. 14.4. A sketch showing the lines A to K and the 231 electrodes. N stand for north.

14.2.2 Equipment

The equipment used for the investigation was the ABEM Lund Imagine system, which consists of instrument Terraohm RIP24 version 2, ABEM Booster SAS 2000, Electrode Selector ES10-64, electrodes (Ø4 mm) together with multiple connection devices, batteries and cables see figure 14.5, 14.6 and 14.7.

Figure 14.5 och 14.6. Cables and electrodes, passes the electricity through the soil.

Each resistivity measurement makes use of two current electrodes to inject current into the ground and of at least two other (potential) electrodes between which a potential difference is measured. A system of relays controlled by a computer program selects the electrodes to be used. The geometrical array for the electrodes we have used here is the pole-dipole array in order to get better depth of investigation even with small electrode spacing (Dahlin and Zhou, 2004). Once the system is in place the whole measurement procedure is atomised. The data are copied to a file and stored until they are finally processed.

14.2.3 Measurements

The geophysical investigation was carried out during four days, between the 3rd-5th of December and 12th of December 2007 by Tyréns AB.

Each line consisted of 21 electrodes with a distance of 0,5 meter, resulting in a total of 231 electrodes in the experimental setup (Fig 14.4). To secure the position of the electrodes, all of the electrodes were installed before the measurements started, and thus, during the measurements only the cables and the instruments needed to be moved. The time required for measurements in one line was twenty to thirty minutes, and thus, to measure all eleven lines took approximately five to six hours. This means that a 3D image can be used to give an overall picture of the underground but does not represent an instantaneous geometry. Only the 2D time-lapse inverted lines should be used when looking at temporal changes.

Each sequence of measurement included measurements from line A to line K. All together seven sequences of measurements were carried out (Table 14.1). Each sequence of measurement started in line A and continued to line K. The time to complete each of the sequences of measurements was approximately five hours. Date and time for start and end of each sequence of measurement are shown in table 14.1. Exact information for each of the separate lines are shown in appendices 8, 9 and 10.

Table 14.1. Date, starting time, end of measurement for each of the seven measurements.

Date	Sequence of measurement	Starting time	End of measurement
03/12/2007	1	11:00	17:00
04/12/2007	2	08:00	13:00
04/12/2007	3	14:00	18:00
05/12/2007	4	08:15	13:30
05/12/2007	5	14:00	18:00
12/12/2007	6	08:15	12:45
12/12/2007	7	14:00	17:15

Altogether 79 separate measurements, designated after line number and part, were carried out (Table 14.2). Of the 79 measurements, 77 follow the scheme above. Another two measurements were carried out on line I, directly after the end of the first measurement. This was done in order to observe differences in resistivity on short time interval. The results from these measurements are not shown in this report.

Table 14.2. Name of measurements.

Line / Series	A	B	C	D	E	F	G	H	I	J	K
1	A1	B1	C1	D1	E1	F1	G1	H1	I1	J1	K1
2	A2	B2	C2	D2	E2	F2	G2	H2	I2	J2	K2
3	A3	B3	C3	D3	E3	F3	G3	H3	I3	J3	K3
4	A4	B4	C4	D4	E4	F4	G4	H4	I4	J4	K4
5	A5	B5	C5	D5	E5	F5	G5	H5	I5	J5	K5
6	A6	B6	C6	D6	E6	F6	G6	H6	I6	J6	K6
7	A7	B7	C7	D7	E7	F7	G7	H7	I7	J7	K7

The points have been fixed within the local system of co-ordinates for the city of Helsingborg. All co-ordinates are shown in appendix 2.

14.2.4 3D Invers modellering

The measured resistivity data are so-called apparent resistivity: each apparent resistivity value is determined by the true resistivity distribution in a volume around the electrodes. It cannot, for that reason, be considered as a local property. The apparent resistivity must be processed numerically in order to obtain a good picture of the geometrical distribution of resistivity in the ground. That kind of processing is called inverse modelling. Computing the data that can be expected to be measured in a known environment with a known signal source is called direct modelling. Inverse modelling is the reverse procedure: it aims at retrieving the source or some physical property in the medium from the actual measurements.

We have processed our data in two slightly different ways:

- First, all the results for all the lines have been processed together to obtain a 3D model of the resistivity in the ground at a given time. (3D inverse modelling with Res3Dinv)
- Then, each line has been processed separately, but taking into account measurements acquired at successive time steps (2D time-lapse inversion with Res2Dinv)

Res3Dinv and Res2Dinv are both commercial programs written by M.H. Loke (de Groot-Hedlin and Constable, 1990, Loke and Barker, 1996) and they are built following about the same principle (smoothness constrained least-squares method). They aim at minimizing the difference between the measured and the computed data. A start model is first defined from the data, and it is iteratively altered until the agreement between the measured and the computed data is satisfying. We have used the so-called L1-norm, which means that we have tried to minimize the sum of the absolute differences for all individual measurements. This way of minimizing the discrepancies between measured and calculated data is also called robust inversion, since it is less sensitive to large disturbances affecting a small amount of data.

To compute the apparent resistivity the ground is divided in a number of cells with a given resistivity value in a finite-element model. The smallest cells are close to the ground surface, since the resolution is better and the actual resistivity is better defined there, close to the electrodes. They also follow the ground topography and their shapes account for it. The size of the cells increases at depth. In 3D modelling the cells have finite dimensions, whereas in 2D modelling their length is infinite in the direction perpendicular to the measurement line. To compare data measured at different times one uses time-lapse modelling and ensures in that way that measured changes in apparent resistivity are interpreted as changes relatively to the first time step.

A large number of computations is involved for the inverse modelling, especially when processing 3D data sets, but it is still possible to perform them on an ordinary modern computer. Several methods and programs exist that can be used for the inverse modelling of resistivity data. We have used the most well-known and well-validated program.

Documentation on resistivity imaging techniques and inverse modelling of resistivity data available at www.geoelectrical.com.

14.3 Results of resistivity measurements

In this section results of the resistivity measurements are presented as absolute resistivity values, i.e., ohmmeter (Ωm), and as changes in resistivity with time (time lap inversion). Furthermore, the resistivity results are compared with results of laser and static chamber measurements performed at the same time as the resistivity measurements.

The fieldwork was performed under good conditions resulting in high quality field data in all seven measurements, showing a fairly consistent picture of the sub-surface formation. The number of electrodes was sufficient in order to get a reliable interpretation of the data to a depth of a few meters.

14.3.1 Resistivity – absolute values

In Figure 13.7 one result section from one of the seven sequences of 3D measurements are shown as 2D-sections. The section in the upper left corner (No. 1) represent a volume parallell to line K, and the section in the lower right corner (No. 20) a volume parallel to line A. The location of the lines are shown in Figure 14.4.

In the upper two meter of the ground, the resistivity was shown to be in the range from approximately 10 to 50 Ωm in large areas. This is in the same range (Guérin et al., 2004) or somewhat lower (Bernstone and Dahlin, 1997), than results presented elsewhere. High water content and ionic content, and high organic content in the waste can partly explain the relatively low resistivity values.

Also zones of much higher resistivity were registered during the measurements. The high gas content may explain high resistivity values, however, for example the temperature may also influence the outcome of the measurements (Guérin et al., 2004). In almost all of the result sections a zone of high resistivity, over 300 Ωm, is shown at the foot of the slope, see Figure 14.7. It is suggested that he high resistivity values in the zone at the foot of the slope is due to gas migration. The bioreactor landfill is connected to the large old landfill at the foot of the slope and the high zone of resistivity is interpreted as gas migration from the bioreactor landfill towards the slope. At the top of the bioreactor landfill there is a plastic liner, which forces the gas in the upper layer of the landfill to move horizontally, resulting in high gas pressure at toe of the slope. This phenomenon, located in the same area of the bioreactor landfill, has also been observed in previous measurements (Rosqvist, et al., 2007).

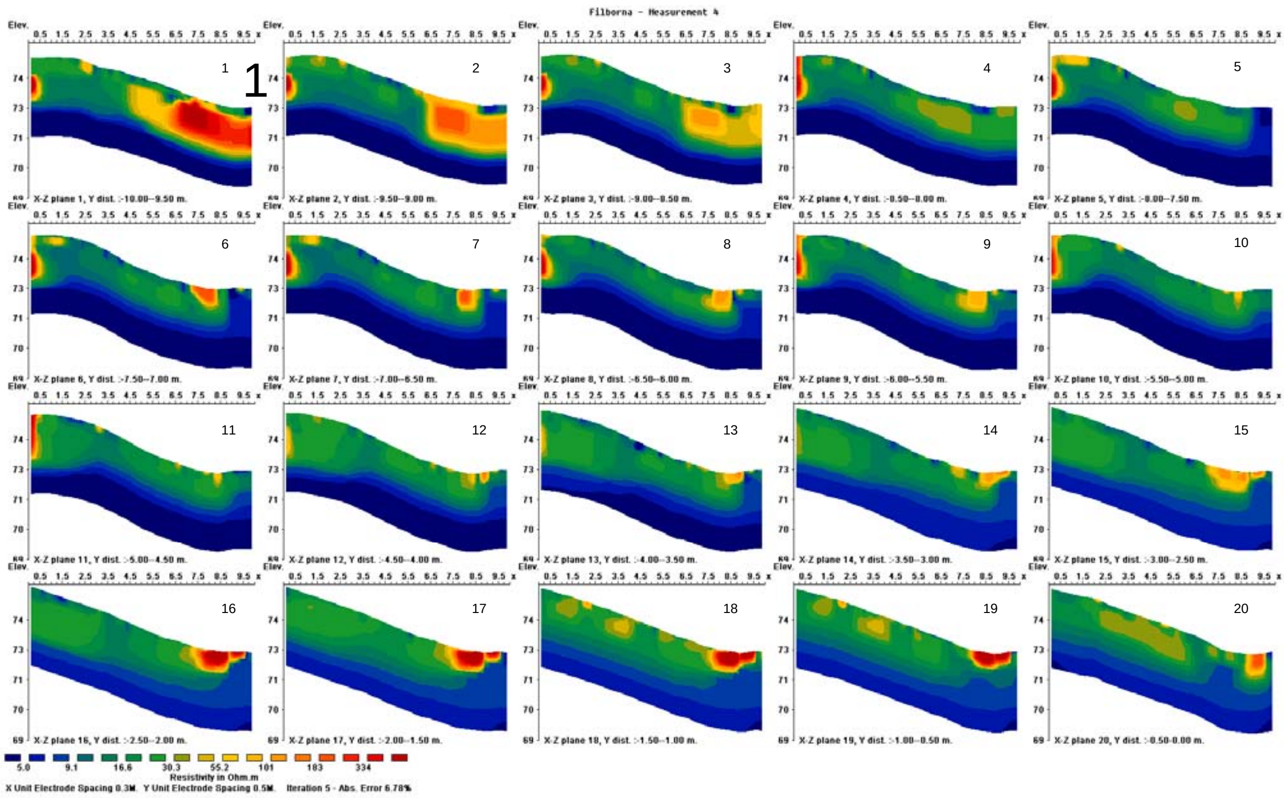
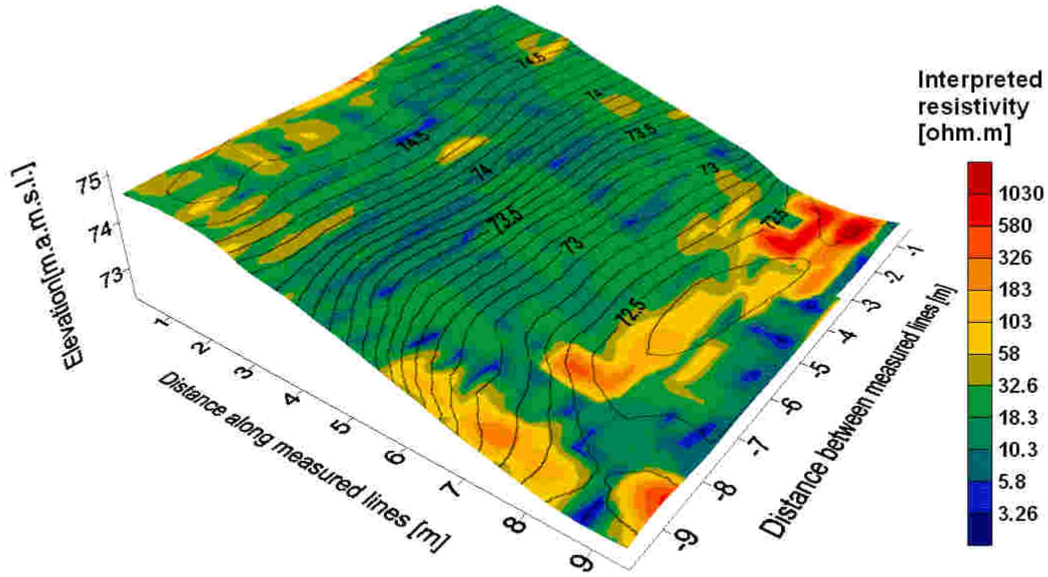
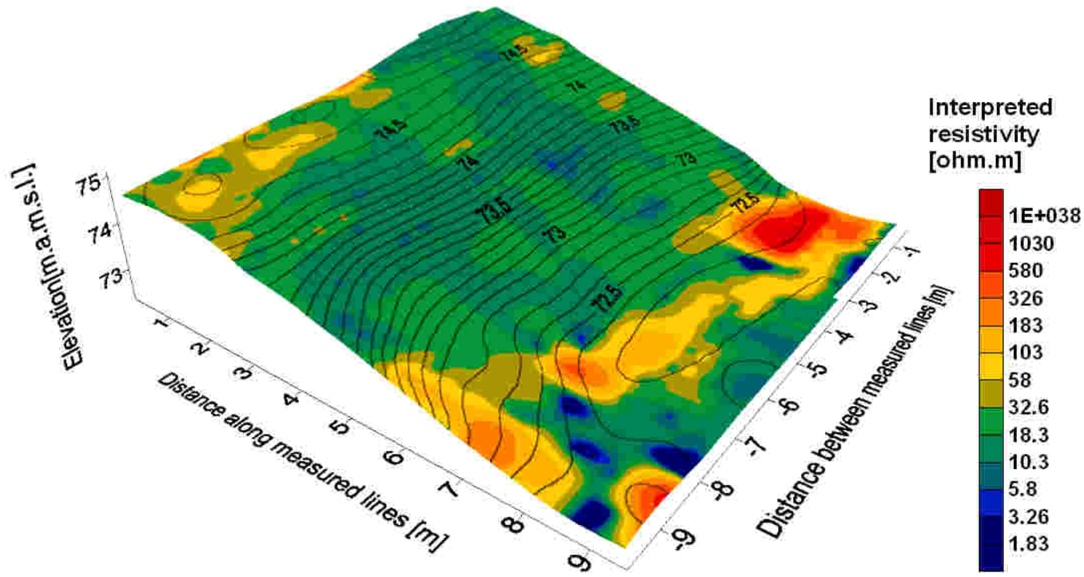


Figure 14.7. Results of the 3D resistivity measurements performed 03/12/2007, shown as 2D-sections. Section 1, upper left corner, represent a volume parallel with line K, and section 20, lower right corner) a volume parallel with line A (see also Figure 14.4.).



Interpreted resistivity for the first time step in the first layer



Interpreted resistivity for the first time step in the second layer

Figure 14.8. Results of the 3D resistivity measurements performed 03/12/2007, shown as 2D-layers, showing the uppermost layer (layer one) and the second layer.

Figure 14.8. shows results as near surface layers based on data from measurements performed 03/12/2007, where each of the layers represents a volume parallel with the topography. In Figure 14.8, the top represents the uppermost layer and the bottom the second layer. The results shown in Figure 14.8. represent the same sequence of measurements (the same data set) as shown in Figure 14.7. In Figure 14.8, the spatial distribution of the high resistivity zone (over 300 Ωm) at the foot of the slope is of particular interest. These high resistivity zones at the foot of the slope are possibly indicating zones where gas is moving in the uppermost layer of the soil cover.

14.3.2 Resistivity – relative changes (time lapse inversion)

To exemplify relative differences in resistivity during the measurements (time lapse inversion), results from line J are shown in Figure 14.9. The time lap inversions provide information about the changes of resistivity with time, for measurements performed along the same line. In Figure 14.9, relative changes between the first measurement, and the three following measurements at line J, are shown. All measurements along all of the lines showed similar changes in resistivity, which indicate the data to be reliable and that the data provides a good basis for interpretation of sub-surface processes.

In Figure 14.9. large changes in resistivity are shown in the sections, in particular at the foot of the slope where considerable increases and decreases were recorded. Since the changes took place within only a few hours, it was shown to be fast processes in the sub-surface. It is suggested that the fast changes in resistivity are mainly due to changes in gas pressure in the soil and thus indicating gas migration, in particular in the zone at the foot of the slope. Both the increase and decrease shown in the sections are mainly attributed to the gas migration. However, also water migration, temperature and other factors may influence the resistivity.

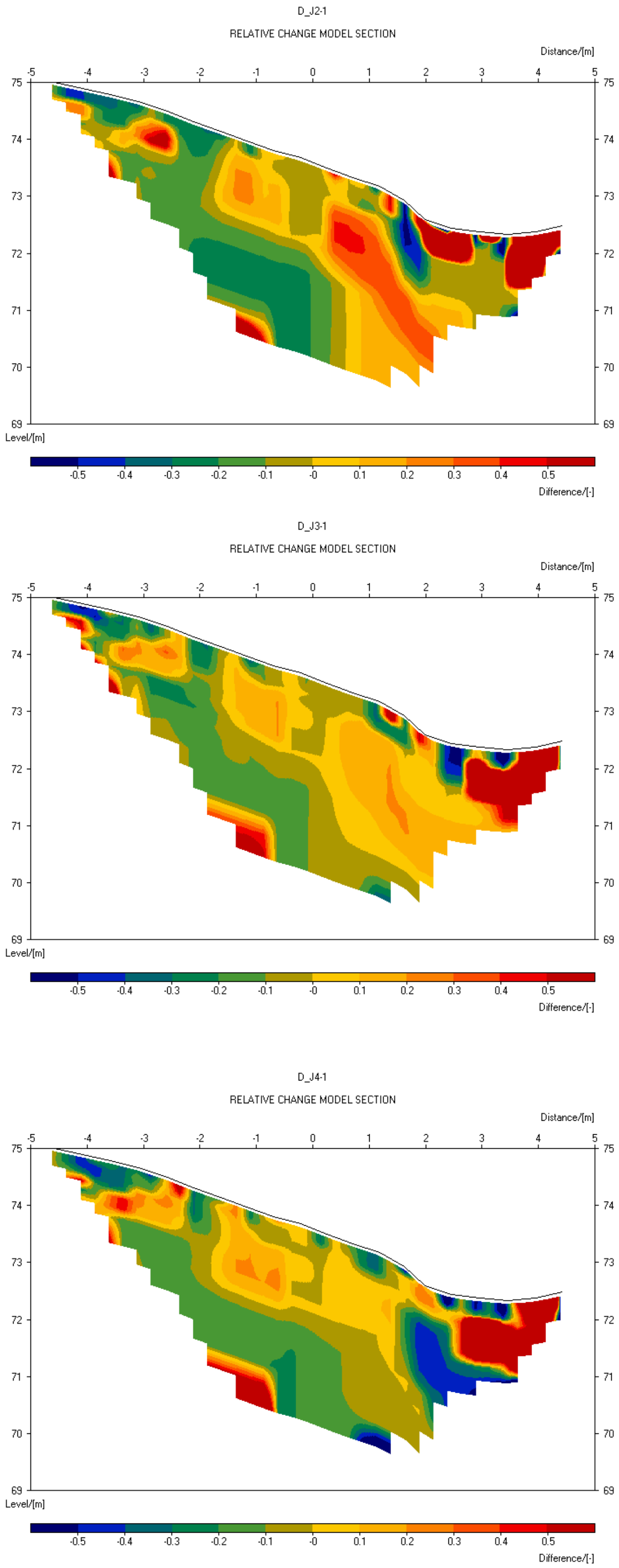


Figure 14.9. Results of time lap inversion for the first four resistivity measurements performed at line J. The measurements were performed in 03/12/2007 and 04/12/2007. See also Table 14.5.

14.3.3 Comparison of laser, static chamber and resistivity measurements

As described above, the size of the experimental plot measured ten by ten meter. The laser measurements were performed in 25 squares, each measuring two by two meter. In each of the squares a mean value of the measurements were estimate as the measurements were performed. At the same time as the laser measurements were performed, also static chambers measurements were carried out. The simultaneous laser and static chamber measurements were performed at five occasions, namely;

- 2007/12/04 morning
- 2007/12/04 afternoon
- 2007/12/05 morning
- 2007/12/05 afternoon
- 2007/12/12 afternoon.

Altogether six static chambers were installed in the field plot. The static chambers were randomly located in the 25 sub-plots measuring two by two meter. In Figure 14.10. the location of the six chambers (A-F) is shown.

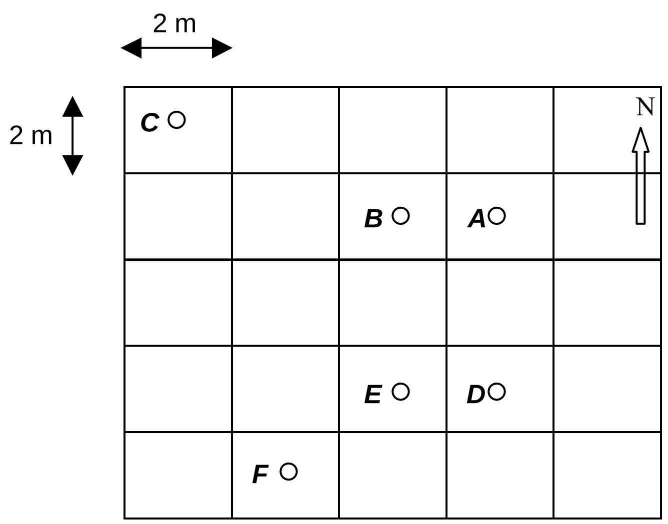
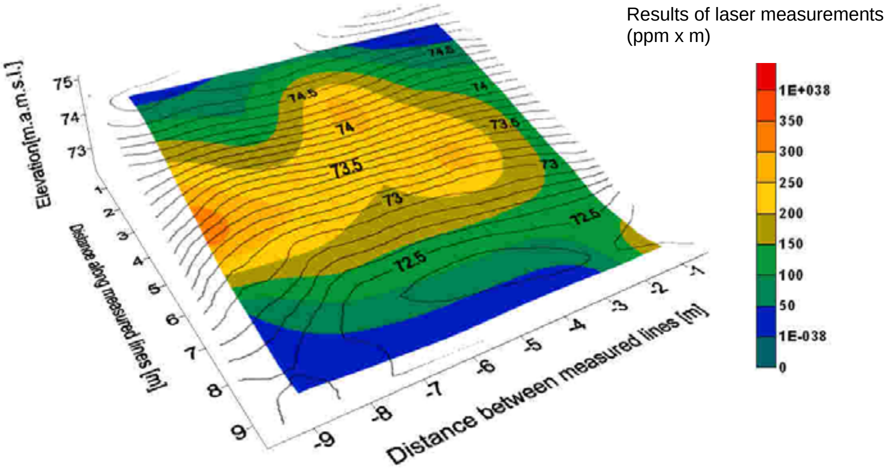
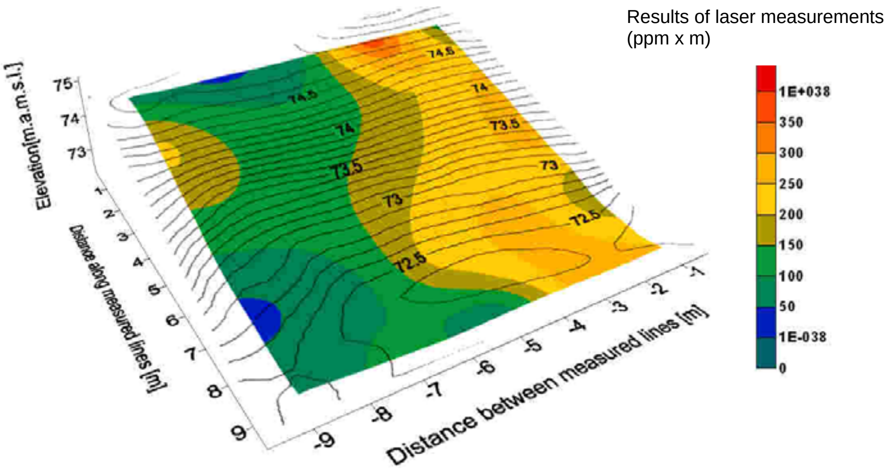


Figure 14.10: A sketch of 25 squares (two by two meter), and the location of six static chambers (A-F).

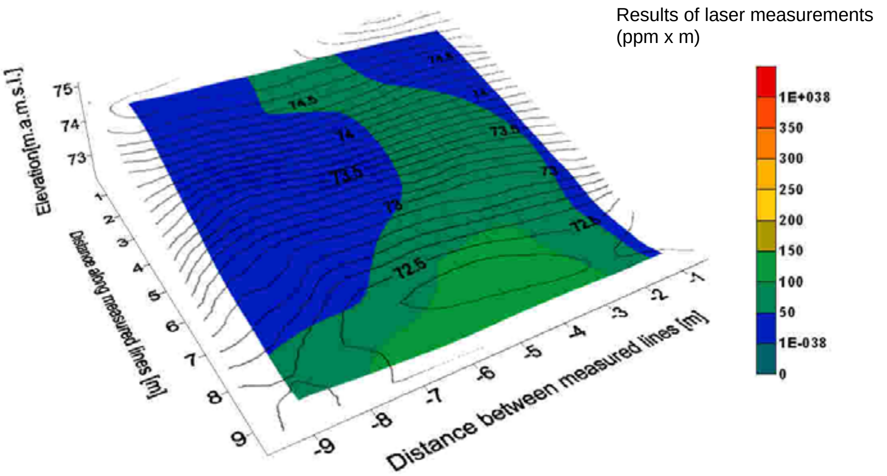
In Figure 14.11. the outcome of the laser measurements are shown as interpolation of the mean values in each of the 25 plots. The numbers in the three dimensional illustration in Figure 14.11. show the topography at the field plot, i.e., 72,5 to 74,5 meter above see level. The results varies between very low value, up to approximately 300-350 ppm x m. No clear pattern or correlation between measurements can be noticed in Figure 14.11. Moreover, no obvious correlation with the pattern showed in the resistivity results can be noticed. Thus, the laser measurements did not indicate a gas migration at the foot of the slope, in the same way as the resistivity measurements did.



Interpolated mean values of laser measurement from the 4 of December 2007



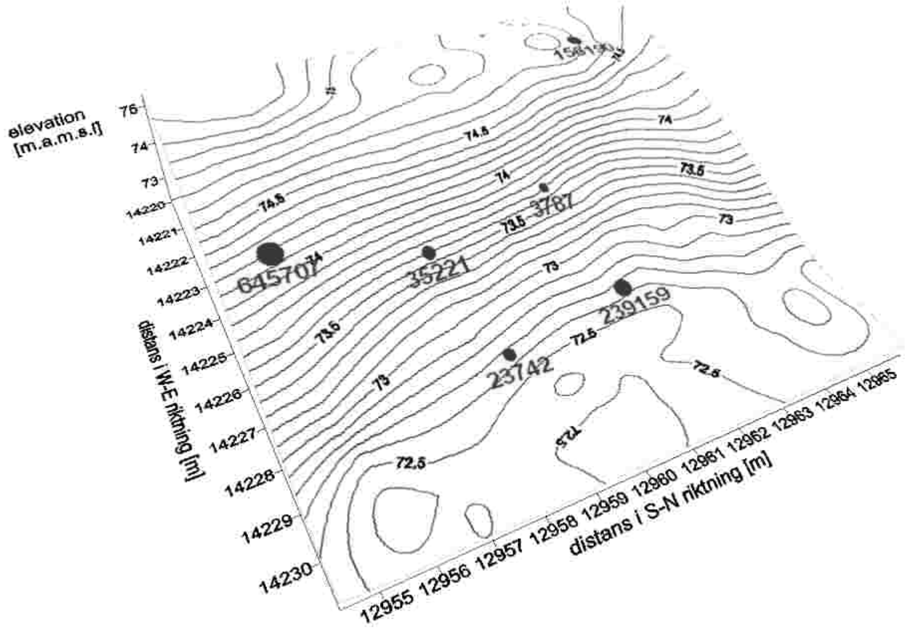
Interpolated mean values of laser measurement from the 5 of December 2007



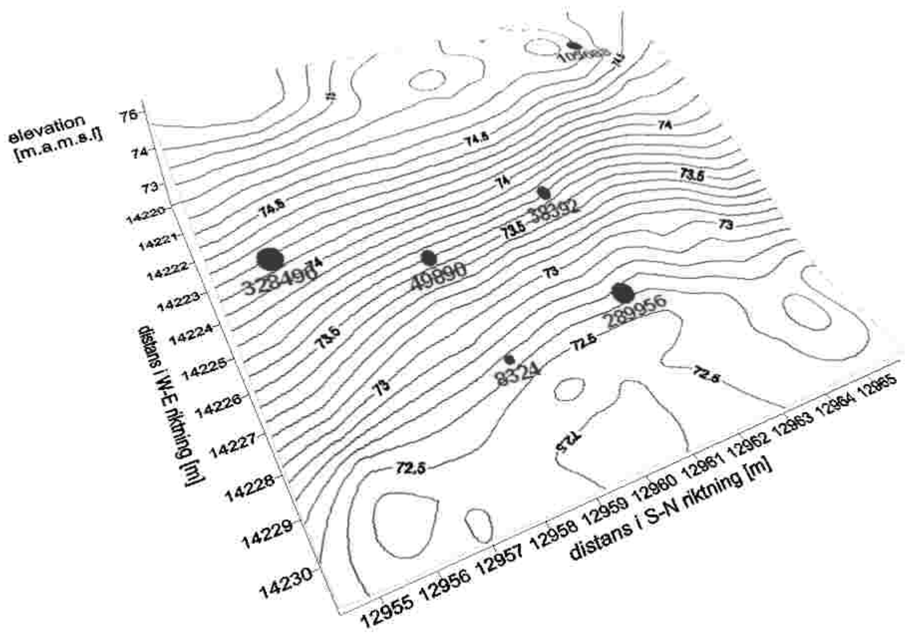
Interpolated mean values of laser measurement from the 5 of December 2007

Figure 14.11. Laser measurements performed on December 4, 5 and 12. Mean values for measurements in 25 squares.

To exemplify the results of the static chamber measurements the results from the measurements on December 4 are shown in Figure 14.12. The sizes of the ”dots” are proportional to the measured gas flow, and the numbers next to the dots are the measured flow. In Figure 14.12. and in Tables 14.3. and 14.4. the correlation between the measurements are presented.



Results from the chamber measurements – 4 December 2007 at 12:22 pm [l/m2/year]



Results from the chamber measurements – 4 December 2007 at 16:00 pm [l/m2/year]

Figure 14.12. Static chamber measurements on 04/12/2007, performed at 12.22 and 16.00. The sizes of the ”dots” are proportional to the measured gas flow, and the numbers next to the dots are the measured flow.

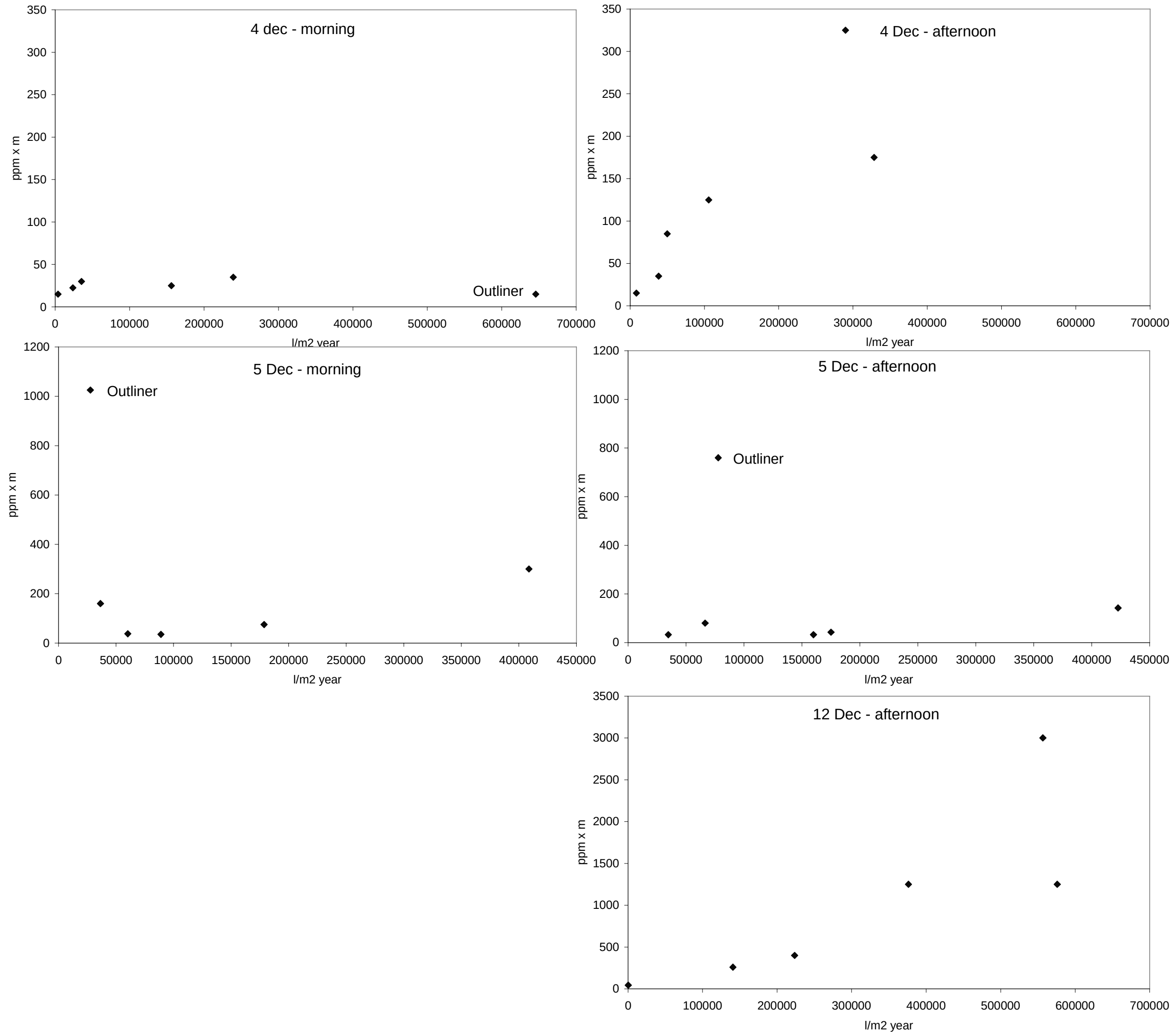


Figure 14.13. Correlation between measurements with the laser and static chambers for the five measurements. Note the different scales.

Correlations between measurements with the laser and static chambers for the five measurements are shown in Figure 14.13. The plots in Figure 14.13. have different scales for different days, however, data representing measurements at the same day are presented using the same scale. As shown in Figure 14.13, some correlation between laser and static chamber measurements are indicated in the results. Also correlation between measurements performed the same day, morning and afternoon, is indicated in Figure 14.13.

In Table 14.3 correlation coefficients are shown. The results of the measurements with laser and static chamber show high variation in correlation coefficient, between- 0.27 and 0.85 (Table 14.3). In three of the data sets (Dec 4 morning, Dec 5 morning and Dec 5 afternoon) one measurement is highly different from the trend in the data set resulting in low, and negative, correlation coefficient. These measurements have been termed *outliner* in Figure 14.4. When the outliners were removed from the data sets, the correlation coefficient were higher and more consistent, varying between 0.72 and 0.79 (Table 14.3).

Table 14.3. Correlation coefficients between laser and static chamber for five measurements, and correlation coefficient for the same data set when outliners have been removed from the data set.

		Correlation coefficient	Correlation coefficient when one outliner has been removed
2007/12/04	Morning	- 0.27	0.72
2007/12/04	Afternoon	0.85	No outliner
2007/12/05	Morning	-0.15	0.78
2007/12/05	Afternoon	-0.16	0.79
2007/12/12	Afternoon	0.83	No outliner

Measurements performed at the same day, morning and afternoon, showed relatively high correlation, with correlation coefficient varying between 0.55 and 0.98 for the laser measurements and 0,89 and 0,90 for the static chamber measurements, respectively.

Table 14.4. Correlation between measurements carried out the same day, in the morning and afternoon.

	Static chamber (l/m^2 year)	Laser (ppm x m)
2007/12/04	0.89	0.55
2007/12/05	0.90	0.98

15 RESULTS OF THE MEASUREMENTS IN FRANCE

15.1 Description of measurements in France

Scanning, detection and quantification with the laser instrument were tested in full scale for entire landfills at two landfills in France, in this report named F1 and F2.

Overview data from the landfills is presented in Chapters 11 and in Appendix 5. The fieldwork was carried out in September 2007. The results were reported directly to SITA Environnement in field reports that included descriptions of the measurement, drawings that show where methane emissions were detected, and tables that describe the emission points in more detail. The drawings showed emissions that were detected from surfaces, and emissions stemming from gas recovery systems and fissures in the covering surface.

15.1.1 French site 1

Measurements at F1 were carried out on an area of 16.6 ha. This included three stages, two old zones filled with waste between 1975 and 1990 (13.5 ha) and and part of another that was filled between 1990 and 2005 (5.2 ha).

In addition to the studied section of the landfill, there is a new zone of approximately 1 ha where waste is currently being deposited.

At present 80 000 tons of waste are deposited annually. The proportion of household waste has decreased over the years, and currently comprises approximately 40 % of the waste deposited. The rest is industrial waste. In the first two stages, it has been estimated that 760 000 m^3 of waste was deposited. Between 1990 and 2005, approximately 675 000 tons of waste was deposited. Consequently, in the parts where the measurements were taken, there is 1.2-1.4 million tons of waste.

The entire 16.6 ha surface could be scanned in 18 hours, i.e. approximately 1 ha/hour. This time included scanning of a plastic surface with many holes and unsealed joints. This part of the scanning was very time consuming. The slope areas that took a long time to scan comprise a relatively small part of F1 landfill. The results of the scan are shown in Figure 15.1. A 2-D and a 3-D illustration were also produced (see Figure 15.2).

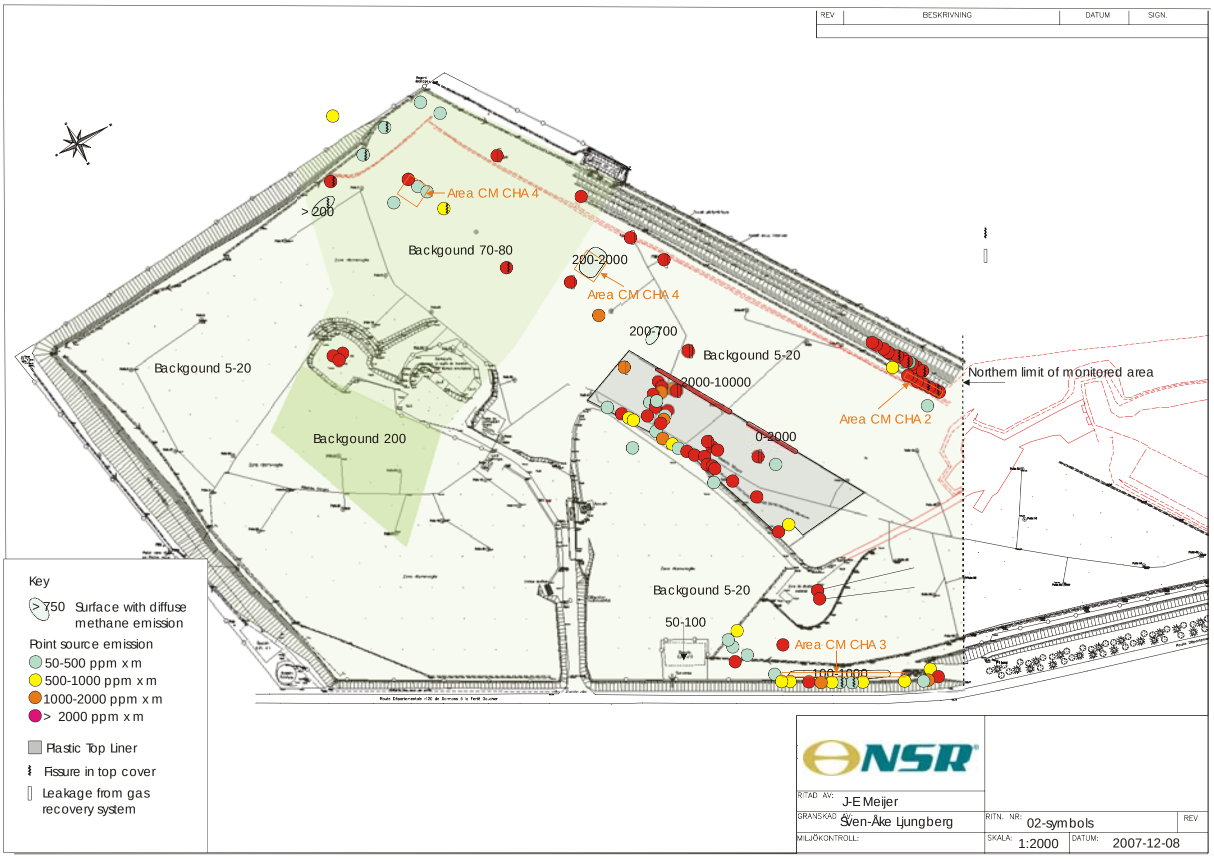
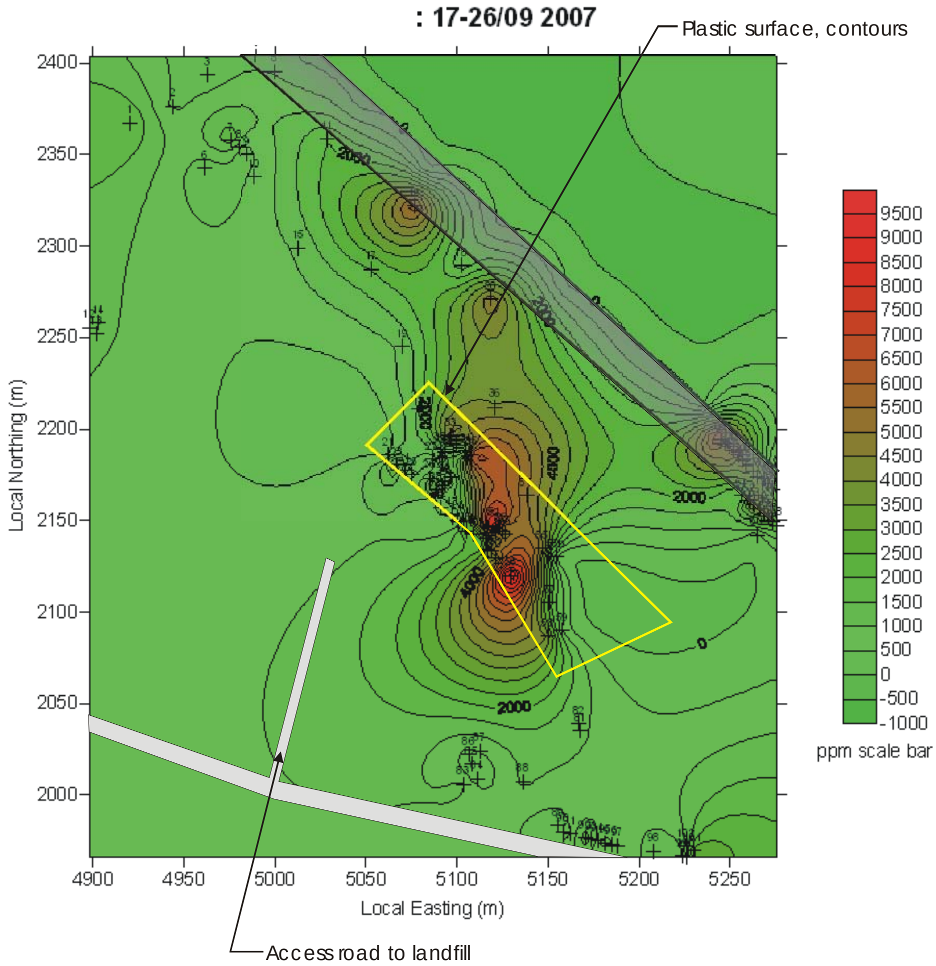


Figure 15.1. Results of scanning with the laser instrument, F1 landfill.



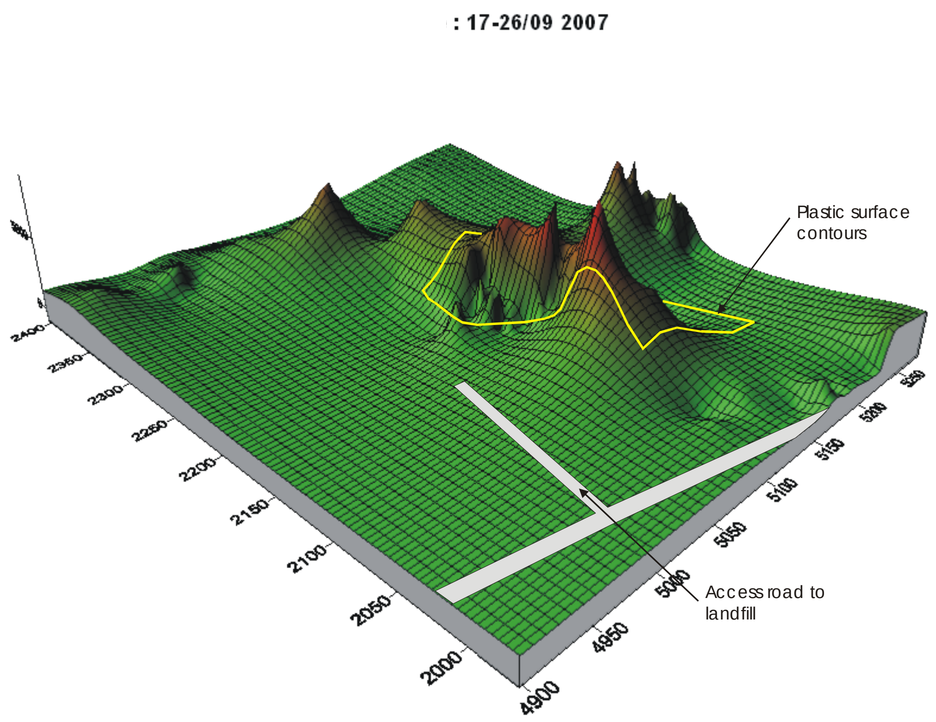


Figure 15.2. 2-D and 3-D illustrations showing distribution of concentration levels and leakage sites, F1

A total of 102 leakage points were found with the laser instrument, and five fields with diffuse emission. The points of emission are shown in Table 15.1.

Table 15.1. Distribution of leakage types, F1

Type of methane emission	Number	Comments
Point source emission, earth	48	
Holes in plastic sheet	25	
Leakage through edge or joint of plastic sheet	9	
Leakage in connection with gas wells	9	
Fissures in covering layer	5	
Leakage from fissures in concrete block	5	
Erosion of slopes that led to washing away of covering layer	1	Major leakage
Total:	102	

The gas recovery system at the facility is installed throughout the part of the landfill studied. In 2004, 1.3 Mm^3 landfill gas was recovered, with average methane content of approximately 30 %. In 2006 the average methane content was 35 %. All gas is flared at the facility. The gas recovery system is probably not optimised for maximum gas recovery, as the methane content would probably fall even further if the recovery rate was higher. The extensive recovery means that, at many of the gas wells, or in connections to the wells, gas leaks out to the atmosphere.

The methane emission from the top surface is mainly from the parts with more recent waste. The oldest parts of the top surface have no methane emissions that could be recorded with the laser instrument. A landfill area covered with a plastic sheet lies in the part of the landfill where waste was deposited from 1990 to 2005, i.e. waste with high gas generation. The plastic cover is a thin sheet, and comprises an interim cover. The plastic sheets are not welded or glued together, and the joints are open, allowing gas emission. A total of 25 leakage points were found, and most of them involved direct perforation of the plastic sheet (see example in Figure 12.10 and 12.11). It could also be noted that gas was emitted from many points at the join between the sheet and the surrounding earth-covered top surface.

One reflection that can be made about measuring methane emissions at a landfill comprising parts with old waste and parts with newer waste. Landfill parts, where the area with old waste is well covered with earth and there is no major settlement that causes fissures in the cover, no point source emissions of methane were discovered. This is in spite of the fact that the gas recovery from the landfill was not optimised. Diffuse emission of methane can occur, but not with high flows (this was shown, for example, by the chamber method measurements). This type of area has the lowest emission level of all areas at a landfill.

15.1.2 French site 2

The measurements at F2 were carried out on an area of 18.5 ha. The landfill comprises two stages, one filled with waste between 1946 and 2001 (12 ha) and another that is currently being filled and that so far comprises seven cells. The area of this newer part is 6.5 ha.

At present 160 000 tons of waste are deposited annually. The proportion of household waste is currently approximately 60 % of the waste deposited. The rest is industrial waste. In the old stage, an estimated 2Mm^3 of waste was deposited. Since 2001, approximately 1Mm^3 of waste has been deposited in the newer part. The total amount of waste in the parts in which measurements were taken is approximately 3 M tons. The landfill height is 30 m, and the proportion of slopes is large, approximately 50 %.

The surfaces at the F2 landfill were scanned in the same way as those at F1. This scanning was done with two instruments and took 12 hours, the equivalent of 1.3 ha/hour per instrument. The geometry of the landfill, with a large proportion of steep slopes, and vegetation on the slopes, meant that a large labour input was needed to scan all parts. The results of the scan are shown on Figure 15.4. A 2-D and a 3-D illustration have also been produced (Figure 15.4).

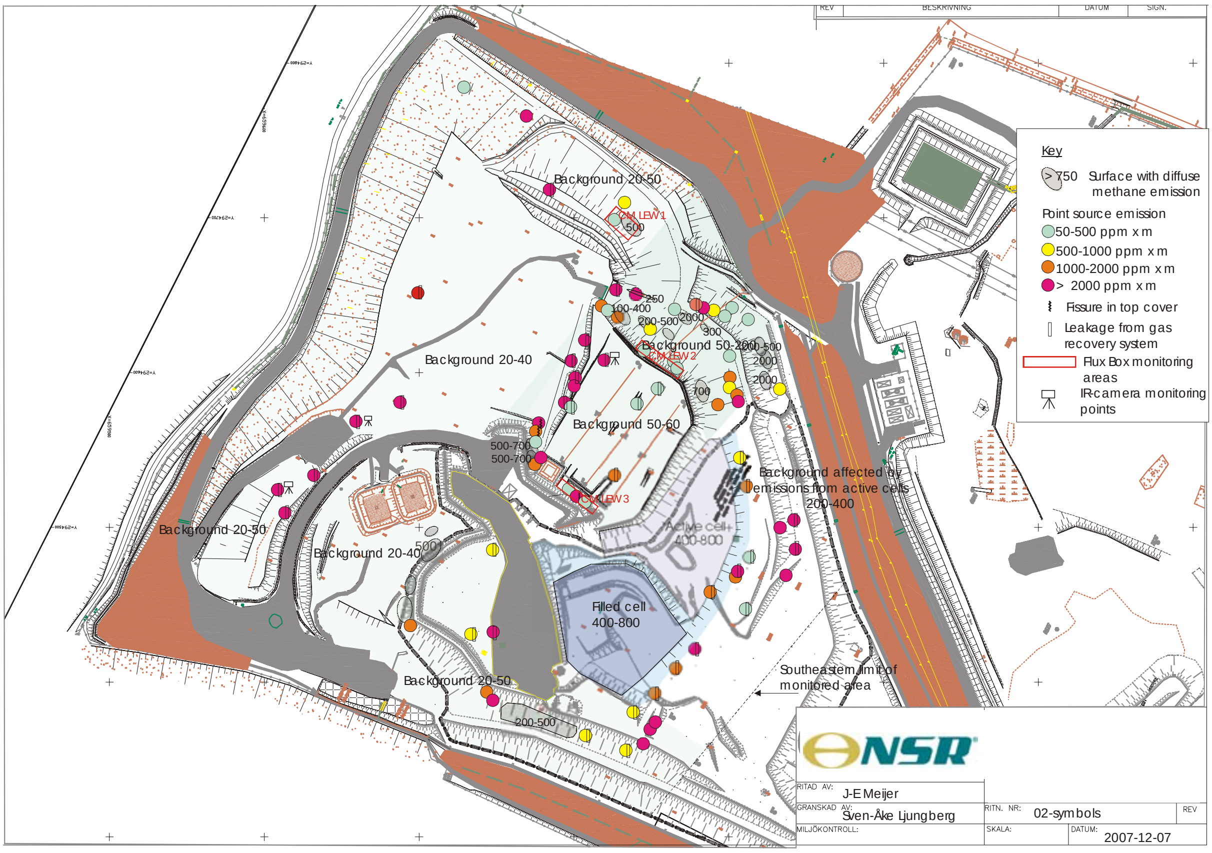


Figure 15.3. Results of the scan of the landfill surface at the F2 facility. Not shown to scale.

The figure shows leakage sites, grouped by concentration that the laser instrument showed near the emission site. Leakage is shown in the diagram if it stemmed from visible fissures in the covering layer, or if the leakage came from sites where the leakage was related to the gas recovery system.

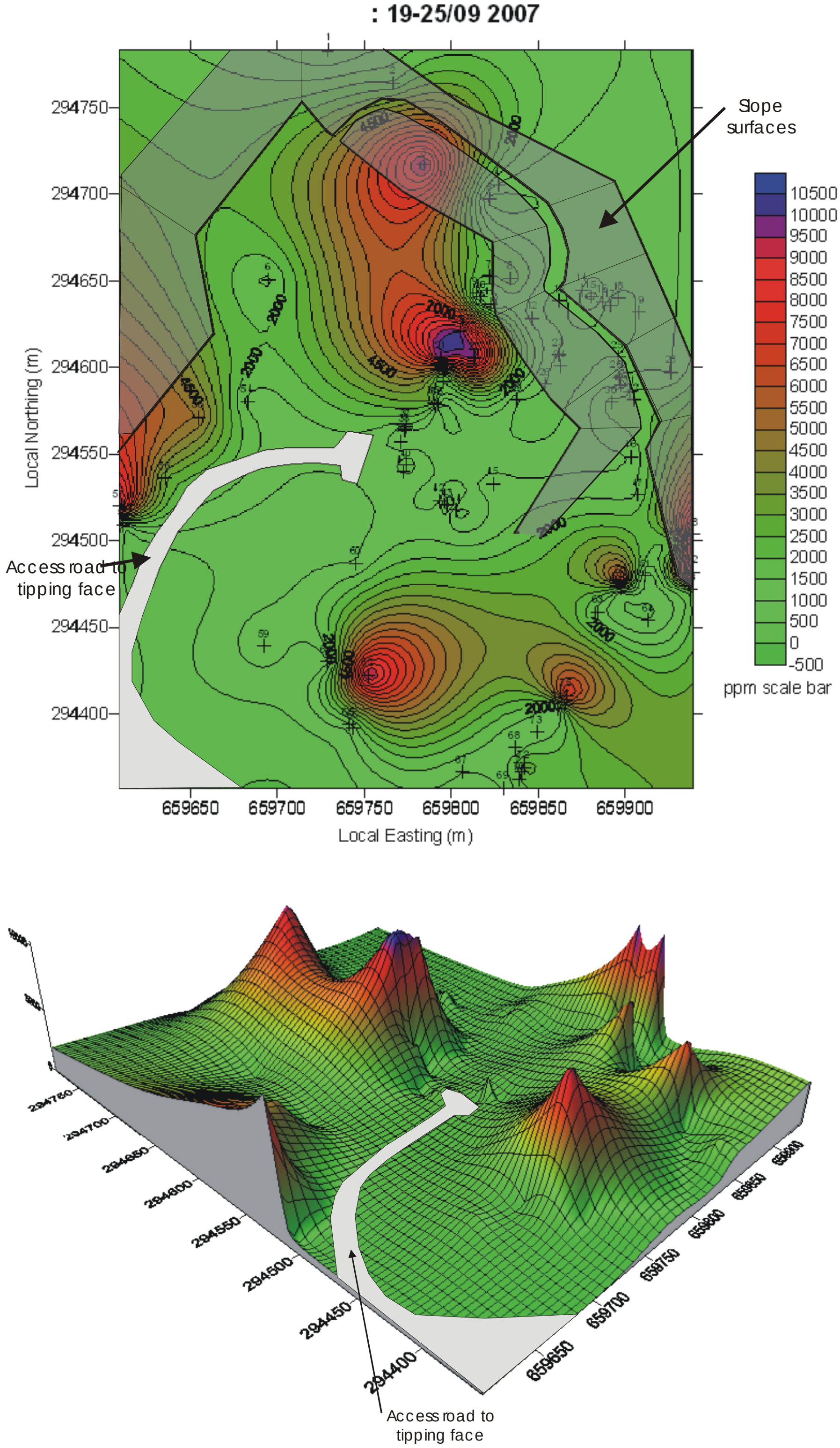


Figure 15.4. 2-D and 3-D illustration showing distribution of concentration levels and leakage sites, site F2.

A total of 75 emission points were recorded on top surfaces and slopes, and also ten fields with diffuse emission of methane. It was also noted that the two most recent cells gave high concentrations in a large area in the cells, and downwind from them. The emission points were distributed as in Table 15.2.

Table 15.2. Division of leakage types, F2

Type of methane emission	**Number**	**Comments**
Point source emission, earth	38	
Leakage from edge or joint of plastic sheet	1	
Leakage stemming from gas wells	30	
Fissures in covering layer	3	
Leakage in slopes	3	
Total	75	

The proportion of leakage sources from the gas recovery system at the F2 landfill is large. It can be calculated that 63 % of the point source leakage comes from the LFG recovey system including leakage near gas wells. The gas recovery system covers the entire landfill, and the landfill gas is used for electricity production (two 1 200 kW gas engines). There are 118 wells. In 2006, 11.3 Mm^3 of landfill gas was recovered, with methane content of approximately 50 %. It is surprising that the extensive leakage is mainly around pipes and gas wells, and the gas recovery does not seem to match the gas generation. According to supplementary information from SITA Environnement, France, a gas engine was not in operation when we conducted our field measurements, which explains the large leakage of methane that was recorded from the gas recovery system. Note that, with the Siemens laser system, we were able to detect and map the effects of a breakdown of a gas engine with no prior knowledge of the event.

The older part of the F2 landfill has few confirmed emission points, and those that have been discovered are mainly due to leakage at the gas recovery system (the ground around gas wells). A field for infiltration of leachate has been placed near the centre of the landfill. Leachate is distributed from a pond along sunken drains. In the field and on the slope below this field, there are a large number of leakage points, both from the gas recovery system and from the top surface. A number of fields with diffuse emission of landfill gas were also noted.

The slopes at the F2 landfill generally leak more than the top surfaces. Over half of the point source emissions are on the slopes. In particular, the slope below the infiltration field has many emission points and surfaces. The processing and covering of the slope is not completed here, which may be because the slope is steep and difficult to work on.

16 TEST CELLS AT SPILLEPENG

16.1 General

The test cells at Spillepeng made it possible to measure methane leakage from an area that is well documented in terms of physical conditions and waste content.

The test cells were created in a test programme belonging to a research project that comprised 12 cells at three landfills in Sweden where biogas generation was to be optimised in several ways. The six cells at Spillepeng were placed on top of old waste within the inner parts of Spillepeng's extensive landfill area. The cells had basal sealing, leachate collection systems and gas recovery systems. A total of 25 250 tons of waste was deposited in the cells in 1988 and 1989. The cells were filled with different types of waste in order to examine the significance of the composition of the waste on the amount of gas production. The cells were covered with 1.0-1.5 m of earth in 1990.

Biogas generation and a number of other variables were measured between 1990 and 1995. During the four-year study period, the rate of gas generation was 39-71 m^3/ton per year.

Since the end of the research project, there has been very considerable settlement. In 2006, the gas recovery system was switched off for renewal, as settlement had rendered large parts of the system unusable. In particular, fissures could be seen in the surface in the areas between the cells. The fissures were caused by major settlement between the cells, where embankments between the cells reduced settlement compared with the waste volumes inside the cells.

16.2 Measurements with the laser instrument, 2006

In October 2006, the six test cells were scanned with the laser instrument. Methane leakage was found from fissures connected with the sidewalls of the cells and near wells for gas recovery and measurements. A consequence of this scan was that the gas recovery system was renovated, and approximately 1 m of new earth was added. Settlement in the cells meant that water seals were formed in the suction pipes and the gas pipes in the cells were connected together in the renovation. Consequently, it is no longer possible to determine whether gas comes from a certain cell.

A new scan was carried out in April 2007, when four of the cells were renovated, but before test cells 5 and 6 were treated. The results are shown in Figure 16.1.

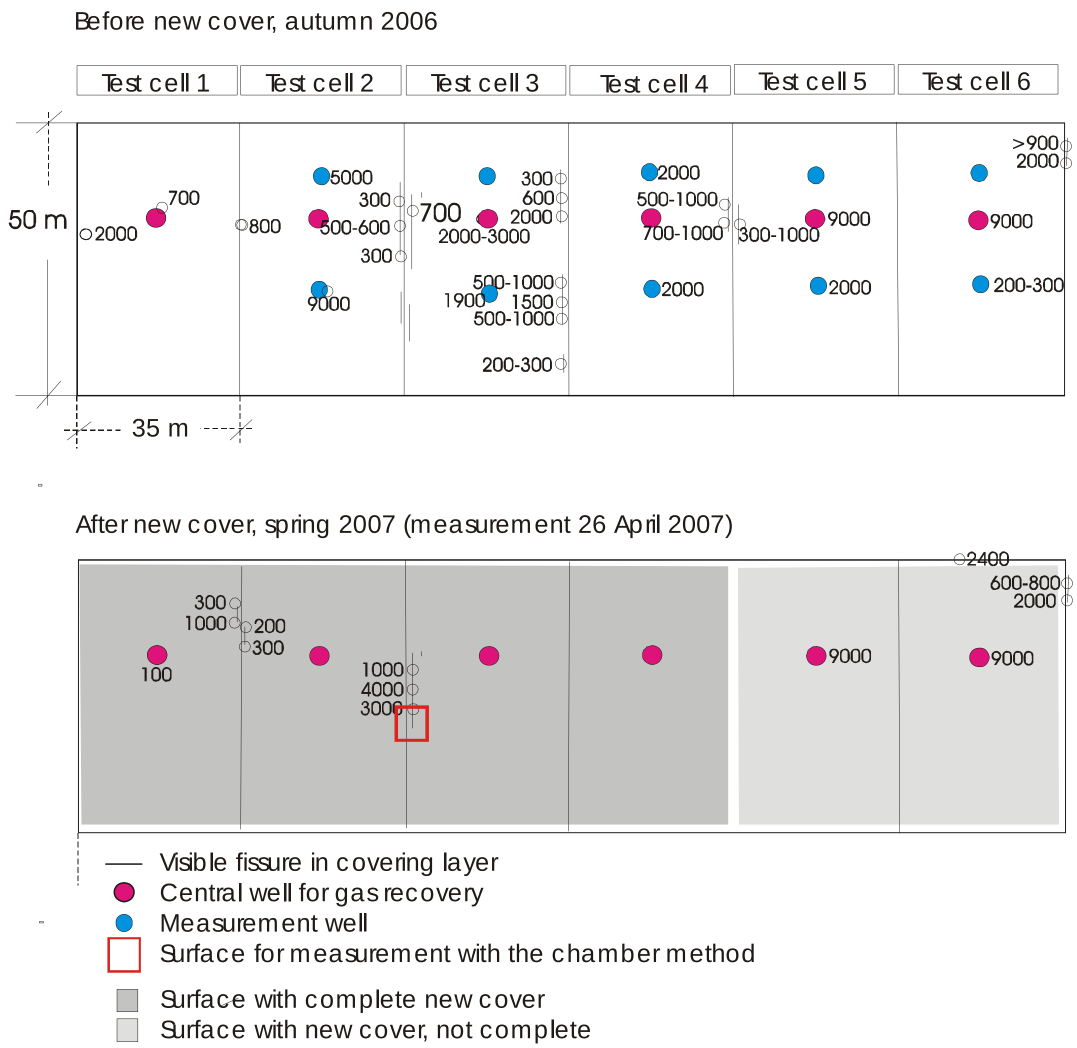


Figure 16.1. Results of laser measurements, October 2006 and April 2007, before and after addition of new cover and renovation of the gas recovery system. Figures at the leakage sites are given in ppm.

16.3 Results of covering measures

The new cover gave considerable less leakage than previously, but it can be noted that new fissures did develop in the covering layer. As previously, these were located at the edges of the cells, indicating that settlement was still taking place. Furthermore, the cells were loaded by the added earth masses.

16.4 Laser measurement with gas recovery system switched off

The new cover was tested in April 2007 by temporarily switching off the gas recovery system. It could be observed that the emission found at the leakage points, shown in Figure 15.2, increased considerably at some points, but not all. The effect of switching off the gas recovery system was very rapid. Elevated leakage was observed within an hour or so. Disconnecting the system also resulted in the detection of leakage in the air above the inlet pipes to the control unit (approximately 500 – 3 000 ppm).

16.5 Measurement with the chamber method in the test cells

Emission through the new cover was measured using the chamber method in May 2007.

The test site contained a fissure where flow was estimated at 148 m^3/year. The laser instrument recorded 3 000 ppm above the fissure. The rest of the surface in the test site for the chamber method measurements gave lower or no emission. Because of the fissure, no reliable estimate can be made of the diffuse gas leakage from the entire test cell surface.

16.6 Gas formation and gas recovery in the cells today

After the gas recovery system was rebuilt, the total landfill gas flow remained stable at approximately 25 m^3/h with methane content of approximately 25 % (converted to 54 000 m^3 CH_4/year).

A calculation with the Landgem program produces a curve as in Figure 16.2. Using the Landgem-curve as a base, gas formation would currently be approximately 56 000 m^3 CH_4/year. Data for waste quantity, gas potential and gas recovery from the test cell project was used to calculate the k-value.

In the project, remaining gas potential has been determined. The results are shown in Table 16.1. In the part of the project that included these cells, the total gas potential was calculated to be approximately 170 l CH_4/kg TS so, of the original gas formation potential, an approximate average of 14 % remains. However, as shown in the table, there are very large differences between the cells. What is interesting to note is that the cells that gave a lower gas yield during the project period of approximately 5 years are the ones that have a higher gas potential remaining.

Table 16.1. Remaining gas potential in l CH_4/kg TS

Cell number	l/kg TS
Cell 2	5.6
Cell 3	38.2
Cell 4	48.1
Cell 5	8.9
Cell 6	18.3
Mean	23.8

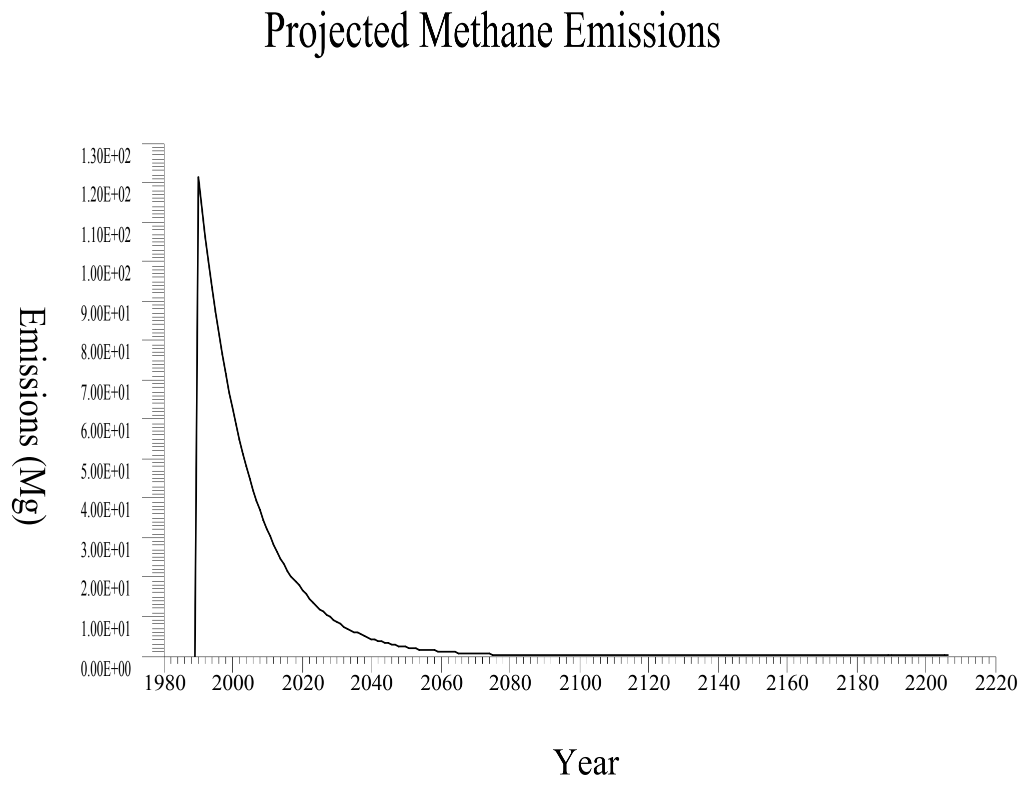


Figure 16.2. Gas formation in Spillepeng's test cells, Landgem, k-value = 0.066, Lo = 109

17 USE OF THE LASER INSTRUMENT IN OTHER APPLICATIONS

17.1 General

The laser instrument can be used to check methane in many different ways, and a number of examples are described in this section. In two examples, reflectors are used. The type of reflector used was a white board coated with the same reflective material as road signs. The reflector was 40 x 75 cm.

17.2 Measurement with the laser instrument over leachate ponds

At Filborna, leachate ponds are used to even out the flow before treatment and, more recently, to pre-treat the leachate through aeration. The leachate is pre-treated in stages, where four ponds are used in a series, i.e. the leachate is pumped from pond 1 to pond 2, and so on. Pond 2 has intensive aeration in the form of a bottom aerator. The first three ponds are shown in Figure 17.1.

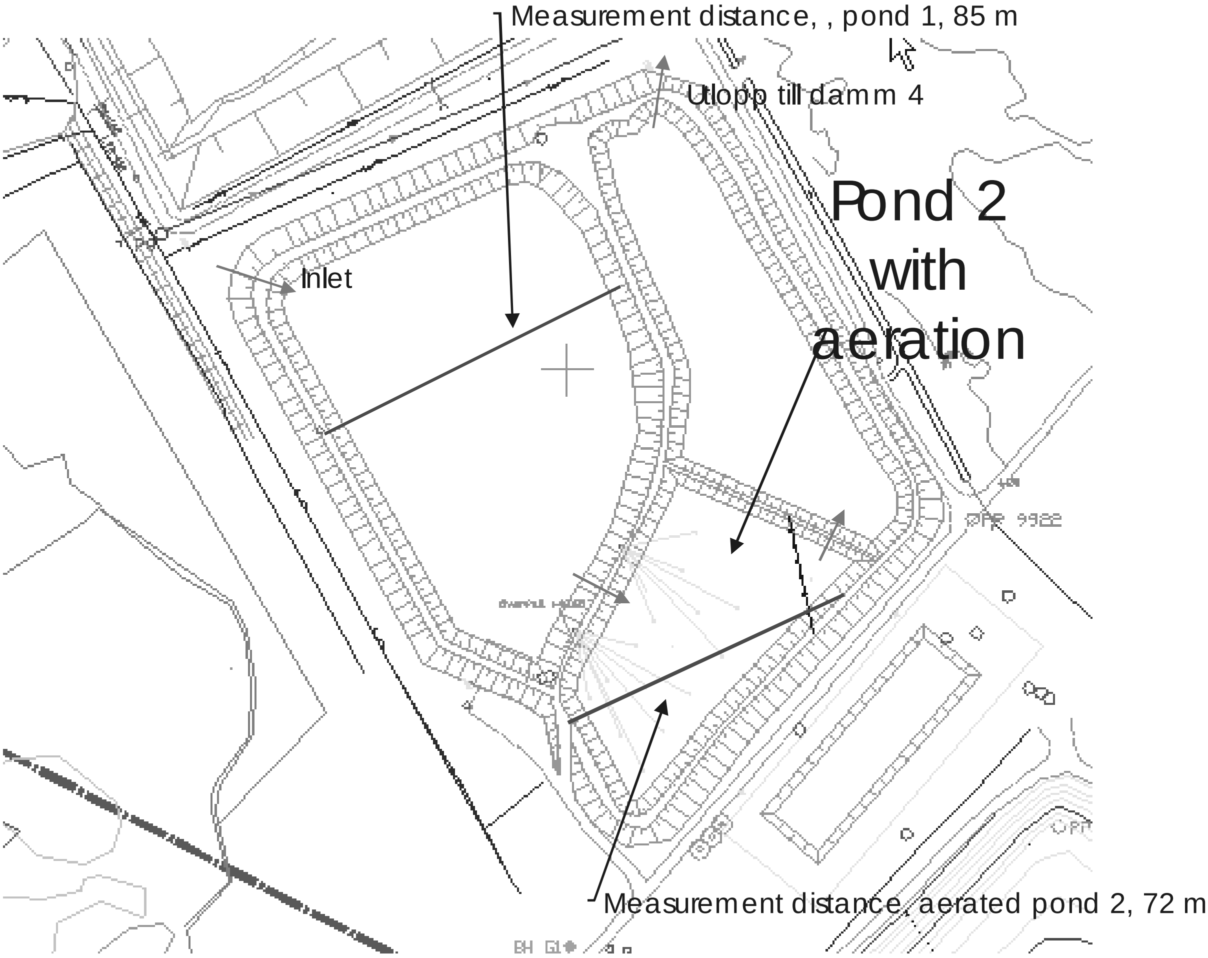


Figure 17.1. Plan showing the location of leachate ponds at Filborna, and showing distances used in laser measurements.

The results of measurement for pond 1, without aeration, are shown in Figure 17.2. At the time of the measurements, the weather was cloudy, which made the measurement possible. However, the diagram shows that the background concentration was significant, which is probably connected to reflected light from the water surface. The distance over the pond was 85 m, and the average reading was 348 ppm x m. The background level was calculated at 301 ppm x m. The difference between 301 and 358, 57 ppm, means that the methane content above the pond is 0.27 ppm above the background content. The margins are so small that several measurements are probably required in order to obtain a reliable picture of the methane concentration over the pond.

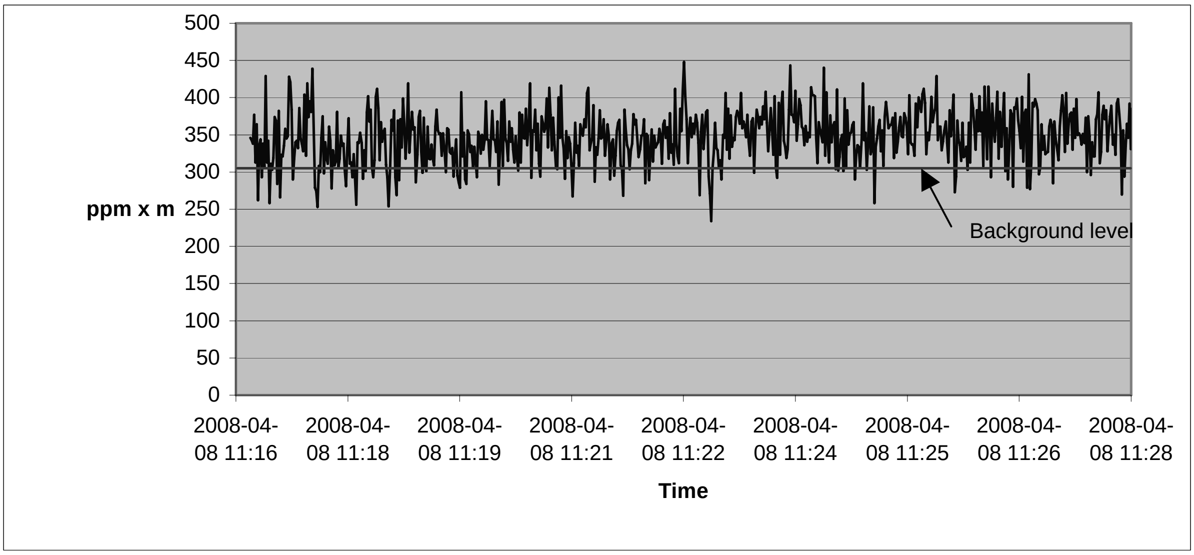


Figure 17.2. Methane concentration over pond 1. Distance 85 m.

Pond 2 is aerated. A bottom aerator is installed in the pond. Distance 72 m (less reliable result), average 232 ppm x m or 1.61 ppm. Here, the instrument recorded a figure *less than* the background level, as shown in Figure 17.3.

A methane concentration over the aerated pond that is lower than the general background level is actually possible. Aeration can reduce the methane content in the air that is used by methane-oxidising bacteria in the pond (conversation with Gunnar Börjesson, 2008). Consequently, the bacteria take care of atmospheric methane. This has previously been seen in the surface layer of landfills. More measurements are required to establish the relationship.

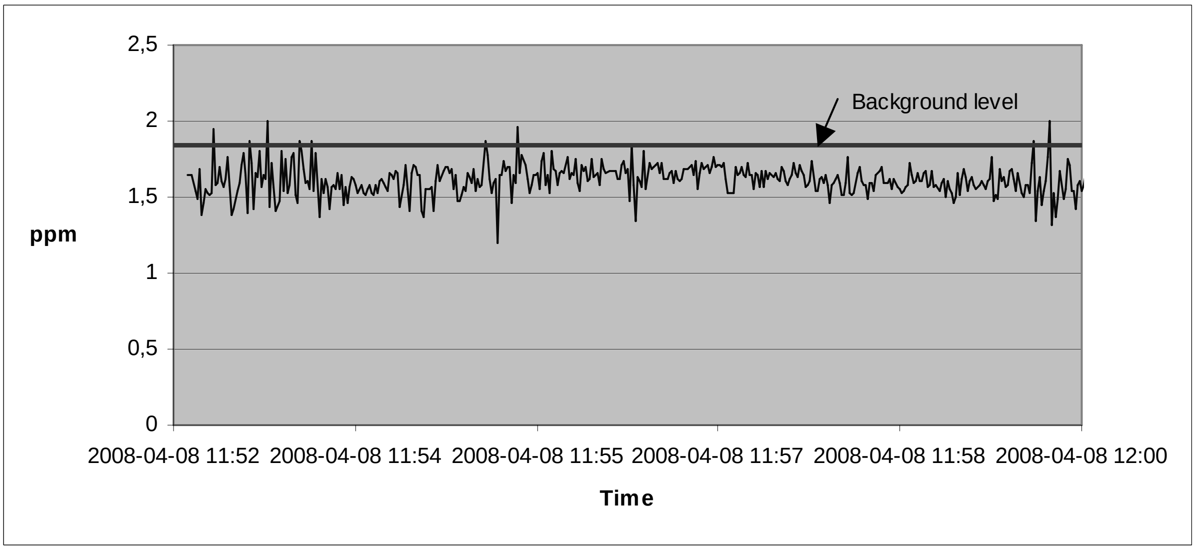


Figure 17.3. Methane concentration over the aerated pond. Distance 72 m.

17.3 Measurements along Välabäck stream, Filborna

Beside the large landfill at Filborna, there is a road and a small stream, Välabäcken. Against the stream, the landfill forms a steep slope that is over 30 m high (see Figure 17.4.).

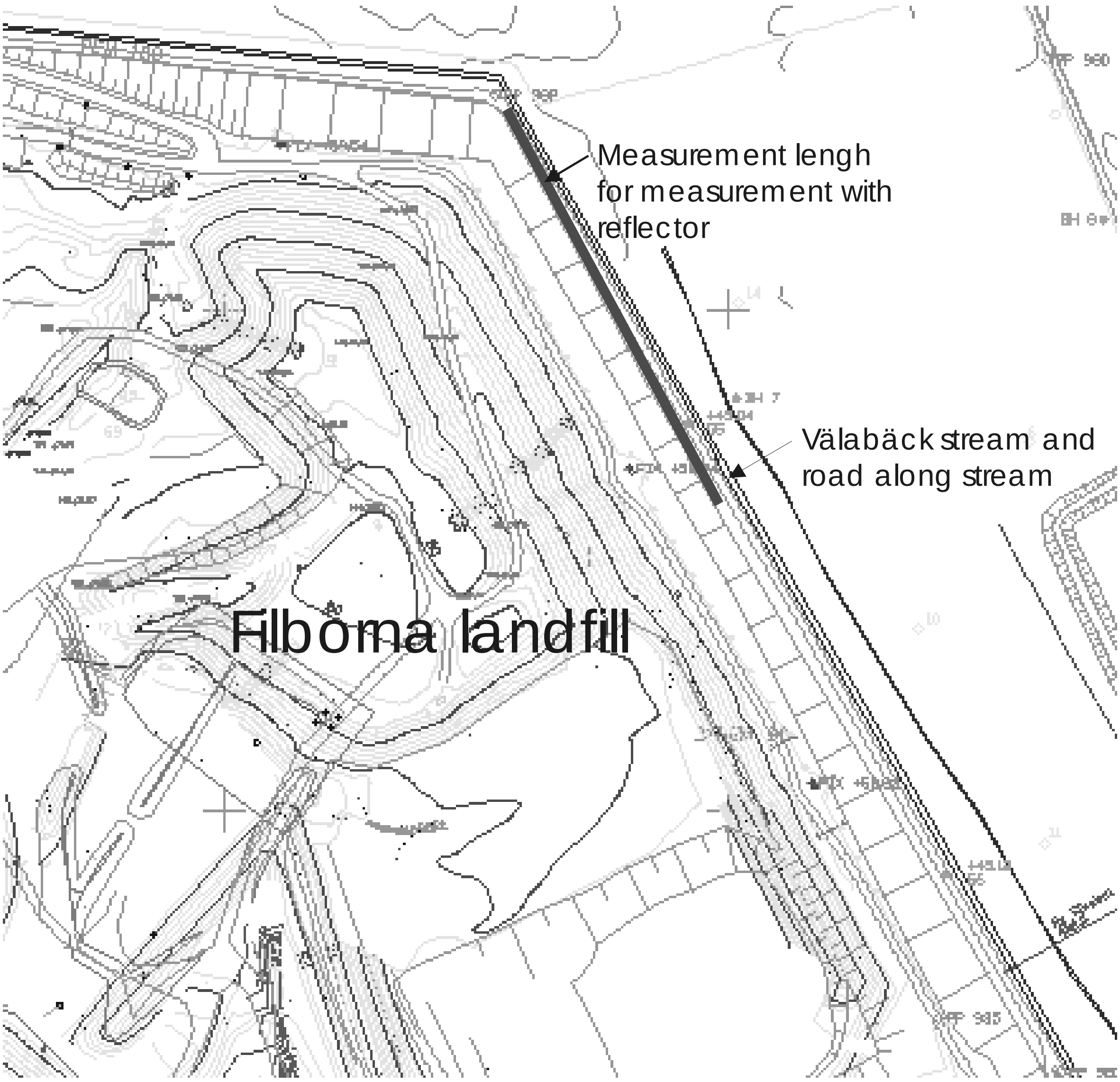


Figure 17.4. Plan showing the location of areas for measurement with the laser instrument along Välabäck stream.

In April 2008, measurements were carried out with a reflector along the stream to examine the range of the laser instrument when there is a backscatter surface in the form of a reflective material (road sign). Measurements were taken during the day, with sunny weather. The measurement point was in shade, but individual sunrays could penetrate dense vegetation.

Figure 17.5 shows measurement with a reflector at a distance of 100 m. The maximum distance for measurement was 200 m. As can be seen in the diagram, there was little back-ground concentration resulting from incoming light even though the measurements were taken during the daytime. The diagram shows that methane from the adjacent landfill is blown past the beam between the reflector and the laser instrument by the westerly wind.

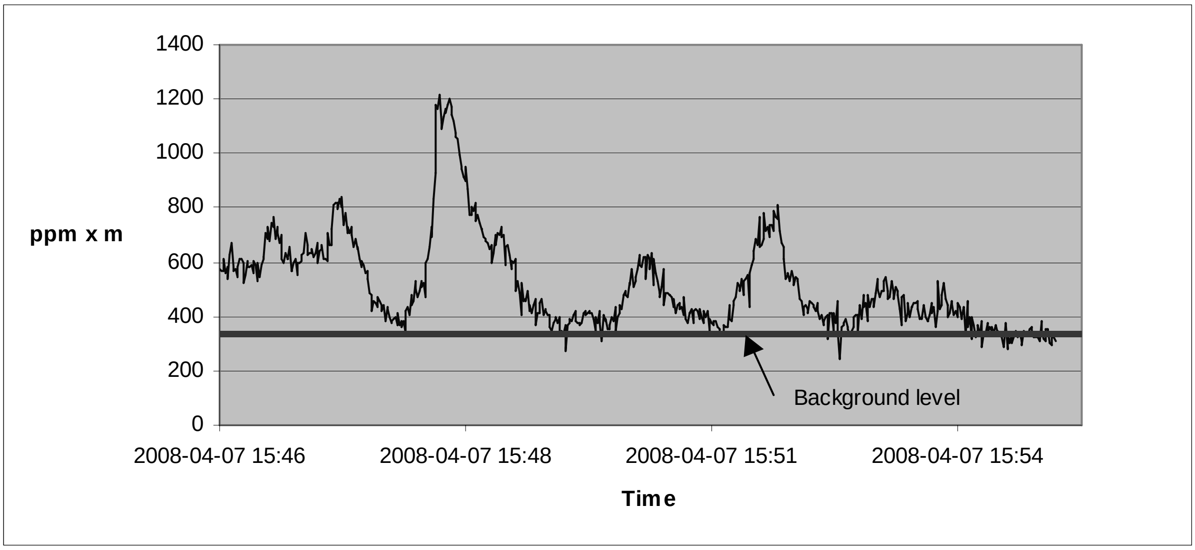


Figure 17.5. Measurement against a reflector along Välabäck stream, Filborna. Length of beam 100 m.

17.4 Measurements during excavation of old waste

In 2008 an old municipal landfill with mixed household and industrial waste in central Helsingborg, Ringstorp landfill, is being excavated. The landfill was in operation between 1930 and 1950 and all the waste is from that time. The waste is being dug out and transported to Filborna for final filling in a controlled landfill. An approximate total of 200 000 m^3 waste will be dug out and transported. During the excavation, the laser instrument was used to investigate whether there was still landfill gas in the waste. No leakage could be traced at the surface.

During excavation, the laser instrument was put in position and directed towards the waste. The distance to the waste surface was 12 m. The arrangement and the conditions on the site are shown in Figure 17.6. Figure 17.7 shows the methane concentration in ppm at the excavation site. It can be seen clearly how the methane concentration increases significantly each time the excavator scoop lifts the waste up to the lorry.

Consequently, the waste that generates landfill gas is being constantly degraded. The gas generation is probably small, which is also shown by the direct decrease in the concentrations near the slope where the excavation is taking place when the scoop has been filled and the waste is loaded onto the lorry.

In this case, the reflector could not be used because the sunlight was too strong. The best measurement conditions are obtained by directing the laser instrument directly towards the waste face and using this as a backscatter surface. Background concentration is evident, and this can partly be caused by pieces of glass, etc. directing unwanted light towards the instrument.

Figure 17.6. Excavation of waste at Ringstorp landfill, Helsingborg in 2008. The picture shows the arrangement of the laser instrument, directed towards the site of excavation.

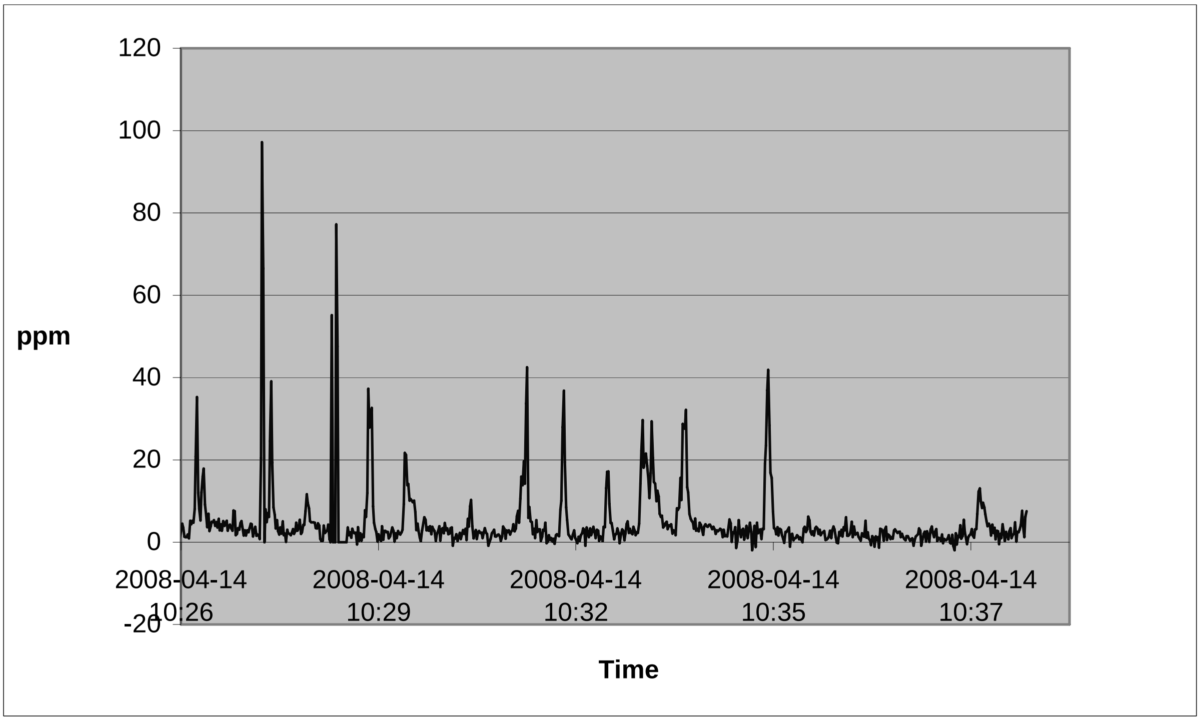


Figure 17.7. Methane concentration in ppm during excavation of waste, Ringstorp landfill.

18 ANALYSIS AND EVALUATION

18.1 Possibilities and limitations of the instruments

The Siemens laser system was developed to detect and map gas leakage from distribution systems for natural gas placed below and above ground. The development took place within the framework of an EU-financed R&D project in collaboration with an international research group and end users in the gas distribution industry. Technical specifications and operative design of the Siemens laser system were developed in accordance with the requirements and wishes of the end users. The work was also guided by requirements and wishes relating to the use of the instrument on landfills.

International safety regulations for distribution of natural gas indicate norms and limits for when the gas distributor is obliged to correct identified emission of methane from gas distribution systems. The background emission for methane is 1.7 ppm. The end users for distribution of natural gas have given 10-20 ppm as an operative figure for indication of elevated gas emission. Like line inspection of high-tension cables, the natural gas distributors are obliged to implement a planned programme for preventative control and maintenance, and inspect gas distribution systems at fixed intervals and correct any gas leakage detected. No limits have been established for field use in landfills, but the rapid mixing of leaking methane with the air above a landfill means that a highly sensitive instrument must be used. For detection of methane leakage from landfill surfaces, the Siemens instrument has a sufficiently low detection limit and is sufficiently fast.

Siemens has developed three prototypes of the laser system, and two of these were used in the project. The Siemens laser system measures the concentration of methane in ppm x m. The laser is an infrared laser that operates in the 1 651 nm wavelength range. The lower limit for detectable methane is 10-20 ppm x m depending on how much energy is reflected from the backscatter surface. The range of the laser is 10-30 m, depending on the reflective properties of the backscatter surface. The laser system measures and records 10 readings per second.

FLIR System AB has developed a ThermaCAM™ GasFindIR LW IR that was used in the project as a complement to field measurements with the Siemens laser system. The GasFinder system operates within the 10-11 μm spectral range, and is equipped with a Focal Plane Array (FPA), QWIP, 320x240 pixels detector. The FLIR IR GasFinder is designed to detect and visualise a series of different gases including methane from landfills, natural gas from pipeline systems placed below and above ground, gas turbines, gas tank stations, etc. Thermal image data is presented in real time on a portable, display unit adapted for field use, and is stored digitally on a small, portable DVD unit. The GasFinder system can be used to detect, visualise and track the diffusion pattern of the gas and to map gas leakage, but cannot be used to quantify the gas flow. Like all IR systems, the IR GasFinder system is temperature dependent. Results from field experiments carried out in the project indicate that a methane concentration of ≥ 1 000 ppm x m and a delta T between the methane and the surroundings of ≥ 2 °C are needed in order to able to detect and visualise methane emissions, depending on wind velocity, radiation conditions, etc.

The description below is to be seen as a summarising analysis and evaluation of the observations and field measurement results in the project, and the results that are presented in research literature. Issues relating to certainties and uncertainties about the methane formation process in a landfill, the transmission process of gas through the landfill mass, factors that influence methane emission from a landfill surface, and the possibility of measuring and recording methane emissions in a satisfactory way, are analysed and evaluated below.

Concentration is measured in ppm, while flow is measured in l/min, so they are two completely different measurement units. It is difficult to convert ppm data to flow data, which is why, for example, an operatively reliable method of determining the flow rate at the time of measurement is needed, and it is probably also necessary to have a reference laser or reference gas cell built in to the laser system.

Detection uses the laser instrument’s recording of the methane concentration along a beam to indicate leakage expressed in ppm x m. The method is fast and the full-surface mapping is as accurate as the results using FID, as shown by the mapping of the F1 landfill. Leakage that is discovered consists primarily of point source emission, but areas with diffuse methane leakage from surfaces can also be detected. Strikingly many leakage sources have also been found near gas wells and pipes out on the landfills.

Detection is carried out as a short-time measurement, i.e. not all emission conditions at the landfill in question are recorded at the same time, and the mapping shows snapshot readings at a specific point in time. We discovered that leakage sites could give high concentration levels on one occasion, and low at another. However, it can be said generally that the areas with a number of leakage points are sites that first and foremost should be monitored, and new measurements taken. Measures should be taken if leakage is found on many measurement occasions.

The five combined measurements with the laser instrument and the chamber method in the same manner in the same area during 10 days at Filborna are convincing examples on great variations in the same area at different times.

Methane is formed inside the landfill, and pressure builds up. At a certain pressure, the methane is transmitted via the easiest route through the landfill masses up to the surface layer, and is emitted via (a) holes, (b) fissures and (c) diffuse exits through permeable landfill/covering materials.

The flow(s) out from a landfill are not constant and, instead, can pulsate in intervals with maximum and minimum flows and in intervals with no measurable flow at all.

Even if it is technically possible to develop a system for detecting and quantifying the methane flows in l/min, the question remains of what is being measured and whether data from a specific time of measurement is representative and can be used to generalise the methane emission from the landfill in question to an annual emission.

Research literature presents results from studies in which methane emissions are measured using different types of ground-based laser methods at beam distances of 100-1 000 m. Naturally, these methods also give snapshot readings of emission that are then generalised to an annual figure or some other measure.

The chamber method has the same limitations as other existing technology and measurement methods, i.e. finding the right time in the cycle, or rather to measure sufficiently many times in a randomly-produced time cycle to capture representative sequences of maximum and minimum flows of gas emissions.

The discussion shows the general need for repeated measurements in order to improve accuracy when calculating methane flow from a complete or representative parts of a landfill.

Results from field measurements in the project indicate that measurement with laser for detection and mapping of methane emissions from landfill surfaces probably includes contributions from surrounding landfill surfaces. The measurement performed at Välabäck stream illustrates the influence of the contribution. However, the problem shall not be overestimated. It is during scanning the laser instrument may include airborne emission contributions, but at the following detailed registration the error is minimised.

Regardless of whether a laser system that integrates emissions along a long measurement distance/beam is used, or direct measurements from 20-40 cm towards an emission source with a Siemens laser system, the problem remains that gas emission pulsates in intervals. Furthermore, the relatively rapid mixing between the methane and surrounding air must be taken into account. This means that, even at high flows, the gas concentration varies and can, even during a very short measurement period of $\leq$ 5-10 seconds give large variations in ppm figures, as illustrated in Figure 12.6, 12.21/22 and 12.25.

Measurements in a field laboratory with simulation of known methane flows showed that the measured methane concentration varied very little with laser measurement at different flows. How can that result be interpreted? Methane is a volatile gas that is also affected at low wind velocities and small temperature differences between gas and the surrounding atmosphere, which leads to a very rapid mixing of the methane with the surrounding air.

Results from field measurements in the project and in international R&D literature indicate that it should be possible to combine existing technology with supplementary and systematically executed field reference measurements to increase the accuracy and usability of remote sensing data for mapping and indirect quantification of gas emissions from landfills.

In the project the chamber method has been used to try to quantify the leakages the laser instrument has detected. If all individual readings with the chamber method are combined with corresponding readings with the laser instrument a correlation a relationship is obtained. It is then possible to get a quantitative measure of the leakage. The great difficulty is that the results cannot be verified. A similar correlation was obtained in a field laboratory test with a sand box with a known landfill gas flow was used. In this test the results from the chamber method differed from the known flows indicating the chamber method has limitations.

The relationship between the results from the laser instrument and the chamber method have been used to quantify all detected point source leakages at the French landfills F1 and Lewarde. The total emissions from the two landfills were 41 tons and 29 tons of methane per year. The quantified methane emissions from detected point sources are small compared with the total emissions from the landfills presented by the landfill owners. The conditions gives a hint that the diffuse methane emission from the landfills are the dominating parts, not the point source emissions from holes, fissures etc.

A third category of methane emission are from the large point sources. The French landfills showed very large emissions from the connection pipes and wells belonging to the landfill gas recovery system. These will be underestimated at a single scanning. They represent large leakages that cannot be measured correctly by the combination of the laser instrument and the chamber method.

Another calculation have been done when presenting the methane emissions from top surfaces and slopes. In every test area mean values from the laser instrument and the chamber method have been used. The correlation was very good for both top surfaces and slopes. From the results it can be said that slopes emit 5-10 times more emissions than top surfaces, which can be verified from other investigations. In this survey, with a small number of observations, one high value have a large impact. It can also be verified that the number of point leakages are higher on slopes compared to top surfaces.

The measurements from top surfaces and slopes show that the age of the landfilled waste, besides the gas recovery system effiency, has significant importance. Landfill zones where the waste is older than 15 years show much lower emissions.

The division of the landfill into different zones has been a good aid to better understand the types of the methane emissions and the locations of point sources.The division into risk groups, made in an early stage, has been useful. The different landfills have different top surface/slope quotients.

In the project, the laser instrument was used to classify characteristic zones, and the chamber method was then used to determine methane leakage for the different zones as classified by the laser instrument. This allows quantitative measurements of the leakage. This manner has been used for the calculation of the methane emissions from the French landfills. The results are reasonable, but differ from the landfill owners own calculations.

If the objective is to find a reliable measurement of leakage from a landfill, then it is most probable that the combination of laser measurements together with the chamber method is not sufficiently accurate for quantitative safe determination of methane emissions. If, instead, the objective is to prioritise and decide where measures should be taken to reduce emission from different landfill surfaces, the combination of laser and chamber method is probably usable.

A good example of the use of scanning with the laser instrument was made at the test cells at Spillepeng. The scanning was here used to produce a foundation for complement of the capping of the cells. The results of the actions could be controlled on site and also in this case, to make a calculation of expected landfill gas amounts related to the actual recovery.

Finally it was demonstrated how the laser instrument can be used making measurements using a reflector. Measurement with a beam path up to 200 m length is possible. Application examples are measurement over leachate ponds, at the side of a landfill and on landfill surfaces. Such measurements can give valuable information about methane emission conditions, hard to get in another way.

18.2 Factors that influence laser and IR measurements of methane emissions

This presentation is restricted to a description and an attempted explanation of such factors that influence methane emissions, and the ability to use modern remote sensing techniques such as laser and high resolution IR technology to detect, measure and visualise methane that is emitted from a landfill.

The results from the first series of laser-based field measurements of methane emissions from landfills that were carried out in autumn 2006 formed a bank of data that, after interpretation and analysis, formed the basis of the subsequent field measurements in the winter, spring and summer seasons. Note that the weather and radiation conditions can vary strongly depending on the location of the landfill in Sweden. This particularly applies in autumn, winter and spring. The summer can sometimes give similar weather and radiation conditions throughout Sweden.

Parallel with the field measurements with the Siemens laser system and the FLIR IR GasFinder system, field reference data was collected using the methods described in Chapter 10.1 (Figure 10.1, 10.2, 10.3). The purpose of the field reference data was to study and explain the influence of the methane formation process, the gas distribution and gas flow that occurs under different weather and radiation parameters. Interpretation and analysis of the combination of laser, IR and field reference data indicate that detection and mapping of methane emissions from landfills, and studies of the behaviour of methane, are very complicated and include several known, but also several relatively unknown, interacting factors.

Influencing and interacting factors on emission of methane from landfills

- Covering material and covering conditions
- Landfill pressure (at different levels inside the landfill)
- Atmospheric pressure
- Wind velocity
- Wind inducement
- Atmospheric radiation temperature (background radiation)
- Air temperature
- Gas temperature – air temperature – convective air streams
- Landfill pressure – atmospheric pressure – pressure differences
- Landfill temperature (in the surface layer and at different depths)
- Precipitation conditions, moisture in the surface layer and in the landfill
- Relative humidity of the air
- Micro topography of the landfill
- Macro topography of the landfill (zones, top surface, slope, toe of slope and crest)
- Distance between measurement point and the instrument (laser = distance-dependent, IR = temperature-dependent)

The following is a brief illustration of different types of factors that interact and influence methane emissions from landfills.

- **Covering material and covering conditions**

  The landfills studied in the project have different compositions, covering materials and covering procedures. The landfills are built up of cells with different landfill materials and over different time periods.

  Different covering causes different types of methane leakage. The following describes two typical cases of influencing factors.

  Case 1. Results from field measurements from a total of 8 landfills indicate that cells with pure household waste or industrial waste, effective gas recovery systems and satisfactory covering material and procedures give low methane emissions in the form of diffuse gas emission through the surface layer over large landfill areas. Higher methane emissions may occur from deficient joints between landfill surfaces or through deficiencies in connected gas distribution and leachate systems.

  Case 2. Cells with deficient covering run the risk that protruding objects force their way through the covering material and form channels through which methane can easily pass and be emitted through the surface layer of the cell. In cases where covering material is thin and permeable, methane can be emitted, both as diffuse emission and as point source emission, which can be frequent and considerable.

- **Landfill pressure (at different levels in the landfill)**
  The methane formation process inside a landfill results in a weak over-pressure in the landfill, which helps transport the gas through the landfill material and causing emission through the surface layer to the atmosphere.

- **Atmospheric pressure**
  Observations during field measurements carried out under different weather and radiation conditions show that, when atmospheric pressure changes from low to high, no measurable methane emissions can be recorded with the laser system in question for points/surfaces that previously gave low to high methane readings. These observations are also reported in the research literature, but so far there is no scientifically documented explanation for the phenomenon, or about the atmospheric pressure at which the landfill closes and opens for methane emission. A possible way to illuminate the effect of atmospheric pressure on methane emissions from landfills is to carry out repeated longer-term measurements over longer measurement periods.

- **Wind velocity**
  The significance of wind velocity as an influencing factor on methane emission and on measurement of methane emission is well documented in the research literature, and results support the observations made during the project.

  Field measurements using the Siemens laser system have shown that methane and surrounding air mix together very rapidly under wind conditions unfavourable to measurement, such as turbulent winds and wind velocities of 2-3 m/s. This can be studied instantaneously and in real time in the image unit (palm-unit) of the laser system. The majority of the field measurements with storage on the logger unit were limited to ≤ 1 minute recording.

Supplementary longer-term measurements of gas emissions were carried out for a selection of features/surfaces (1-2 hours). Results from this type of field measurement can vary both in short and long time intervals from 0 ppm up to 10 000 ppm. Whether these variations are mainly caused by the effect of wind or a combination of the methane formation process, pressure conditions inside the landfill, atmospheric pressure, wind effect, and the landfill's microtopography could not be examined within the framework of the project, and results from similar studies have not been published in research literature to the best of our knowledge.

Observations in the project indicate that measuring methane emissions at wind velocities ≥ 3 m/s is unfavourable, depending on the nature of the microtopography in the area of measurement and also because of the risk of emission contributions of airborne methane from adjacent features/surfaces, landfill slopes, etc.

It is usually possible to detect methane leakage even if there is a contribution from nearby landfill surfaces, but it can be difficult to differentiate between what is emission from the specific measurement surface and emission contributions from surrounding landfill surfaces.

- **Wind inducement**
  Results from repeated field measurements in the project indicate that wind inducement influences the gas flow where wind-induced turbulence increases methane emission through pores in the covering layer, through microscopic channels and small fissures in the landfill surface. Observations from field measurements in the project show that this phenomenon occurs principally at low turbulent wind movements, with a wind velocity of 1-2 m/s. Authors such as Poulsen and Moelndrup (2006) examined the effect of turbulent wind movements on transport and emission of methane from the ground surface of a landfill. The results from a combined computer-based model and field measurements of the methane flows indicated that wind-induced gas transport through turbulent wind movements accounted for approximately 40 % of the total gas emission during the measurement period in question. The permeability of the covering material and earth layer permeability to air, and the amplitude of wind-induced pressure-related fluctuations, are considered here to be the most important parameters for measurement and control of the scale of wind-induced transport of methane in the surface layer of a landfill.

- **Atmospheric radiation temperature (background radiation)**
  The influence of the atmospheric radiation temperature is a well-documented phenomenon in modern remote sensing, both in the application of laser technology and also in IR technology. Clear sky conditions at night and during the day are the types of weather that can affect readings, both positively and negatively. When skies are clear, the atmospheric radiation retains a temperature of -50/60 °C, regardless of whether it is day or night.

  In measurements of gas emissions, for example with laser, clear skies can mean that insolation or contributions from the night sky can be reflected into the beam of the laser, affecting input data, or disrupt the backscatter signal to the laser, depending on whether the laser is directed in a horizontal direction or towards a backscatter surface with highly reflective properties. If the operator is aware of the potential effect of atmospheric radiation from clear skies, the laser can be directed so that it largely avoids reflective radiation contributions.

In contrast, when using the FLIR IR GasFinder for detection and visualisation of methane emissions, the chance of recording methane can be improved, on condition that the camera is not directed towards any highly reflective surface such as water.

The landfill surface emits energy to the colder atmosphere. During the night, the methane gas is warmer than the surrounding surfaces (light-grey tone) and, in the day, it is colder (dark-grey tone). The grey tone variations in the thermal images come from a determination of a radiation temperature and grey tone scale designed for classifying the temperature range that the IR GasFinder system records, and electronically converts converted photons in the specific wavelength range of the IR unit. The radiation temperature and the radiation temperature pattern from features/surfaces on the landfill are shown clearly when there is a large difference in temperature (delta T) between the gas and its surroundings. There are occasions when the gas and surrounding air have the same temperature and, on these occasions, methane cannot be detected.

- **Air temperature**
  Temperature variations between methane and its surroundings should not affect the measurement results when the Siemens laser system is used to detect methane emissions from landfills, because it is temperature independent. In contrast, temperature variations do affect the readings, and the possibility to detect and visualise methane emissions, when IR systems like the FLIR IR GasFinder are used. Low delta T between the gas and the surroundings gives inferior temperature resolution, and make it difficult to detect and visualise methane in the thermal image, while high delta T makes it easier to detect and visualise methane. Cloud-free skies with low atmospheric radiation temperature at night, or low air temperature during the day, are the best temperature conditions for detecting and visualising methane using the IR GasFinder technology. However, this ignores complications caused by unfavourable wind conditions.

- **Gas temperature – air temperature – convective air streams**
  Temperature differences between methane and surrounding air cause density differences. It is not the density in itself that is interesting in measurement and analysis of methane emissions from landfills, but rather the difference in density.

  Natural convection. Differences in density between methane and surrounding air cause natural convection. In this context, the density difference has two effects. (a) At the same temperature, methane is lighter than air. This causes an upward stream of methane. (b) If the gas is warmer than the surrounding air, the upward movement is exaggerated. If the gas is cooler than the surrounding air, the upward motion is weakened, and the gas may flow out parallel with the ground surface.

  This is not to be confused with turbulence caused by the wind, which is probably the most important factor for understanding the rapid mixing of the methane with the surrounding air.

- **Landfill pressure – atmospheric pressure – pressure differences**
  Differences in pressure between the atmosphere and the landfill create air movements. When the pressure is higher in the landfill, this reinforces the upward movement of the methane.

Forced convection. The air movement created by pressure differences is called forced convection. When the pressure is higher in the landfill, the landfill gas is transported from areas of high pressure towards areas of low pressure. Higher atmospheric pressure counteracts and initially weakens the upward transport of methane.

Consequently, temperature differences between methane and the surrounding air cause convective air movements about the ground level where the methane is leaking out through diffuse emissions and through point source emissions via fissures in the sealing layer of the landfill. Observations from field laboratory studies at Malmö Fire Service's gas testing facility and from various field measurements in the project indicate that even small air movements at ground level in a landfill can cause a rapid mixing of the methane with the surrounding air.

Likewise, pressure differences between the landfill and the atmosphere are an important influencing factor that at high landfill pressure can increase the methane emissions and at high atmospheric pressure can counteract, weaken or prevent the emission of methane to the atmosphere. Observations from field measurements at, for example, Forsbacka landfill indicate that pressure differences between the landfill and the atmosphere affect methane emission.

- **Flow – flow rate**
  High flows from leakage sources with narrow passages through small fissures and small hollows in the landfill surface give rise to jets, which means that the convective flow process takes place slightly up in the air above the leakage source. This phenomenon has been shown through, for example the field laboratory studies with controllable simulations of leakage of natural gas carried out at Malmö Fire Service's gas testing facility (BARBARA) and the controllable simulations of biogas and measurements with laser carried out at Filborna landfill (NSR). Similar observations were made when measuring emissions from, for example, protruding objects such as pipes or metal objects in mixed landfill material, such as at Forsbacka and Löt, and methane leakage from gas distribution pipes at Lewarde landfill in France.

  Results from the field laboratory measurements, and observations during field measurements, indicate that the flow/flow rate in relation to the specific properties of the leakage source can affect and give varied results depending on where the laser beam is directed when there are high flows from narrow passages. If the laser beam is directed as normal for pinpointing directly adjacent to or near the leakage source (≤ 0.5 m), incorrect ppm readings can be obtained regardless of whether completely different methane flows are simulated. Because methane is invisible to the human eye, the operator does not see where in the gas plume the measurements are taken. If the laser measurement is supplemented with an IR GasFinder system, the leakage source can be detected and the gas plume can be visualised, so the laser system can be directed to measure the gas concentration in ppm for the desired part of the gas plume.

- **Precipitation conditions, moisture in the surface layer and in the landfill**
  Observations from repeated field measurements at, for example, the F2 area at Forsbacka landfill indicated that ground moisture is an important parameter that affects the conditions for methane emission from a landfill. When moisture content in the surface layer is high, the pores in the covering material close, and the moisture functions as a seal that prevents the emission of methane through the surface layer of the landfill. At the

same time as methane leakage through diffuse emission or through microscopic fissures is reduced, increased emissions have been documented from nearby large fissure zones. If no other parameters (wind, pressure, etc.) are changed, greater emission of methane through the open fissure zones seems to be a consequence of the gas seeking the easiest route out through the surface layer because of the high moisture content in the surface layer of the landfill.

If precipitation in the form of rain is followed by strong and persistent wind, the moisture from the rain will quickly dry, and the methane is once again emitted through its earlier channels before the rain. However, under conditions with more prolonged powerful precipitation, or if there is a heavy snow cover on the landfill surface, previous leakage sources can be completely closed, and the gas finds other routes and breaks open new channels than those that were previously documented and located with GPS.

Landfill gas that streams to the surface in a landfill is saturated. When it reaches the surface and the atmosphere, the moisture in the gas often condenses on the surface of the landfill. In turn, high moisture content prevents gas from streaming out, and the gas then finds other routes out of the landfill (G. Börjesson, 2008). In this way, the gas itself contributes to the dynamics we observed, i.e. that emission sources in the surface are moved, and smaller and larger flows alternate.

The conclusion from the project and from research literature is that further field-based studies are required in order to increase knowledge about methane transport through landfill layers, and the behaviour of methane in relation to the moisture content in the top layers and in the surface layer of a landfill. A possible method is a combination of laser measurements and geoelectricity measurements in the landfill layer immediately below the covering layer.

- **Relative air humidity above the landfill**
  In the project, there have been insufficient studies of variations in relative air humidity in the air layer immediately above the landfill surface to determine the role of air humidity as an influencing factor in mapping of methane emissions from landfills. Observations were made during a number of field measurements that indicate that relatively high air humidity, like light precipitation, can cause the pores to close and reduce or prevent emission of methane from landfill surfaces. Relative air humidity can have its greatest influence on methane emissions as an augmentation factor on occasions when the ground surface is already moist from earlier precipitation.

- **The landfill's microtopography**
  In conjunction with different field measurements of methane emissions using the Siemens laser system, it has been noted that the microtopography is important as an influencing factor in conditions of both small wind movements and high wind velocities. Small irregularities in the surface layer, generally termed roughness, can give rise to relatively small variations in air movements in the microlayer in the landfill surface, and these can cause rapid variations in the methane emission. With snapshot field measurements, even with small variations in methane emission, it can be difficult to visually determine the representative ppm figure at the leakage source. However, simultaneous logging of laser data allows the calculation of average ppm data and the choice of maximum and minimum values for a selected measurement period.

- **The landfill's macrotopography (zones, top surface, slope, toe of slope and crest).**
  A landfill normally comprises landfill surfaces (top surface, slope, toe of slope and crest,) with variations in topography, partly caused by settlement in the landfill mass, and partly dependent on the structure of the landfill. A landfill lacking a final cover undergoes constant changes in topography, and usually consists of different cells of different heights, geometric form and surface size.

- **Emission contributions from other points or landfill surfaces**

  A laser instrument measures the concentration between the instrument and the backscatter surface. For detection, the task is to find methane leakage, often emission from a point source. There is a risk that methane from adjacent landfill surfaces will be included in the reading, especially when scanning over the landfill surface with the instrument pointing 10-15 m towards the backscatter surface. 'False' leakage is recorded.

  Consequently, it is important to be aware of major leakage in the different parts of the landfill at an early stage in a scan, at the same time as it is important to be aware of wind direction, as the wind transports imported methane. Here, topography is also important as the hills and hollows of the landfill affect the wind direction close to the landfill surface where the laser instrument records the methane concentration.

- **Distance between the measuring point and the instrument (laser - distance dependent, IR - temperature dependent)**
  The laser instrument for detection of methane is distance-dependent, and the IR system for detection and visualisation of methane is temperature-dependent.

  If the distance between the laser instrument and the backscatter surface is known, the average concentration can be calculated.

  As shown in the field laboratory experiments, each laser system has a special range/distance at which the laser can receive a backscatter signal that allows detection of the gas in question. The Siemens laser system is specified to approximately 30 m, but use of a suitable reflector surface can extend the operative distance to 150-200 m depending on the prevailing light conditions during measurement. The reflective material used on road signs is an ideal surface for a reflector.

  The temperature dependence of the IR systems is a greater problem. One way is to choose the time for the field measurement that gives a high temperature difference between the gas and the surroundings. Field laboratory measurements at Malmö Fire Service's gas testing facility, BARBARA, indicate that measurements at night under clear skies give stable measurement conditions for detecting and visualising methane emissions.

18.3 Georesistivity, conclusions

The fieldwork was performed under good conditions resulting in high quality field data in all measurements, showing a fairly consistent picture of the sub-surface formation. All measurements along all of the lines showed similar changes in resistivity, which indicate the data to be reliable and that the data provides a good basis for interpretation of sub-surface processes.

The results of the resistivity measurements showed values in the same range or somewhat lower than results presented elsewhere (Bernstone and Dahlin, 1997, Guérin et al., 2004). Also zones of much higher resistivity were registered during the measurements. High water content and ionic content, and high organic content in the waste can partly explain the relatively low resistivity values. It is suggested that a higher gas pressure in the sub-surface may partly explain the zones of high resistivity. However, also other processes such as temperature variations may influence the resistivity.

Relative differences in resistivity during the measurements were investigated by time lap inversion. The time lap inversion showed considerable changes in resistivity in the measurements, in particular at the foot of the slope. The sub-surface processes were considered to be fast since they took place within only a few hours. It is suggested that the fast changes in resistivity are mainly due to changes in gas pressure in the soil and thus indicating gas migration. To get a better understanding of the sub-surface processes in a landfill, other information such as pore pressure and temperature should be recorded simultaneously with the resistivity measurements.

Correlation between measurements with the laser and static chambers were investigated. By plotting the results a correlation was indicated, however, in some of the data sets high variability was indicate by low correlation coefficient. When some extreme values (so called outliners) were removed from the data sets, high and relatively consistent correlations coefficients were calculated. Thus, a correlation between the measurements with laser and static chamber were indicated.

When the resistivity data was compared with the laser and static chamber data, i.e., sub-surface and on-surface measurements, no apparent correlation could be identified. The resistivity measurements indicated a gas flow near the surface at the foot of the slope. However, in the laser and static chamber measurements these indications could no be confirmed. It is therefore concluded that to get a technical system for sub-surface measurements combined with measurements at the surface for identification of gas migration, further development of the techniques are required. It is also concluded that the sub-surface system is temporally and spatially highly variable, resulting in a system that is difficult to predict and further investigation are necessary to improve the methods to predict gas migration in landfills.

18.4 Manuals for use of the laser instrument and the IR camera

See Appendix 1.

19 CONCLUSIONS

Results from repeated field measurements of methane emissions from 6 landfills in Sweden and 2 in France indicate the following.

- Modern remote sensing technology, such as the Siemens laser system and the FLIR IR GasFinder system and georesistivity measurements, is considered to have large information and application potential for detecting, mapping and determining the position of methane emissions from landfills. The Techniques kan be used to increase knowledge about the specific properties of methane gas and behaviour at landfills.

- The slopes at a landfill give higher and more frequent methane emissions than a top surface. This particularly applies for steep and high slopes. Other factors that affect methane emissions from a landfill are cover, age and settlement. These factors vary between different landfills.

- The Siemens laser system, can be used for (a) systematically scanning and indicating the occurrence of gas emissions for large landfill surfaces, and (b) for detecting and determining the position of methane emissions from different leakage sources, features and surfaces in a landfill. The laser instrument can be used to scan for and detect methane at a rate of approximately 1 ha/h at a landfill.

- Infrared technology, such as the FLIR IR GasFinder, can for example be used as a complement to laser measurement for detecting, visualising, and showing emission of methane, identifying the leakage source, and for studying the diffusion pattern of methane.

- Results from repetitive field measurements with laser and IR systems indicate that remote sensing technology is generally accurate and is relatively easy to operate in the field.

- The Siemens laser system was developed to measure and record methane emissions in ppm, which is a measurement of concentration. It is point source emissions from the landfilled surface that can be detected by the laser instrument. The smallest detectable source emission gives a concentrations av about 35 ppm x m which corresponds to a methane concentration of ca 60 ppm in the air above the point source. This in turn corresponds to a leakage in the magnitude of 35 – 290 m^3 CH_4/year.

- All detected point sources at the landfills where the entire landfills have been scanned constitute a small portion of the total methane emission. The strength in the measurement method is not to find the total emission but rapidly detect where the emission point sources are located. The rapidity allows also repeated measurements that increases the reliability. Measurements after actions made to reduce the emissions show in an easy manner if the actions have been successful.

- Together with field reference data, data from field measurements with laser, IR and positional data from GPS can be stored in real time on a logger for comparative interpretation and analysis after fieldwork.

- The diffusion pattern of gas concentrations recorded by laser and field reference data can be shown cartographically in 3-D images, which makes it more possible to visually study and analyse the diffusion pattern of methane emission, the distribution and location of leakage sources, with methane concentration expressed in ppm for each leakage feature/surface.

- In the project the chamber method has been used to try to quantify the leakages the laser instrument has detected. If all individual readings with the chamber method are combined with corresponding readings with the laser instrument a correlation a relationship is obtained. It is then possible to get a quantitative measure of the leakage. The great difficulty is that the results cannot be verified.

- In a separate investigation experiments were made to map and study landfill gas movements in the landfill with georesistivity measurements. The results from the investigation indicate that rapid changes in resistivity occur which in turn can be interpreted as landfill gas movements. Much development work remains in order to get data that clearly can show then gas movements in a landfill.

- The disadvantages of the Siemens laser system are its limited range, specified at ≤ 30 m, and also that it is a prototype system that must be upgraded and made more robust for use in the field, in accordance with the end user's needs and wishes. According to field experiments in the project, the problem of the limited range can be solved by using a suitable reflective material, like that used on road signs, protective clothing, etc. as a backscatter surface. This simple measure can extend the laser's range to 150-200 m depending on the weather and radiation conditions.

- Together with field reference data, data from field measurements with laser, IR and positional data from GPS can be stored in real time on a logger for comparative interpretation and analysis after fieldwork.

- Research literature shows that there is an extensive research and development in progress studying the complex of problems surrounding methane emissions in order to develop techniques and methods to survey the emissions status at different types of landfills.

- A landfill consists of different zones, each having different methane gas emission potential. Such surfaces are top surface, slope crest, slope and slope toe. The top surfaces most often has low diffuse emissions due to a top cover with a goos function. Slope crests, slopes and toes have a more complicated structure and are more difficult to cover. Here settlement and insufficient cover cause fissures and other kinds of emission point sources. Open tipping faces must be mentioned as large methane emissions sources.

- When investigating emission status at a landfill it is suitable to divide the surface into zones typical for different emission potential. The zones are then investigated separately when identifying for diffuse point source emissions. When presenting an action program the division into zones also is advantageous.

- Landfill gas recovery systems and leachate collection systems are other important parts on a landfill to investigate systematically when scanning for methane emissions and evaluate their technical status.

- The division of the landfill surfaces into zones has structured and made the scanning- and evaluation work easier.

- The diffusion pattern of gas concentrations recorded by laser and field reference data can be shown cartographically in 3-D images, which makes it more possible to visually study and analyse the diffusion pattern of methane emission, the distribution and location of leakage sources, with methane concentration expressed in ppm for each leakage feature/surface.

- The slopes of a landfill gives higher and more frequent methane emissions than top surfaces. This is particularly valid for steep and high slopes. Methane emissions are also influenced by cover efficiency and waste age.

- The degradation of organic waste and methane producing processes in a landfill can continue for a long time after closure. This has been confirmed by results from laser measurements at a landfill mining project at the Ringstorp landfill in Helsingborg. The 50 years old waste still produces landsfill gas.

- Waste, in the form of objects that protrude through the cover, often gives rise to leakage because the cover is perforated.

- Field measurement with the Siemens laser system, supplemented with reflector material, means that this type of laser, like considerably more expensive laser systems on the market, can be used to measure and map the methane concentration over large landfill surfaces.

- Correctly developed and adapted to the end users' needs, modern remote sensing and operative remote sensing methods can become a cost-effective method for a series of different applications, such as:

  (a) Preventative control and maintenance of gas recovery systems in order to indicate whether the gas recovery system is in good functional order or that it has technical problems and deficiencies that can result in uncontrolled methane emissions.
  (b) As an aid for producing information for various types of measures/landfill activities.
  (c) Conducting checks, before and after measures have been applied.
  (d) Quality control and checking of different work processes in design and installation of pump stations and gas distribution systems.
  (e) Checking for involuntary transport of methane via gas pipelines and leachate systems (pipes, wells, ponds, etc.).

- Results from field measurements to determine the status of gas recovery systems indicate that modern gas pipe and pump systems (gas wells, etc) are generally in good functional order, while older gas recovery systems need continual supervision and upgrading of entire, or parts of, systems.

- Repeated long-term measurements over long measurement periods in different seasons, and under different weather and radiation conditions, seem to be the only way forward to describe and increase knowledge about the cyclical course of methane emissions, and to understand the behaviour of methane in landfills.

- It seems important for manufacturers of laser and IR systems for detection of methane emissions from landfills to jointly coordinate the development of the next generation of remote gas detection systems, adapted to the needs of end users.

20 FURTHER RESEARCH INTO SIGNIFICANT RESEARCH PROBLEMS

Like other R&D projects, such as the VOGUE project and the pilot studies in the field laboratories in Malmö and at Filborna landfill, this project has provided results that answer or illuminate important research issues but that also give rise to new issues that are considered important to study within the framework for more detailed research.

The VOGUE project led to the development of prototype laser systems for detecting and mapping methane emissions from distribution systems for natural gas, expressed in units of ppm x m, but also provided knowledge about the diffusion pattern and behaviour of methane under different pressure, flow, weather and radiation conditions.

Pilot studies at the field laboratories in Malmö and at Filborna landfill in Helsingborg provided knowledge about the usability and limitations of the prototype laser systems developed in the VOGUE project. These studies also provided information for assessing whether field measurements with laser and a newly-designed IR GasFinder system can be used to detect and map methane emissions from landfills.

These three projects, along with information obtained from research literature about landfill structure, methane generation, usability and limitations of established field measurement techniques, formed an important part of the knowledge bank used in planning and implementing the current project.

In a joint review during reference and work group meetings, and through contacts and discussions with researchers in neighbouring disciplines and subject areas, a number of questions have crystallised linked to the future technological development and upgrading of existing laser and IR systems, but also questions of a basic research nature. These questions concern the generation of methane in a landfill, the importance of the landfill material for the formation of methane, function and status of gas recovery and leachate systems, microbiological processes, etc. and also links between the development of knowledge, technology and methods in the field of landfills in Sweden relative to other countries.

The following is a brief presentation of some of the questions that are considered to be important to examine and try to answer within the framework of a more detailed R&D project.

1. It is important that the end users are provided with an inexpensive system that is practical in the field for detecting, quantifying, visualising and determining the position of gas emissions from landfills. Here, it should be observed that such a system should be adapted so that it permits measurements of a rapid course of events. In order to design such a system, both continued research and development activities are required, and a sufficiently large market.

   Against the background of the major initiative in the EU VOGUE project, there is reason to believe that there is both suitable expertise and interest in implementing this type of R&D project. The results of the research in the current project could be used as a knowledge bank and provide the basis for more detailed studies of field operation factors related to the detecting and mapping of methane emissions under realistic field conditions described in the project. This knowledge is necessary for the development of technology and field methods for the detection and mapping of gas emissions from landfills, adapted to the needs of end users.

2. Results from the project show that there is a need to carry out long-term measurements with lasers for a selection of landfill surfaces with known methane leakage, under different weather and radiation conditions and in different seasons. This is to increase understanding of the relationship between different factors and their influence on gas emission from landfills.

   Greater knowledge and understanding is needed about the behaviour of methane, and also about how different moisture, wind and pressure conditions influence the methane emission from landfill surfaces and can be used as input in flow models. This can also provide the basis for development of new measurement techniques, and also for preventative control and maintenance of a landfill and its distribution systems. Long-term measurement in this context relates to laser and combined field reference measurements for continuous measurement periods of 2-4 weeks.

   The field measurements in the framework of the current project, as reported in the chapter on methods, were carried out in the form of scanning of large landfill surfaces and also as detailed measurements of detected leakage sources. It was not until a relatively late stage of the project that a logger system was introduced that would allow measurement over longer time periods.

   In its present form, the laser system in question does not permit long-term measurements of the type described above. However, as shown by the results reported in Chapter 12, field measurements carried out with lasers and field data stored on the logger indicated large and rapid variations in methane emissions from leakage sources for both short-term measurements (0.5-1 minute) and for longer-term measurements (1-2 hours).

   The results from the completed project could be used as a basis for prioritising factors that should be the subjects of special study in order to increase understanding of how different landfill, weather and radiation conditions influence methane emission from landfills.

3. There is a need to carry out controlled field laboratory studies for a limited landfill surface in order to measure and study methane emissions with laser, IR technology, chamber method and resistivity measurements. The purpose of this type of field laboratory study is to, as far as possible, be able to study each variable in turn and evaluate its effect on methane emission. This type of field laboratory should also make it possible to measure diffuse methane emission from the landfill surface under controlled conditions.

4. Experiments with geoelectricity (resistivity) measurements carried out at landfills such as Filborna indicate that it is possible to map the movements of landfill gas at different depths. The method also permits the mapping of moisture conditions in the surface layer and localisation of water stores in a landfill. It is considered important to study the relationship between the movements of landfill gas and compare this with

the location of methane emissions in the landfill detected with laser and IR systems, combined with flow measurements using the chamber method.

5. In the research literature, observations and results are reported that, like the results of the current project, indicate that much of the methane from landfills is emitted from the distribution networks of gas recovery and leachate systems. It is considered important to examine whether these observations are correct and, if so, the scale on which the emissions occur. This question can either be studied within the framework of a separate project or be included as part of a more general R&D project.

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APPENDICES
Detection and quantification of methane leakage from landfills
Energy-Environment-Safety

APPENDICES:

1. Manual on the use of the Siemens laser instrument and the FLIR ThermaCAM™ GasFindIR LW

2. Technical Data for VOGUE Siemens AG, CT PS 8 Remote Natural Gas Leak Detector Field Unit

3. ThermaCAM™ GasFindIR LW

4. Selection of study sites and landfill surfaces

5. Methods for measuring concentrations and flows of methane

6. Field observations, laser instrument

7. Chamber method measurements, results

8. Georesistivity measurements, time of start for all sequences and at all lines

9. Georesistivity measurements, coordinates of all electrodes

10. Georesistivity measurements, timelaps

11. The use of remote sensing to determine the status of waste facilities – applications relating to energy and environment

APPENDIX 1

Manual on the use of the Siemens laser instrument and the FLIR ThermaCAM™ GasFindIR LW

1 GENERAL

The purpose of these guidelines is to help an operator assess methane emission from landfills. Determining the size of methane emissions from a landfill, as well as obtaining information about the location of the leak on a landfill surface, is important information for the landfill operator who is responsible for the external environment and operation of the gas recovery system at the landfill.

The method used in this project involved the use of a hand-held laser instrument for detecting the methane concentration over a landfill surface. The Siemens AG CT PS 8 laser instrument was used, which is especially designed to measure the concentration of methane in air.

In order to establish the scale of methane emission, the laser measurements as described in this manual must be supplemented with surface exit measurements using the chamber method or some other method.

The manual is divided into the following sections:

- Emission of methane from landfill surfaces
- Description of the laser instrument
- Introductory scan
- Preparatory field examination and measurements
- Full-surface scanning
- Compilation of results
- Measures and follow-up checks

The manual is intended for use for:

- Detection of methane emissions from surfaces in landfills
- Detection of methane emissions from installations, e.g. gas wells

The method can be used for landfills with systems for recovery of landfill gas and for landfills that have no such systems.

Methane is an odourless, invisible gas that is formed in a landfill when the waste is degraded anaerobically together with carbon dioxide. The gases are formed in approximately equal parts. In this context, the gas mixture is called landfill gas, and it can contain other gases in small quantities, such as hydrogen sulphide and methyl mercaptan, giving the gas an unpleasant odour.

A survey to detect methane emissions can be divided into two parts. Before direct field measurements, data is collected about the landfill components, as well as information needed for field measurements and compilation.

The first stage in field measurements of methane emission involves identifying major deficiencies relating to gas recovery. The system should operate as intended. The first stage includes identifying any major methane leakage that can affect the overall surface scanning that is carried out in the second stage. Such leakage sites can be the tipping face or sites of excavation into the waste in some part of the landfill. The laser instrument is used for the survey in the first phase.

Detection can then be started through a surface scan for undesirable methane emissions. The laser instrument is used to detect methane concentration in the atmosphere directly, usually expressed in ppm x m, thereby indicating the occurrence of methane leakage.

2 INSTRUMENT

At present, there are only a few instrument types available that can be directly used to measure methane in air in the way described here. However, it is likely that there will be more laser instruments in the future that can measure the methane concentration in the atmosphere above a landfill.

The following section shows how the Siemens laser instrument works. It differs in some ways from other instruments, but the properties, method of working, etc. are probably largely the same. A manual is always enclosed with an instrument that describes how it is to be used. Always read the manual for the specific laser instrument that is to be used.

The laser instrument measures the methane concentration along a beam. The laser beam sent out from the instrument is reflected back from the background (the backscatter surface) it strikes. The reflected part of the beam is recorded in a photosensor, and this signal is translated to the methane concentration along the beam. The instrument measures the concentration in ppm x m. If the beam's length can be measured, the methane concentration in ppm can be calculated by dividing the ppm x m figure by twice the beam length. The ppm figure obtained is the mean of the methane concentration along the beam.

As an aid to using the instrument, a visible laser beam (pointer) marks the route of the beam.

The instrument is hand-held, and is of low weight, approximately 1.5 kg. It is easy to point the instrument in different directions.

NB. The laser beam must not be pointed towards the sun, or the photodetector may be damaged. Avoid the cone that is formed 30^{o} around the sun.

The ppm x m figures are recorded 10 times a second, so the measurement is very fast. A display shows the current reading, and a concentration/time diagram that shows the most recent 16 seconds of readings.

The instrument is equipped with an output socket for transferring the data to an external logger.

The following information is also shown:

a) A warning when the battery is losing power, 10-20 minutes before the instrument automatically switches off.
b) Indication of the laser temperature, if it is too low or too high.
c) Indication that the laser's wavelength is not fixed to that of methane. This situation can arise, for example, when the instrument is taken from an indoor temperature to a cold outdoor temperature.
d) Indication that shows if too much laser light is reflected from the reflective surface, in which case the instrument shows zero.
e) Indication if too much light is entering to the photosensor from an external source of light. The instrument then shows zero.

After switching on with the yellow on/off button, the instrument is ready to use after 10-20 seconds. The pointer can be switched on and off with the red button as required when the instrument is operating. NB. The pointer uses quite a lot of battery energy and should principally be used for detailed measurement with the laser pointed directly towards the source of the leak, or when measuring over a long distance towards a reflective surface.

In the field, the instrument shows readings in ppm x m. There is a background concentration that is evident at low ppm x m figures. Up to a distance of 10 m to the reflective surface, the background concentration outdoors is approximately 10 ppm x m, and this can increase to approximately 200 ppm x m at longer distances.

The range of the instrument is approximately 30 m. With a reflector as the background surface, measurement can be taken over a much longer distance, up to 200 m. When directed towards highly reflective material, the instrument switches itself off and displays zero, because the intensity of the reflected light is too great.

3 INTRODUCTORY SCAN

Initially, information is recorded about the properties of the landfill surface. The total area is divided into zones. A zone should be a surface with relatively homogeneous conditions for landfill gas emission, where factors such as surface cover and slope are the same over the entire surface. Suitable zones are top surface, crest, slope and toe of slope. Top surfaces can have different coverings, and the quality of covering can vary in different parts, so it is advisable to divide up the surfaces into sub-zones, and the same should be done for slopes.

Older waste produces less gas than newer waste. Settlement is greater in parts of landfills with newer waste, so the surface cover can be subjected to greater strains. The risk of leakage is generally greater if the landfill section in question contains newer waste, i.e. waste that is less than ten years old. When dividing the area into zones, the age of the waste should be taken into account.

Crests are vulnerable parts of a landfill because they are exposed to the wind and because it is often difficult to cover crests satisfactorily.

From the perspective of methane leaks, the toe of slopes is also a sensitive part because the base of embankments can be permeable for gas, and the leachate system can also often lead out landfill gas from under a landfill.

Information is collected about:

1. The entire surface of the landfill.
2. Zones that can be assumed to have different emission properties. A zone is a surface that can be assumed to have similar covering, etc. over its entire area.
3. Installations that could cause methane emission.

   A suitable division is:

   a) Top surfaces, good covering (here, defined as ≥1 m covering with earth)
   b) Top surfaces, unsatisfactory covering (< 1 m cover, or visible waste in the surface)
   c) Slopes, covered, treated slopes, > 1 m cover with earth, no erosion damage
   d) Slopes, not levelled, inadequately covered slopes, < 1 m cover, protruding waste
   e) Crests
   f) Toes of slopes
   g) Ground by gas wells and pipes at the landfill
   h) Wells that are part of the leachate collection system

4. State of the landfill gas recovery system. The following is examined:

   a) The design of the landfill gas recovery system, and which parts of the landfill have an active gas recovery system. A plan showing the components of the recovery system is to be included in the initial study. Location of the recovery wells, the control station, and where and how the landfill gas system is monitored.
   b) Recovery measured in m^3/h or other unit.
   c) Comparison with normal figures for the facility.
   d) Survey if any part of the recovery system is switched off.

An active tipping face is often associated with large emissions of methane because the landfill surface is not covered. Nowadays, organic waste is only deposited in exceptional cases, and the risk of major methane leakage is therefore smaller because there is no fresh waste near the surface in the tipping face.

The above information is collected and compiled. This then describes the main features of the landfill gas recovery system, as well as the division of the landfill into zones, where each zone is characteristic in terms of emission.

4 PREPARATORY FIELD EXAMINATION AND MEASUREMENTS

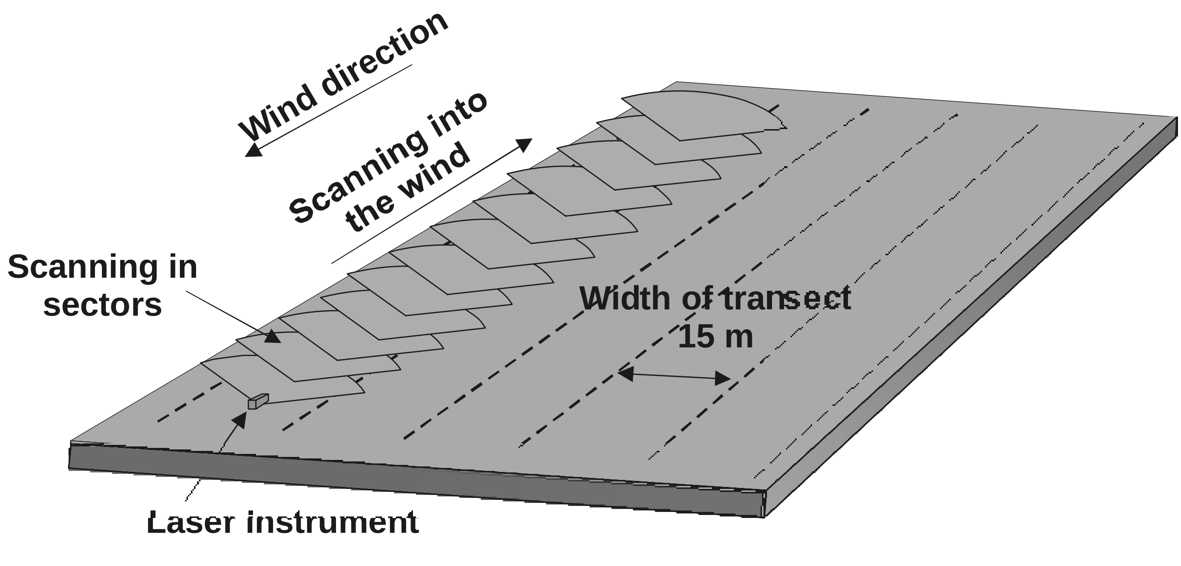
Before the full-surface scan, an initial survey is carried out in the field to ensure that the zones have been correctly selected. At the same time, the laser instrument is used to see whether high concentrations are evident at tipping faces, sites of excavation, leachate wells or other sites or surfaces where major leaks can occur.

This initial survey is carried out to detect the location of major methane leakage before the detailed surface scan.

5 FULL-SURFACE SCANNING

The survey starts with a full-surface scan over all zones. Each zone is scanned individually.

The laser instrument is moved in a sweeping motion, back and forth, so that the beam hits the ground surface 15-20 m in front of the operator. The operator has previously planned the transects so that the laser instrument is moved forwards in the sweeping motions and against the wind (see the principle in Figure 5.1. Where concentrations exceed the background levels, the sweeping motion is intensified in the direction of the higher concentrations, at the same time as the operator walks in the direction of the leakage source. The leakage point is marked with a pole for later accurate measurement.



The leakage source is documented as follows:

a) Marking of leakage site.
b) Documentation of the leakage site. Depending on the accuracy required, the site can be marked directly on the drawing used directly in the field, or its position can be determined with GPS.

c) Measurement with the instrument near the source. Based on the concentration level, the distance from which the leakage is to be measured is determined. At 0.5 m, the instrument measures directly in ppm. In a first scan, it is sufficient to measure in the instrument's ppm x m, but in that case recording must be done at the same distance from the leakage from all points, to allow comparison between the points. Because methane mixes with air very quickly, and because the methane can stem from another leakage point than that being measured, the distance should be relatively short, 30-50 cm.
d) A leakage site can comprise leakage from visible fissures in the cover of a landfill, individual points (which also may be invisible fissures, leakage by protruding waste, etc). The leakage may also stem from the ground near a gas well.

Surface scanning yields the following information:

a) Information about the number of leakage points in a zone;
b) The position of each leakage point;
c) The concentration level of methane above each leakage site. This is a relative measurement that cannot be directly translated to a flow measurement.

6 COMPILATION OF RESULTS

The results of the field measurements are compiled on a drawing on which the sites of detected methane emissions are entered. An analysis is carried out, and zones with large or many points of methane leakage are highlighted. At this point, a check is made as to whether the gas recovery system (if any) in the marked sections is working normally. The surface covering of the marked parts is checked. Measures are proposed for surfaces with unacceptable methane leakage.

7 MEASURES AND FOLLOW-UP CHECKS

Measures such as supplementary surface covering should be followed up with a new surface scan. The measures may result in a move in the site of the gas leakage, so the new surface scan should also cover adjacent zones.

Manual for FLIR ThermaCAM™ GasFindIR LW (shortened to the FLIR IR GasFinder in the manual)

The FLIR IR GasFinder is a thermal camera with a detector that has a spectral range sensitive to gases such as methane. Like all IR systems, the thermal camera is temperature-dependent, so that in order to record and create an image for methane emission, a temperature difference between the gas and the surrounding air/surface of ≥ 2 °C is needed. In this project, the limit of detection for methane in relation to that of the Siemens laser was fixed at ≥ 2,000 ppm, depending on delta T between the methane and the surrounding temperature and the prevailing weather and radiation conditions at the time of measurement.

The FLIR IR GasFinder is a hand-held system that detects and visualises methane in the long-wave spectral range, 10-11µm, at an operative temperature in the interval –15 - +40 °C. The normal lens is 50 mm (11°) with supplementary lenses of 25 and 100 mm. Measurements are stored digitally on a small hand-held DVD and display unit.

Settings and calibration of the system before and during field measurements

1. For field measurement, it should be noted that the IR GasFinder system has three sensitivity settings or temperature ranges. At the start of the field measurements, the operator determines the temperature range that gives best thermal and geometric resolution for the application. While conducting field measurement of methane emissions from, for example, a landfill, the weather and radiation conditions can change, so the operator may have to switch to a different sensitivity setting during the course of measurement.

2. **NB.** The IR GasFinder system has a built-in reference for internal calibration of the detector. In order to retain an optimal and stable thermal and geometric resolution, the operator should manually calibrate at regular intervals. This is done by placing a lens cap on the lens and pressing a button to carry out calibration, where the black surface inside the lens cap serves as a black body radiator against which the detector is calibrated.

3. The operator sets the depth of field manually. It is important that the operator adjusts the definition against a stable point/surface before and when the focus is changed. This is done by focusing on a feature or landfill surface located further from the camera lens than when the field measurement was started.

   Note that, unlike laser technology, infrared technology is not distance-dependent but is temperature-dependent, as described above. This means that the IR GasFinder system can record and visualise methane emissions, and monitor and study the diffusion pattern of a methane cloud located far from the thermal camera, on condition that delta T between the methane and the surroundings is sufficiently large, ≥ 2 °C, and that conditions, particularly the wind, are such the gas is not quickly mixed with the surrounding air.

4. The IR GasFinder can either be used held in the hand of the operator, or can be fitted on a stable camera tripod and manoeuvred manually in horizontal and vertical directions. Thermal image data in the form of a moving thermal picture can be studied visually in the camera or in the display unit of the DVD recorder.

   The FLIR IR GasFinder system can also be fitted on a mast on a car, or on a helicopter platform where the camera unit is controlled via a joystick unit inside the vehicle. A manual for vehicle and airborne applications is not included here.

5. Thermal image data is stored digitally on the DVD unit for editing, analysis and evaluation after the field measurements are complete. Stored moving thermal image data can be presented as video films or as still frames selected from video sequences.

Operation of the IR GasFinder in the field

The FLIR IR GasFinder system can be used separately for detecting, mapping and visualising gas emissions from landfills, or as a complement to measurements using the Siemens laser system or similar laser systems for measuring gas.

Procedure:

- Like the Siemens laser system, field measurements begin by scanning the landfill or landfill surface for which the emission status is to be mapped. After the scanning stage, the operator returns to the features and surfaces that are considered interesting, and supplements the data with detailed measurements in which the operator tries to detect and track the methane's diffusion pattern from the leakage source until the methane is mixed with the air so much that it can no longer be detected with the GasFinder. Where there is access to a laser, such as the Siemens laser system, the field measurements are carried out in reverse order; the area is first scanned with the laser, followed by detailed laser measurements, and supplemented with a detection and visualisation stage using the IR GasFinder system.
- Where methane emission is large, the IR GasFinder system is used, for example, to locate the leakage source, study the diffusion pattern, and provide a basis for detailed measurement of the methane concentration with the Siemens laser system.
- The operator detects and visualises methane emissions from gas recovery and leachate systems by positioning the equipment vertically against the wind direction and the assumed gas leakage flow from the gas control or leachate well. An attempt is made to find the optimal distance between the GasFinder system and the leakage source in order to try to capture and record the diffusion pattern and the course of the gas plume, from emission at the source to mixing, and finally, dissolution of the methane cloud into the surrounding air.

Experiences from the combined use of the laser and IR systems indicate that the best and operatively optimal solution for detecting and mapping methane emissions from landfills would be to have, in a single system, access to both laser and IR technology and a built-in GPS system. Such a system has existed since the end of the 1980s, developed by Laser Imaging System, LIS, Punta Gorda, Florida, USA. There is a manual for use of the system, but it only applies for stationary use in refineries.

APPENDIX 2

TECHNICAL DATA FOR VOGUE SIEMENS AG, CT PS 8 REMOTE NATURAL GAS LEAK DETECTOR FIELD UNIT

Laser operating wavelength	1,651 nm
Laser output power	< 10 mW
Beam divergence	60 mm @ 10 m distance
Laser class	1
Visible laser wavelength	635 nm
Laser output power	<1 mW
Laser class	2
Response time	100 ms
Methane gas concentration range	Depending on reflected power 0 >1,000 ppmm[1]. When the reflected power increases, the max. resolvable concentration decreases.
Power consumption	2.5 - 4 W depending mainly on ambient temperature
Operating time with one battery charge	3-5 hours with rechargeable cells (2,000 mAh) depending on ambient temperature, probably longer with primary cells.
Operating temperature range	-10 - +40 °C
Operating distance range	>10 m depending on reflecting surface
Lower detection limit	10 -20 ppmm depending on reflected power

[1] When the concentration exceeds the max. resolvable concentration, the display shows the max. resolvable concentration as long as the concentration is higher

APPENDIX 3.

FLIR SYSTEMS The global leader in infrared cameras

ThermaCAM™ GasFindIR-SW

Specification:

Description
ThermaCAM™ GasFindIR allows you to detect gas leaks quickly and safely. ThermaCAM™ GasFindIR is capable of rapidly scanning large areas and hundreds of components. ThermaCAM™ GasFindIR is a real-time infrared camera for visualization of gas leaks. The camera is a rugged piece of equipment and is designed specifically for use in harsh industrial environments.
§ IR camera for real-time visualization of gas leaks § Trace leaks to its source § Reduced inspection time § Perform safer inspections § Lightweight, small rugged designed § Very good thermal sensitivity <35 mK @ 30°C (+86°F) § Allows you to detect methane and other volatile organic compound (VOC) gas leaks

Detects the following gases:
Benzene, Ethanol, Ethylbenzene, Heptane, Hexane, Isoprene, Methanol, MEK, MIBK, Octane, Pentane, 1-Pentene, Toluene, Xylene, Butane, Ethane, Methane, Propane, Ethylene, Propylene

Licensing and classification
License informationFixed (non-removable) lens version of the ThermaCAM™ GasFindIR requires US Department of Commerce License, except inside US.

Imaging and optical data
Lens mountingFixed (non-removable) lens
Field of view (FOV) / Minimum focus distance22° × 16° / 0.2 m (0.66 ft.)
Focal length25 mm (0.98 in.) Spatial resolution (IFOV)1.2 mrad
F-number2.3
Thermal sensitivity/NETD35 mK @ +30°C (+86°F) Image frequencyMax 25 Hz (PAL) FocusManual Zoom2× and 4× Digital Zoom

Detector data
Focal Plane Array (FPA) / Spectral rangeCooled InSb / 3–5 µm IR resolution320 × 240 pixels Sensor coolingStirling Microcooler (FLIR MC-3) Well capacity18 e^6

Electronics and data rate
Intergration type (electronic shutter speed)Snap shot Intergration timeSelectable: 1–64 ms Read-out modesIntegrate while read Dynamic range12-bit Full frame rate12.5, 25, 50 Hz (PAL)

Scene temperature range (50 Hz/60 Hz)
High (50 Hz/60 Hz) (power switch setting = 3)15°C to 65°C (59°F to 149°F)
Medium (50 Hz/60 Hz) (power switch setting = 2)40°C to 175°C (104°F to 347°F)
Low (50 Hz/60 Hz) (power switch setting = 1)–15°C to 15°C (5°F to 59°F)

Image presentation
InterpolationNone
Video outputRS-170 EIA/NTSC or CCIR/PAL composite video ViewfinderBuilt-in viewfinder, 800 × 600, OLED, B/W External displayVia personal video recorder

Storage of images
Image storage typeIncluded personal video recorder File formatsStandard .avi or .asf video format

Video recording and streaming
Video recording typeRecording of video sequences to personal video recorder.
Streaming type8-bit analog output

Data communication interfaces
Serial communication, purposeCommand and control Serial communication, standardRS-232 Serial communication, connector type7-pin Fischer connector Video, standardCVBS (ITU-R-BT.470 PAL/SMPTE 170M NTSC) S-video Video, connector typeBNC (CVBS) 5-pin Fischer connector (S-video)

Power system
Battery typeNiMH
Battery voltage6 V
Battery capacity4.2 Ah
Battery operating timeApprox. 2 hours at +25°C (+77°F) ambient temperature and typical use Charging systemIncluded battery charger (AC adapter or 12 V from a vehicle)

Environmental data
Operating temperature range–15°C to +50°C (+5°F to +122°F) Storage temperature range–40°C to +70°C (–40°F to +158°F) Humidity (operating and storage)20–80% (non condensing) EMC§ EN 55011:1998 (Emission) § EN 61000-4-2:1995 (Electronic Discharge) § EN 610000-4-3:1996 (Electromagnetic Field Immunity) § EN 61000-4-3:1993 (Magnetic Fields)

Physical data
Camera weight, incl. lens and battery2.20 kg (4.85 lb.) Camera size (L × W × H)262 x 158 x 132 mm (10.3 x 6.2 x 5.2 in.) Tripod mountingUNC ¼"-20

Scope of delivery
Packaging, contents§ ThermaCAM GasFindIR Camera § 25 mm lens cap § Optical cleaning kit § Neck strap § Battery charger, 2 ea.
§ NiMH battery, 3 ea.

§ User’s Manual
§ Hard transport case
§ S-Video cable
§ Video cable
§ Personal Video Recorder (PVR) and battery § A/V Cable for Personal Video Recorder

Administration
Revision20438-251, 1.05

Supplies & Accessories
§ EXT-WAR-GCAM One Year Extended Warranty for InSb GasFindIR § 25147-210 GasFindIR upgrade to GasFindIR HSX § 03198-000 Cable-BNC 6FT § 14730-000 Cable-RS-232 Remote § 20981-500 Cable S-Video GasFindIR § 21466-000 A/V Cable for Archos PVR § 21465-000 Personal Video Recorder § 17619-200 DR 11 NiMH Battery § 3301011 Hard Transport Case § 09289-200 Optical Cleaning Kit § 17151-002 Battery Charger (NiMH)

APPENDIX 4

SELECTION OF STUDY SITES AND LANDFILL SURFACES

1 GENERAL

Measurements with the VOGUE laser and the FLIR GasFindIR instruments were carried out in Sweden at six landfill facilities with gas recovery systems, and a smaller landfill without gas recovery. The selected facilities vary in volume and scale, and differ in terms of gas generation and methane emission. The landfills were studied at different seasons and were located in different climatic regions of Sweden (see locations in Figure 1.1). Four of the landfills were also examined using the chamber method for determining the size of the emission.

Laser and IR techniques were also used to carry out measurements at two landfills in northern France. At these landfills, complete scanning, pinpointing of specific methane leakage features, and chamber method measurements were carried out.

Figure 1.1. Swedish landfills studied in the project

2 SPILLEPENG LANDFILLS

The old parts of Spillepeng, the regional landfill for the Malmö region, which is owned and operated by SYSAV, lie on the coast at the edge of Malmö harbour. The oldest parts are on land, while the younger parts comprise embanked parts of Lomma Bay and are below sea level. The older parts are finished, and have been transferred to a foundation that manages the completed areas.

The older parts are gently sloping and have been covered with earth masses of varying thickness. These parts have gas recovery systems that have been in operation since 1983.

The embanked stages have been filled since 1985, and the landfill is still in operation. Before the ban on deposition of combustible waste, the waste comprised industrial waste, slurry and ash. The different types of waste have been deposited in large, separate cells. The areas that have received degradable waste have gas recovery systems. The total area of Spillepeng is approximately 120 ha, of which the newer part comprises 55 ha.

3 SPILLEPENG TEST CELLS

The test cells at Spillepeng were examined as part of a research project comprising 12 test cells at three waste facilities in Sweden. (Samordnad deponigas, Forskning, Utveckling, Demonstration; RVF Rapport 97:7; ISSN 1103-4092). The aim of the project was to optimise degradation of waste and thereby landfill gas production. The six cells were placed on top of older waste in the land-based parts of Spillepeng. All cells had sophisticated basal sealing, leachate collection systems and gas recovery systems. A total of 25,250 tons of waste was deposited in the cells in 1988 and 1989. The waste was of different types in order to examine the significance of the composition of the waste on the amount of gas production. All the cells were covered with 0.5 m moraine clay, and a surface cover of 0.3 m soil.

During the study period 1990-1995 (four years), the rate of gas formation in the cells was 39-71 m^3 biogas/ton, normalised to 50 % CH_4.

After covering, considerable settlement has occurred in the waste. In the summer of 2006 and the spring of 2007, the cover was renewed on all cells where settlement had, over time, ruptured the original covering layer and rendered the gas recovery system unusable. At the same time, the gas recovery system was rebuilt.

4 FILBORNA WASTE FACILITY

The landfill at the Filborna waste facility is owned and run by NSR AB in Helsingborg. Deposition on the site began in 1951 with household waste from the city of Helsingborg. A special feature about this landfill is that the external slopes comprise a bank of earth. Of the total landfill volume, 11 Mm^3, an estimated 4-5 Mm^3 comprises earth.

The landfill is rectangular in shape with relatively steep external slopes and a top surface with gentle slopes. The landfill is approximately 45 m above the base level and comprises 35 ha.

In 2006 and 2007, the landfill received approximately 70,000 tons of waste annually, comprising mixed household and industrial waste. This older part will be completed in 2008. In the 1990s, approximately 200,000 tons of waste was deposited per year. For many years, new waste was deposited on top of the older waste. Since 1990, all waste has been deposited in separate cells.

Landfill gas recovery was started in 1985. At present, approximately, 1,800 m^3/hour is recovered. Recovery was greatest in 2004 with approximately 2,200 m^3/hour, after which it decreased. The recovery is through horizontal drains in the cells and through vertical wells down to a depth of approximately 20 metres. The most common problem with the gas recovery system is water in the landfill that blocks recovery wells and collection pipes. New supplementary wells are installed approximately every fifth year in order to retain a high level of recovery.

The landfill gas is used for the production of electricity and district hearing as part of the Helsingborg district heating network. The total installed power is approximately 20 MW.

Approximately 10 ha of the Filborna landfill have a final cover. Today, waste is deposited in an area of approximately 4 ha. The remaining areas comprise intermediate covering, storage surfaces for earth products, etc.

Four cells are covered with plastic sheeting. Waste was deposited in these cells from 2001 to 2005, so the waste is relatively fresh.

5 HAGBY WASTE FACILITY

Hagby waste facility is located in Täby municipality in northern Greater Stockholm. The facility, including a large landfill (Löt), is run by SÖRAB. Waste has been deposited on the site since 1960. At the start, the landfill was placed on a sloping piece of solid ground but since 1970, an area of wetland adjacent to the older landfill has been used. The landfill area totals 49 ha. The two large stages, I and II, comprise 3 Mm^3 of waste.

5.1 Stage I

Stage I lies approximately 10 m above the base level. It was completed in 1977 and is covered with 0.5-1.5 m unsorted earth masses. All parts are covered with vegetation, and pine forest covers much of the landfill. Ground vegetation is grass.

The stage has a landfill gas recovery system that has been in operation since 1977.

5.2 Stage II

Stage II comprises a landfill part situated in the wetland. It is surrounded by large embankments of crushed stone that have sunk down into the wetland's basal layers of loose clay and increase the stability of the landfill. The crushed stone works in the same way as leachate draining. The landfill has gentle slopes and comprises a total of 22 ha. Waste was deposited in the landfill between 1977 and 1995.

5.3 Test cells E89 and E90

In 1989, SÖRAB started an experimental programme aimed at optimising landfill gas production. One cell, an energy cell (E89), was filled in 1989 with 9,000 tons of crushed household waste. The leachate was recirculated and heated before reinfiltrating the waste masses. Landfill gas production started rapidly and was initially very large. A new reactor was commissioned in 1990 but without heated leachate recirculation.

Both the cells are covered with low-permeable peat, a plastic sheet, and earth masses 0.5-1.0 thick.

6 LÖT WASTE FACILITY

The Löt waste facility is situated between Stockholm and Norrtälje, 40 km north of Stockholm. The facility, operated by SÖRAB, was opened in 1995 as a new large waste facility for northern Greater Stockholm.

Deposition of combustible waste was banned in Sweden in 2002 and deposition of organic waste in 2005. Because of this, much less waste is now deposited at the Löt facility.

The landfill used in these studies comprises a 6 ha, 25-metre high landfill in which industrial waste is deposited. The total waste volume is 380,000 m^3. The slopes are relatively steep and are not completely levelled. The northern slope is levelled and has been covered. The flat top surface is small compared with the slope surfaces. The top surface is covered with approximately one metre of earth.

In 2006, i.e. during the study period, the landfill was equipped with a recovery system for landfill gas.

7 HÖGDALA WASTE FACILITY

Waste deposition at Högdala began at the end of the 1960s. At that time, the landfill area was smaller, and it was expanded in the 1970s. Since 1 January 1999, no waste has been deposited at Högdala waste facility. The quantities deposited in 1988-1999 are shown in Table 1.1. However, earth masses have been accepted and stored for use as final cover for the landfill. The landfill was finally covered in 2000-2001.

SITA’s office in Solna lacks data from the 1970s and 1980s, so information for this period is missing from the presentation below. Since the start of the landfill, in addition to industrial and household waste, ash has also been deposited.

Table 1.1. Högdala waste facility: quantities of waste deposited

	Industrial (m^3)	Household (m^3)	Clay (m^3)	Screenings (m^3)	Excavation masses (m^3)	Soot (m^3)
1988	493,400	41,100		1,100	9,000	
1989	526,200			800	4,700	550
1992	488,100	5,900		800	7,608	
1993	386,147	6,750		836	10,590	
1994	367,852	3,120	10,000		6,444	
1995	293,286	60			5,740	
1997	122,446	0	0		9,183	
1998	137,918	0	0		26,311	
1999*					50,000	

* Deposition of waste ended in 1999.

The landfill has a gas recovery system. The recovered gas is flared.

8 FORSBACKA WASTE FACILITY

Forsbacka waste facility is situated between Gävle and Sandviken, 170 km north of Stockholm. Organised deposition began in 1975 at an old landfill comprising 5.8 ha. The part that is now being used is from 1984 (16 ha). Waste deposited comprises a mixture of household and industrial waste. Since 2002, the amount of waste deposited has fallen considerably, and the annual addition is now approximately 10,000 tons of non-combustible, inorganic waste. The height of the landfill is approximately 17 m.

The landfill has relatively steep slopes not all of which are satisfactorily covered. In the east, the top surface is flat, and the rest slightly undulating down to the slopes. The surface of the western part has been levelled and covered with earth masses and waste slurry. Approximately 1.5 Mm^3 waste is deposited in the more modern part of the landfills.

Landfill gas is recovered in a recovery system and is used for electricity production.

9 ÄNGLARP WASTE FACILITY

Änglarp waste facility is situated south of Svenljunga in Svenljunga municipality. The facility has a landfill that has been in use since the 1960s. The landfill is in two parts.

Older part, no longer in operation
Area: 5 ha
Average height of landfill: 4 m
Lowest elevation: + 160 m
Highest elevation: +177 m
Volume of waste deposited: 200,000m^3

Types of waste: Household waste, industrial waste, sewage slurry, ash from solid fuel incineration

Present part, in operation

Area: 2.5 ha
Average height of landfill: 6 m
Lowest elevation: + 157 m
Highest elevation: + 169 m
Volume of waste deposited: 150,000 m^3
Types of waste: Household waste, industrial waste, sewage slurry

The older part is now used for composting of garden waste, and storage of wood shavings and scrap metal. The part that is now used is dominated by a slurry lagoon, where slurry from a tannery is deposited.

10 FRENCH SITE 1

The landfill is situated in northern France. The landfill was started in 1975 and it is still being filled. It is divided into three adjoining zones. Information about the three zones is shown in Table 1.2.

Table 1.2. Area, waste quantities, etc. in zones 1-3 of F1, France

Zone	Area, ha	Deposited quantities (tons)	Years of operation	Cover
1	6.2	400,000	1975-1990	0.5 m clay
2	4.2	260,000	1975-1990	0.5 m clay and 1 m earth
3	6.3	640,000	1990-2005	1.0 m clay and vegetation layer
Expansion	1.0	225,000	2005-	

Information is lacking about the quantities of waste deposited before 1991. However, an estimate of the landfill volume for the period prior to 1991 suggests that 35,000-47,000 tons were added each year. Over the period 1991-2006, an average of approximately 70,000 tons of household and industrial waste was added. Most of the waste was household waste.

The landfill gas system comprises 60 vertical wells in the three zones. The gas is not used, but is flared in a BG 2000 burner placed centrally in the landfill. Every month, approximately 800,000 m^3 landfill gas is recovered, the equivalent of 9.6 Mm^3 per year. The methane content is 30-35 %.

Methane emission quantities were measured in 2005 using FID and the chamber method. The results of these measurements are shown in Figure 1.2.

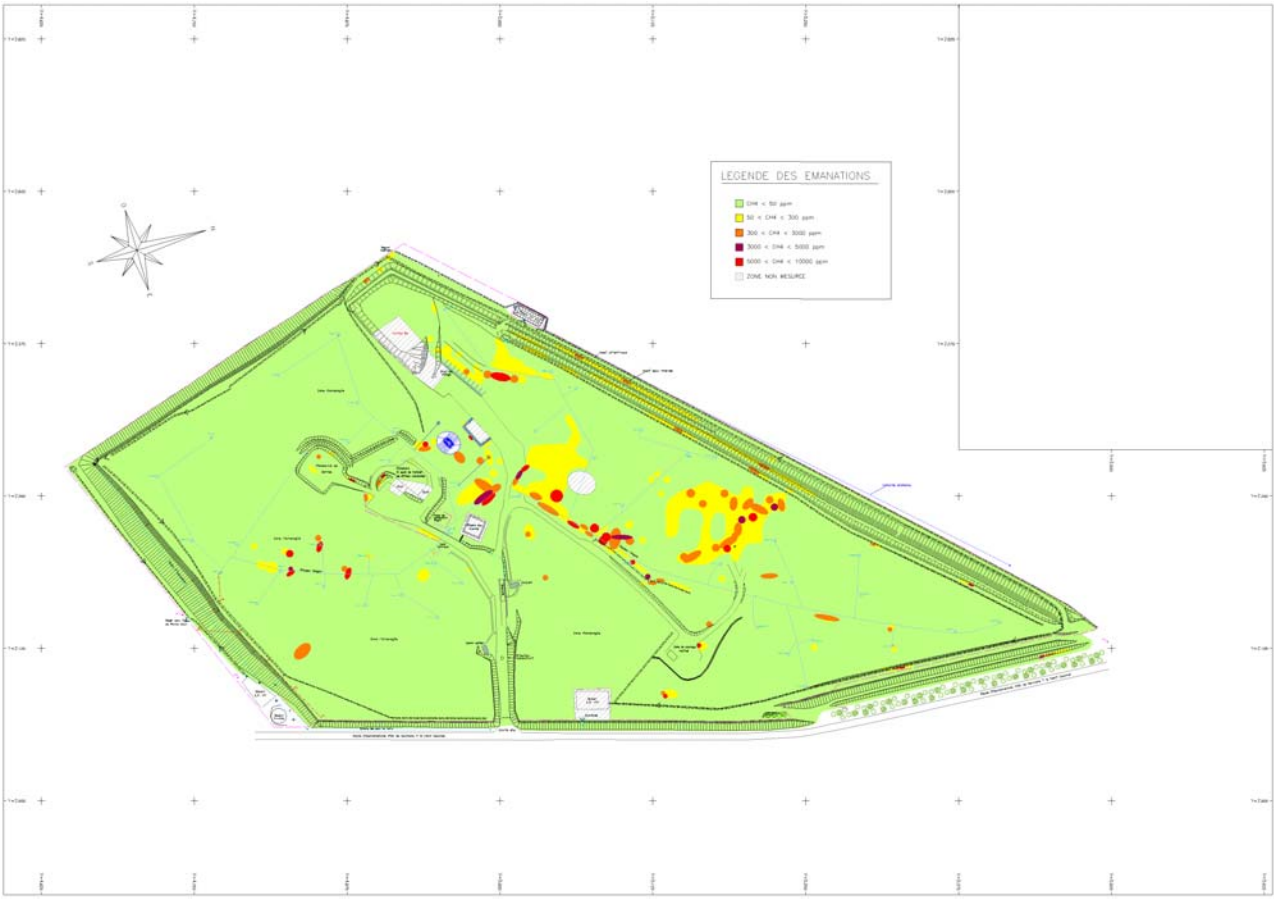


Figure 1.2. F1, Centre de Stockage de Dechets, site layout. The plan also shows the results of the field measurements with FID, carried out in March 2005.

11 FRENCH SITE 2

The F2 landfill is situated in northern France.

The landfill, which is owned and run by SITA, was started as early as 1946. It can broadly be divided into an old part, which has a final cover (1 m clay) and a newer part that is currently in operation (see Figure 1.3). The older part was fully filled in 2001. The site comprises a sand quarry that was used as a landfill after quarrying activities ended. The old part comprises 12 ha. In 2002, this part was fitted with a gas recovery system. Previously, waste was added at a rate of less than 21,000 tons/year.

The newer part that is now in use is divided into seven cells, and has an area of 6.5 ha. The filled cells have different types of covering. One cell is used for reinfiltration of leachate. The others are covered with 0.25 m earth or similar. Current deposition is 160,000 tons/year, approximately equally divided between household waste and industrial waste.

The recovery system for landfill gas comprises 118 wells, of which eight are combined recovery wells for both leachate and landfill gas. In 2006, slightly over 11 Mm^3 landfill gas was recovered. The EPER register shows that methane emission in 2004 was 1,370 tons, corresponding to approximately 3.9 Mm^3 landfill gas (at 50 % methane). The proportion of recovered gas, based on the figures reported, is approximately 75 %.

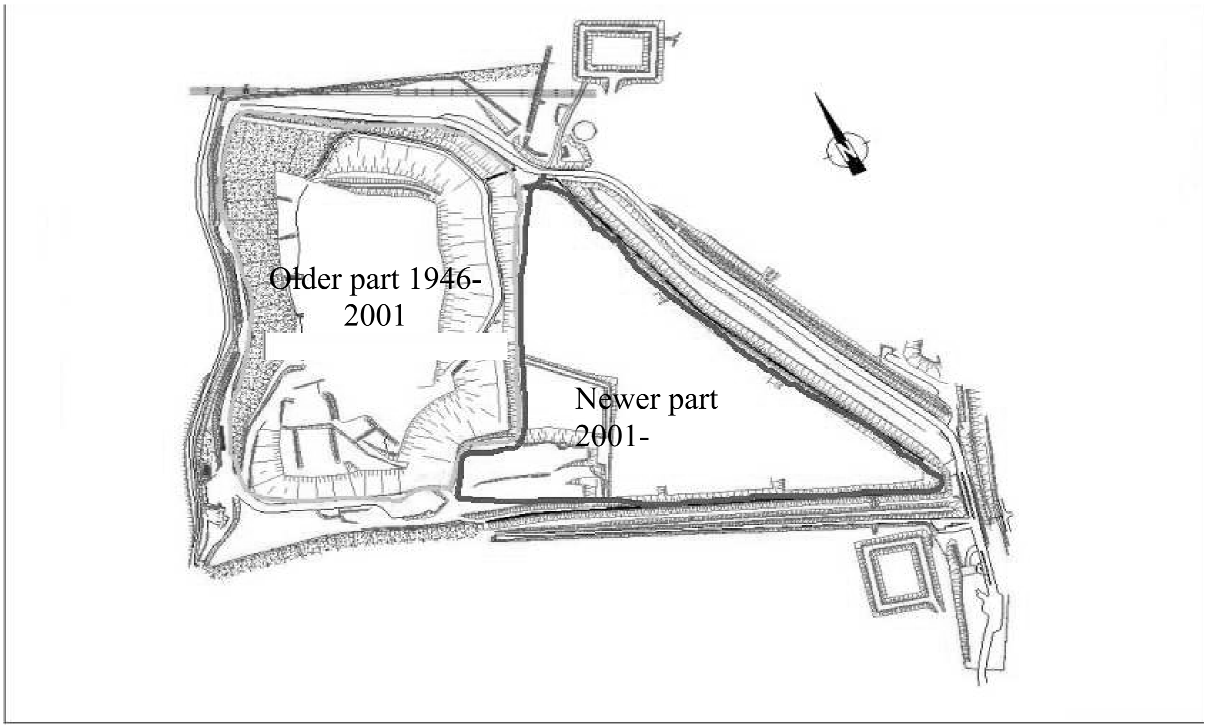


Figure 1.3. F2, site plan. The newer part is now partly filled (2008).

APPENDIX 5

METHODS FOR MEASURING CONCENTRATIONS AND FLOWS OF METHANE

1 GENERAL

There are a large number of methods for measuring methane gas. The purpose of this chapter is to systematise the methods and to review them according to how they are used. The methods described in the following section are either established or are under development.

The methods available naturally depend a lot on the criteria applied. These can be criteria placed by the operator (the entity running or responsible for a landfill) or various criteria placed by authorities.

No official emission limits have been placed, neither qualitative nor quantitative, for landfills.

Techniques and methods for detecting and quantifying methane from landfills can be divided as follows (Envirotech Engineering 2007):

1. Methods for detecting point source emissions and measuring concentration;
2. Methods for quantifying the size of leakages;
3. Methods for measuring areas, both leak detection and quantification.

Methods for detecting point source emissions are those developed in the natural gas industry, principally for measuring leakages from main pipelines (primary networks) and local networks (secondary networks). The methods available for measuring large areas cover parts or all of a landfill.

2 DETECTION OF POINT SOURCE EMISSIONS THROUGH MEASUREMENTS OF CONCENTRATION

The methods for detection can be divided as follows:

1. Close range detection of point source emissions
2. Remote sensing
3. Airborne methods

Once again, this division of methods has been taken from the natural gas and petroleum industries. The application of the methods in the waste industry has been added, increasing their value.

Generally speaking, an instrument that is to be used for detection should have the following properties (Environtech Engineering, 2007):

- Stable and accurate recording at ppm level, and preferably also at percentage level.
- Rapid response time
- Specifically set for methane, without recording other gases
- Be classified for use in explosive gas-mixtures environments
- Robust outer casing
- Resistant to bad weather and dust
- Sustainable operation
- Stable settings
- Easy maintenance
- Can be used by an operator without lengthy training
- Low purchase and running costs

The methods for detection and measurement close to the point source of emission are as follows:

1. Flame ionisation
3. Catalytic combustion
4. Solid State (SS)
5. Infrared absorption (IR)
6. Tunable Diode Laser Absorption Spectroscopy (TDLAS)
7. Bubble test
7. Vegetation changes
8. Acoustic detection

Remote sensing methods are as follows:

1. Passive IR Gas Imaging - Thermal visualisation
2. Passive IR Gas Imaging - Multi-Spectral visualisation
3. Open beam - Tunable Diode Laser Absorption Spectroscopy (TDLAS)

Airborne systems use the following measurement methods:

1. Tunable Diode Laser Absorption Spectroscopy (TDLAS)
2. Differential absorption LIDAR
3. Passive gas filter correlation radiometry

Flame ionisation (FID)

The technique is not described but, as the name implies, ions formed in the presence of hydrocarbons are measured. Flame ionisation can be used to detect methane. At higher concentrations than 50,000 ppm, the instrument can be extinguished. The instrument requires time to warm up. As with many instruments where gas is captured, the instrument can be unusable if water enters with the gas.

Flame ionisation is used for surveying point source emissions on landfills. Some instruments are portable. One model has combined the FID detector with a GPS, so that both position and concentration can be recorded simultaneously.

Catalytic combustion

Catalytic combustion is the original method for measuring, for example, methane concentration. The method is mostly used for stationary measuring points, but measures very quickly.

Thermal conductivity

A physical method that does involve any chemical reaction, and that can measure, for example, methane in the complete range 0-100 %, but not yet with great accuracy.

Semi-conductor (Solid State)

A semi-conductor can also measure methane directly in ppmv, even at low concentrations. It can be used, for example, for 'sniffing' over a landfill surface, but other gases may affect the measurement results.

IR

The method is based on the principle that a gas absorbs infrared radiation at defined wavelengths. The more absorbent the gas present, the more IR light is absorbed. A detector can measure the intensity in the IR light exposed to the gas and compare it with the original source. The method can measure within the entire measurement range from ppm level to 100 %.

TDLAS

Concentration measurement of for example methane with laser. The gas mixture is pumped into the instrument and laser is used transmitting into a cell cotanining the gas mixture. The wavelength is tuned to one of the absorbtion lines of methane. The absorbtion is measured and the concentration can be calculated. The fraction of emited laser power that is transmitted trough the gas mixture is monitored with a photo detector.

Bubble test

Foam is sprayed over the surface where leakage is suspected. New bubbles appear at the point of leakage. This is primarily used to check the seal when pipes are screwed together.

Vegetation changes

Gas leaking out from the interior of a landfill through the surface often means there is no natural air in the ground. Surfaces that would usually be vegetated may lack vegetation in parts where the landfill gas is escaping. The lack of vegetation indicates gas emission, and this can be used to indicate gas leakage. The method is used purely as an indicator, and is not a direct measurement method. Bergman et al. showed that vegetation as a gas indicator can be divided up into a) areas with no vegetation at all, b) areas with dry or damaged vegetation (yellow leaves, for example), and c) large variation between plants of the same species within an area of a landfill (Maurice el al, 1995).

3 METHODS FOR QUANTIFYING GAS LEAKAGE

There are fewer methods available for quantifying a specific gas leakage. The methods described in literature are as follows:

1. Containment
2. Rotameter or other flow measurement

Containment

Containment is a method usually applied to equipment. A plastic sack is placed and sealed around the site where the leakage is suspected. The sack is fitted with a controlled outlet. A known flow of an inert gas is fed into the sack. The methane concentration is then measured at the outlet and the flow can be estimated. The methane concentration can, for example, be measured using FID.

Rotameter or other flow measurement

These are flow measurement methods for gas flowing in enclosed pipes. Landfill gas is often measured with a V-cone meter, as this is not affected by particles in the gas.

4 METHODS FOR QUANTIFYING LEAKAGE FROM LARGE AREAS – PARTS OF OR ENTIRE LANDFILLS

The method that is often used for quantification of methane leakage from entire landfills is tracer gas together with methane measurements. A tracer gas, such as SF6, is released with a known flow at the landfill, and the plume from this emission is assumed to coincide with the emission of methane from the landfill. Both the methane and the tracer gas concentrations are then measured in the plume that is formed downwind from the landfill. For measurement and calculation of the emission, the following methods are used:

1. Detection with light, differential absorption (LIDAR/DIAL), quantitative method in kg/hr or mg/m^3
2. AIR detection and AIRDAR, quantitative method with results in E3m^3/yr
3. Tunable Diode Laser Absorption Spectroscopy (TDLAS), semi-quantitative, results in ppm x m
4. FTIR, open beam Fourier Transform, semi-quantitative, results in ppm x m

Firma Afvalzorg has launched a modified measurement technique to measure flows from entire landfills that also uses tracers and concentration measurements downwind.

Air samples are collected in vacuum bottles (14-15) over four hours at the same time as tracer gas is released from a spot in the landfill. Calculation is carried out in the same way as above. (Jakobs, 2007).

VRPM, Vertical Radial Plume Mapping, is a new method launched by the US Environmental Protection Agency. This method can measure the flow from parts of landfills, using a laser instrument fixed on a tripod. The laser instrument can be pre-programmed for aiming towards different reflectors that are placed in the corners of the area for which the flow is to be determined. The principle is shown in Figure 1.1.

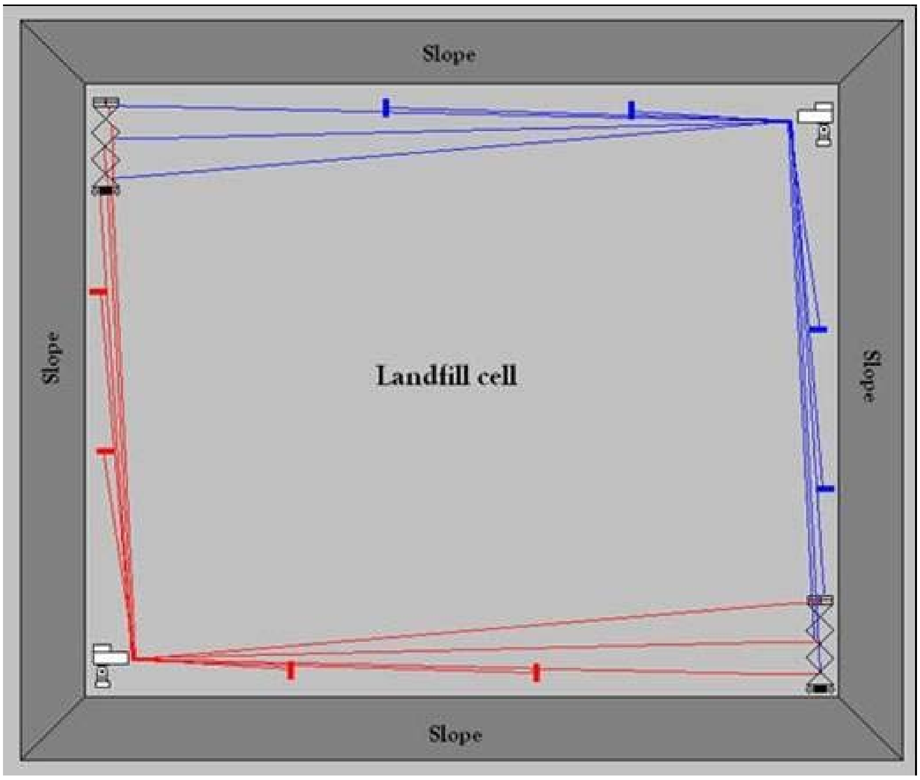


Figure 1.1. Measurement with laser aimed at reflectors in order to determine gas flows from a landfill cell according to the VRPM method.

The laser instrument is directed, using a special automated method, towards each reflector for approximately 10 seconds, and the concentration data is stored. The beam is then moved to the best reflector, and new measurements taken. Several rounds of measurements are taken.

All data is processed in a specially designed program that converts concentrations to flow data. Unfortunately this computer program is not available commercially, and the data must be processed at the University of Washington, USA (Hamish Adam, 2008).

According to Boreal, the company that launched the equipment, the method could be developed for field operation in the future. At present, the method is too complicated, and development work remains.

The chamber method is a method that has long been used to calculate flows from landfill surfaces over a long period. This project shows how the method is used.

APPENDIX 6

FIELD OBSERVATIONS, LASER INSTRUMENT

Data used in Chapter 12

Table 12.1 shows variations in ppm data for the western slope, SYSAV, Spillepeng, Biocell 8 (BC8). All 22 measurement points involved the emission of methane through narrow, barely visible fissures, Figure 12.15. Field measurements using the Siemens laser system, carried out in 2006.

	Landfill 2006	**Date - File name**	**ID feature**	**Laser ppm**	**GPS**
6	SYSAV	Sysav_SBC8_1-3_ 061011_01	Biocell 8 (BC8)	1=300 2=50-100 3≤400	x
7	SYSAV	Sysav_SBC8_4_ 061011	Biocell 8	4≤600	x
8	SYSAV	Sysav_SBC8_5_ 061011	Biocell 8	5=400	x
9	SYSAV	Sysav_SBC8_ 6-10_061011	Biocell 8	6≤2,000 7≤1,100 8≤4,500 9≤3,000 10≤2,000	x
10	SYSAV	Sysav_SBC8_ 11-22_061011	Biocell 8	11≤4,000 12≤2,000 13≤1,000 14≤500 15≤1,000 16≤1,000 17≤450 18≤3,400 19≤150 20≤2,500 21≤2,000 22≤100-500	x

<u>Table 12.2</u>. Variation in ppm data at Löt shown by snapshot field measurement with the Siemens laser system, carried out in 2006.

	Landfill 2006	**Date - file name**	**ID feature**	**Laser ppm 2006**	**Laser ppm 2007**	**Date - file name**
1	Löt	Löt_L1_1-8_ 060914_01	Slope+ crest + toe of slope	1 ≤ 1,400 2 ≤ 50 3 ≤ 300 4 ≤ 100 5 = 500-700 6 ≤ 500 7 = 400-500 8 ≤ 300	1 = 1,800 2 ≤ 35 3 ≥ 6,000 4 ≤ 20 5 ≤ 500 6 = 2,000 7 ≤ 25 8 ≤ 20	Löt_L1_1-8_ 070719_01
2	Löt	Löt_L2_1-5_ 060914_01	Lower crest	1 = 250 2 ≤ 400 3 = 6,000 4 ≤ 5,000 5 ≤ 1,000	1 ≤ 20 2 ≤ 300 3 ≤ 200 4 ≥ 3,500 5 ≤ 3,700 4-01 ≤ 4,000 = new meas. Point with k-measurement.	Löt_L2_1-5_ 070719_01
3	Löt	Löt_L3_1-3_ 060914_01	Crest	1 ≤ 4,000 2 ≤ 1,200 3 ≤ 1,500	1 ≤ 20 2 ≤ 20 3 ≤ 225 4 ≥ 500 = new meas. point	Löt_L3_1-4_ 070719_01
4	Löt	Löt_L4_1-5 060914_01	3rd slope crest	1 = 1,000-1,400 2 =data missing 3 = data missing 4 = data missing 5 = data missing	1 ≤ 500 2 = data missing 3 = data missing 4 ≤ 500 5 = 50-1700	Löt_L4_1-5_ 070719_01
5	Löt	Löt_L5_1-5_ 060914_01	Crest	1 ≤ 1,500 2 ≤ 2,000 3 = 800 4 = 1,000 5 = data missing	1 = 7,000 2 = 0 3 = 1500	Löt_L5_1-5 200703_05

Table 12.3. Table showing comparative ppm data for the same features/surfaces on two different measurement occasions, 2006 and 2007. Field measurements carried out using the Siemens laser system.

	Landfill 2006	**Date - file name**	**ID feature**	**Laser ppm 2006**	**Laser ppm 2007-**	**Date - file name**
1	Forsbacka	Forsbacka-F1_01-07-060919	S slope-toe-crest	1 ≥ 4,000 2 ≥ 4,000 3 ≤ 500 4 ≥ 400 5 ≥ 2,500 6 ≥ 500 7 ≥ 3,000	1 = 500-7,000 2 ≤ 500 3 ≤ 1,400 4 ≤ 250 5 = 1,500-2,000 6 = 10-30 7 = 1,500-2,000	Forsbacka_F1_1-7_070712
2	Forsbacka	Forsbacka-F1-8-15_060919	S slope-toe-crest	8 ≥ 5,000 9 ≥ 3,000 10 ≥ 700 11 ≥ 6,000 12 ≥ 6,000 13 ≥ 12,000 14 = 6-7,000 15 ≥ 3,000	8 ≤ 1,100 9 ≤ 700 10 ≤ 7,000 11 = 15 12 = 15 13 = 30 14 ≤ 6,000 15 ≤ 3,800	Forsbacka_F1_9-15_070712

Table 12.4. Table showing comparative ppm data for the same features/surfaces on two different measurement occasions on the crest, F3 area, Forsbacka landfill, 2006 and 2007. Field measurements carried out using the Siemens laser system.

	Landfill 2006-2007	**Date - File name**	**ID feature**	**Laser ppm 2006**	**Laser ppm 2007**	**Date - File name**
1	Forsbacka	Forsbacka_F3-01-08_060919_01	Northern slope	1 = 11-12,000 2 ≥ 2,000 3 ≥ 7,000 4 ≥ 4,000 5 ≥ 6,000 6 ≥ 1,500 7 ≥ 1,700 8 ≥ 1,000	1 ≥ 5,000 2 ≤ 1,200 3 ≤ 2,200 4 ≤ 500 5 = 2,100 6 ≤ 1,500 7 ≥ 1,000 8 = 1,000-3,000	Forsbacka_F3_1-8_070712
2	Forsbacka	Forsbacka_F3-9-12_060919	Northern slope	9 ≥ 5,000 10 ≥ 4,000 11 ≥ 1,500 12 = 4-6,000	9 ≥ 1,700 10 = 4,300 11 ≥ 4,000 12 = 3,800	Forsbacka_F3_9-15_070712
3	Forsbacka	Forsbacka_F3_rör_1-4_070712_01	Northern slope (pipe)	1 ≥ 4,000 (short pipe) 2 ≥ 4,000 (bare surface + pipe 1) 3 ≥ 5,000 (short pipe) 4≥5-10,000	1 = 6,000 (short 1) 2 = 4,000 (bare surface + pipe) 3 = 7-9,000 (short 2) 4 = 20,000	Forsbacka_F3_9-15_070712

				(long pipe)	(long pipe)	

Table 12.5. Comparative ppm data for the same leakage feature/surface, recorded on two different measurement occasions, toe of slope Löt_L2_1-5, 2006 and 2007, western slope.

Landfill 2006-2007	**Date - File name**	**ID feature**	**Laser ppm 2006**	**Laser ppm 2007**	**Date - File name**
Löt	Löt_L2_1-5_ 060914_01	Lower crest	1 = 250 2 ≤ 400 3 = 6,000 4 ≤ 5,000 5 ≤ 1,000	1 ≤ 20 2 ≤ 300 3 ≤ 200 4 ≥ 3,500 5 ≤ 3,700 4-01 ≤ 4000 = new feature with k-measurement	Löt_L2_1-5_ 070719_01

Table12.6. Compilation of field measurements so far at Högdala landfill, 6-7-2007 to 28-11-2007.

	Landfill 2007	**Date - file name**	**ID feature**	**Laser ppm**	**mb**	**m/s**	**Ts**	**Tl**	**Field method**
1	Högdala	Högdala_slänt-V-N-Ö-S-SW_ Platå_ 070706_01	Plateau + Slopes - gas flare not in operation	W = 100-400 N = 100-400 E = 50-100 S = 100-400 SW = 1,500-2,000 Plateau ≤ 1,000					Field measurement
2	Högdala	Högdala_ slänt-V-N-Ö-S-Pla-tå_070720_01	Plateau + Slopes - gas flare in operation	W = 50-100 N = 50-100 E = 50-100 S = 50-200 SW = 50 Plateau = 50-100					Field measurement
3	Högdala	Högdala_fält-observ_ 071115_01	Plateau + slopes-flare on	S = 100-400 W = 150-300	1,016	1-4	-50		Field measurement
4	Högdala	Högdala_ 071127	Plateau + slopes-flare on	General = 100-200 Blustery wind!	1,004	6-12	-50	-3,3	Field measurement stopped due to blustery wind
5	Högdala	Högdala_ 071128	**Flare switched off**	Logger meas. 14^{45}-16^{15}* Good results = see examples on diagram.	1,003= falling! See logger meas.			+1	Logger meas. 16^{15} heavy snowfall-New logger meas. planned with flare on.

Appendix 7

Chamber method measurements, results

Landfill	Position in test area	Laser instrument Concentration ppm	Chamber Method Emission Litres/år, m2	Comments
1				
Spillepeng, test cells, 2007-05-31				
10 x 10 m				
Spillepeng	B4	0	0	
Spillepeng	B5	0	0	
Spillepeng	C2	0	0	
Spillepeng	C3	0	0	
Spillepeng	E1	3333	148183	Fissure with convective flow?
Spillepeng	E4	0	3311	Perfect curve
2				
Spillepeng, older part, 2005-05-31				
10 x 10 m				
Spillepeng	A5	0	0	
Spillepeng	B5	0	0	
Spillepeng	C4	0	0	
Spillepeng	D1	0	0	
Spillepeng	E2	0	0	
Spillepeng	E5	0	0	
3				
Filborna, eastern slope, 2007-06-01				
24 x 4 m				
Filborna	B1	25	0	Crushed bottle
Filborna	E2	25	0	
Filborna	G2	25	0	
Filborna	H1	25	0	
Filborna	I1	25	3518	
Filborna	K1	25	0	Crushed bottle
4				
Filborna, final cover, 2007-06-01				
10 x 10 m				
Filborna	A2	1,7	112	Inside margin of error
Filborna	B1	1,7	114	Inside margin of error
Filborna	B2	1,7	109	Inside margin of error
Filborna	B3	1,7	0	
Filborna	B4	1,7	27	Very low value, can be set to zero.
Filborna	E2	1,7	424	
5				
Filborna, sand box, 2007-06-01				
1 x 2 m				
Kontrollerat	FK1	125	147825	
Kontrollerat	FK2	90	95397	
Kontrollerat	FK3	491	333344	
Kontrollerat	FK4	95	164308	
6				
Löt top surface, 2007-06-12				
10 x 10 m				
Löt	B1	1333	663	
Löt	B2	83	0	
Löt	D1	500	11500	
Löt	D3	1833	259739	Fissure with convective flow?
Löt	E3	1167	38639	
Löt	E5	0	0	

Landfill	Position in test area	Laser instrument Concentration ppm	Chamber Method Emission Litres/år, m2	Comments
7				
Löt, slope, 2007-06-12				
24 x 4 m				
Löt	C1	0	0	
Löt	D2	333	115653	
Löt	G1	0	0	Very low value, can be set to zero.
Löt	H2	0	0	
Löt	I2	1333	73915	
Löt	K1	542	15710	
Löt	EX	6667	1379999	
8				
Hagby test cell E 89, 2007-06-11				
24 x 4 m				
Hagby	D2	0	0	Ser ut som metanoxidation i de flesta provpunkterna på limpan
Hagby	H1	50	0	
Hagby	I2	50	0	
Hagby	J1	50	2637	
Hagby	K1	75	0	
Hagby	K2	333	0	
9				
Hagby, part II near test cell E 90, 2007-06-11				
10 x 10 m				
Hagby	A4	25	0	
Hagby	B4	25	23	Very low value, can be set to zero.
Hagby	C2	25	0	
Hagby	C3	25	119	Very low value, can be set to zero.
Hagby	D2	25	0	
Hagby	D5	25	15	Very low value, can be set to zero.
Hagby	EX	25	0	Extremely bad curve, varies irregularely at a hig level
10				
Forsbacka, slope in the north, 2007-06-13				
24 x4 m				
Forsbacka	C1	25	2	Very low value, can be set to zero.
Forsbacka	C2	25	391	
Forsbacka	F2	25	0	
Forsbacka	H2	417	2580	Extremely linear
Forsbacka	J1	25	0	
Forsbacka	K2	25	0	
11				
Forsbacka, top surface, 2007-06-13				
10 x 10 m				
Forsbacka	A1	25	0	
Forsbacka	A3	417	10773	
Forsbacka	B4	25	26	Very low value, can be set to zero.
Forsbacka	D2	25	36	Very low value, can be set to zero.
Forsbacka	D3	1250	84500	
Forsbacka	E4	25	0	
12				
F2	**top surface, 2007-09-25**			
24x4 m				
F2	A2	42	0	Zero, bad correlation
	B1	833	74866	Extremely good correlation
	C1	58	0	
	E1	3333	257460	Extremely good correlation
	I1	42	0	Zero
	J1	25	10	Very low value, can be set to zero.

Landfill	Position in test area	Laser instrument Concentration ppm	Chamber Method Emission Litres/år, m2	Comments
13 F2 18x6 m F2	slope, 2007-09-25			
	B1	500	34156	Extremely good correlation
	B3	25	160	Can be set to zero, extremely good correlation
	D1	25	0	Bad correlation
	D2	1167	341658	
	E2	833	242881	Extremely good correlation
	F1	25	0	Zero
14 F2 Linje 6 punkter F2	Outlined			
	1	1667	467255	Extremely good correlation
	2	2000	1537401	4 cubic meters per day!/ 175 litresper hour! Extremely good correlation
	3	3333	291330	Extremely good correlation
	4	1667	331517	Extremely good correlation
	5	1167	200414	Extremely good correlation
	6		344040	Extremely good correlation
15 F1 10x10 m F1	top surfacwe,eastern corner, 2007-09-27			
	A4	250	54981	Extremely good correlation
	A5	83	245245	Extremely good correlation
	B4	33	2457	
	B5	1667	51819	
	C4	17	233	Very low value, can be set to zero.
	C5	1667	11088	Extremely good correlation
16 F1 24x24 m F1	slope in the north, 2007-09-27			
	B1	500	43892	
	C2	2500	2467	
	D1	5000	959862	
	F1	2500	25083	Bad correlation
	G2	3000	71760	Bad correlation
	K2	1000	169779	Extremely good correlation
17 F1 50x2 m F1	crest at road, 2007-09-27			
		25	25632	Extremely good correlation
		25	3652	
		25	8060	Extremely good correlation
		25	214345	Extremely good correlation
		25	72	Dvs noll
		417	18099	Extremely good correlation
18 F1 10x10 m F1	top surface, 2007-09-27			
	A1	833	259466	Extremely good correlation
	C1	333	42907	Extremely good correlation
	D2	833	352925	
	D5	133	182395	Extremely good correlation
	E1	25	26514	Extremely good correlation
	E3	58	110318	Extremely good correlation

Landfill	Position in test area	Laser instrument Concentration ppm	Chamber Method Emission Litres/år, m2	Comments
19				
Filborna, surface, georesistivity, 2007-12-04, kl 1222				
10 x 10 m				
Filborna v 4	A	58	239159	Extremely good correlation
Filborna v 4	B	25	3787	Extremely good correlation
Filborna v 4	C	42	156190	Extremely good correlation
Filborna v 4	D	38	23742	Extremely good correlation
Filborna v 4	E	50	35221	Extremely good correlation
Filborna v 4	F	25	645707	Extremely good correlation
20				
Filborna, surface, georesistivity, 2007-12-04, kl 1620				
10 x 10 m				
Filborna v 4	A	542	289956	Extremely good correlation
Filborna v 4	B	58	38392	Extremely good correlation
Filborna v 4	C	208	105683	Extremely good correlation
Filborna v 4	D	25	8324	Extremely good correlation
Filborna v 4	E	142	49890	Extremely good correlation
Filborna v 4	F	292	328496	Extremely good correlation
21				
Filborna, surface, georesistivity, 2007-12-05				
10 x 10 m				
Filborna v 4	A	58	89047	Extremely good correlation
Filborna v 4	B	208	27737	Extremely good correlation
Filborna v 4	C		178597	Extremely good correlation
Filborna v 4	D	63	60223	Extremely good correlation
Filborna v 4	E	267	36452	Extremely good correlation
Filborna v 4	F	500	408767	Extremely good correlation
22				
Filborna, surface, georesistivity, 2007-12-05, kl 1450				
10 x 10 m				
Filborna v 4	A	133	66490	Extremely good correlation
Filborna v 4	B	1267	77765	Extremely good correlation
Filborna v 4	C	54	159988	Extremely good correlation
Filborna v 4	D	54	34743	Extremely good correlation
Filborna v 4	E	71	175105	Good correlation
Filborna v 4	F	238	422706	Extremely good correlation
23				
Filborna, surface, georesistivity, 2007-12-12, kl 1424				
10 x 10 m				
Filborna v 4	A	5000	556720	Extremely good correlation
Filborna v 4	B	2083	576011	Good correlation
Filborna v 4	C	667	223461	Extremely good correlation
Filborna v 4	D	75	285	Extremely good correlation
Filborna v 4	E	433	140680	Extremely good correlation
Filborna v 4	F	2083	376245	Extremely good correlation

Appendix 8
Georesistivity measurements
Time of start for all sequences and at all lines

	Sequense						
	1	2	3	4	5	6	7
Line	2007-12-03	2007-12-04		2007-12-05		2007-12-12	
A	10:33:51	07:44:43	13:39:26	08:00:22	13:42:12	08:11:13	12:47:06
B	10:56:43	08:07:13	13:58:08	08:24:00	14:25:26	08:28:57	14:07:40
C	11:19:08	08:40:32	14:17:41	08:51:21	14:45:05	09:19:28	14:29:23
D	11:41:24	09:16:13	14:36:51	09:40:33	15:03:10	09:55:24	14:49:50
E	12:06:06	10:08:43	14:54:51	10:02:31	15:21:43	10:19:38	15:07:55
F	13:55:59	10:46:52	15:14:46	10:23:03	15:41:15	10:41:16	15:26:17
G	14:16:03	11:09:15	15:46:23	10:53:13	15:58:21	11:03:43	15:43:49
H	14:37:08	11:32:46	16:09:24	12:11:44	16:17:16	11:22:37	16:01:03
I	14:58:45	12:05:57	16:36:29	12:29:44	16:38:21	11:41:24	16:17:50
J	15:19:25	12:26:04	17:01:01	12:48:06	16:55:58	12:08:02	16:36:14
K	15:44:17	12:44:11	17:29:32	13:06:24	17:26:26	12:25:25	16:54:21
IB	14:58:45	-	-	-	-	-	-
IC	16:16:12	-	-	-	-	-	-

Appendix 9

Georesistivity measurements

Coordinates of all electrodes

Electrode	Z	X	Y
A1	75.115	14221.554	12954.239
A2	75.002	14222.027	12954.315
A3	74.896	14222.487	12954.403
A4	74.790	14222.964	12954.502
A5	74.667	14223.447	12954.621
A6	74.504	14223.949	12954.677
A7	74.319	14224.415	12954.774
A8	74.157	14224.841	12954.858
A9	73.987	14225.329	12954.929
A10	73.816	14225.757	12955.065
A11	73.689	14226.258	12955.099
A12	73.502	14226.683	12955.190
A13	73.335	14227.184	12955.282
A14	73.184	14227.607	12955.339
A15	72.930	14228.091	12955.452
A16	72.591	14228.498	12955.572
A17	72.437	14228.967	12955.631
A18	72.375	14229.428	12955.671
A19	72.336	14229.954	12955.774
A20	72.377	14230.422	12955.846
A21	72.485	14230.912	12956.018

Electrode	Z	X	Y
B1	75.150	14221.552	12955.179
B2	75.007	14221.935	12955.250
B3	74.899	14222.340	12955.312
B4	74.738	14222.829	12955.453
B5	74.603	14223.309	12955.564
B6	74.427	14223.783	12955.602
B7	74.278	14224.223	12955.651
B8	74.086	14224.731	12955.828
B9	73.945	14225.127	12955.926
B10	73.740	14225.571	12956.028
B11	73.547	14226.018	12956.169
B12	73.391	14226.493	12956.203
B13	73.175	14227.004	12956.302
B14	73.055	14227.377	12956.382
B15	72.848	14227.841	12956.486
B16	72.646	14228.356	12956.588
B17	72.554	14228.855	12956.642
B18	72.480	14229.261	12956.658
B19	72.399	14229.717	12956.769
B20	72.519	14230.294	12956.884
B21	72.503	14230.848	12956.954

Electrode	Z	X	Y
C1	75.243	14221.336	12956.160
C2	75.097	14221.832	12956.242
C3	74.907	14222.244	12956.281
C4	74.781	14222.666	12956.391
C5	74.564	14223.201	12956.477
C6	74.418	14223.569	12956.571
C7	74.238	14224.065	12956.693
C8	74.103	14224.511	12956.753
C9	73.887	14224.965	12956.947
C10	73.664	14225.437	12957.000
C11	73.450	14225.878	12957.144
C12	73.284	14226.275	12957.167
C13	73.059	14226.845	12957.312
C14	72.963	14227.227	12957.325
C15	72.808	14227.707	12957.448
C16	72.638	14228.239	12957.509
C17	72.566	14228.663	12957.594
C18	72.504	14229.094	12957.649
C19	72.473	14229.528	12957.740
C20	72.473	14230.101	12957.950
C21	72.439	14230.665	12957.922

Electrode	Z	X	Y
D1	75.182	14221.176	12957.110
D2	75.054	14221.628	12957.218
D3	74.878	14222.113	12957.261
D4	74.758	14222.540	12957.355
D5	74.614	14222.988	12957.505
D6	74.426	14223.479	12957.526
D7	74.265	14223.954	12957.708
D8	74.090	14224.367	12957.770
D9	73.884	14224.801	12957.919
D10	73.661	14225.263	12957.986
D11	73.418	14225.717	12958.079
D12	73.190	14226.148	12958.168
D13	73.016	14226.659	12958.268
D14	72.982	14227.049	12958.307
D15	72.752	14227.576	12958.481
D16	72.621	14228.074	12958.500
D17	72.505	14228.481	12958.564
D18	72.438	14228.900	12958.633
D19	72.438	14229.334	12958.698
D20	72.524	14229.981	12958.916
D21	72.491	14230.505	12958.886

Electrode	Z	X	Y
E1	74.961	14221.023	12958.197
E2	74.966	14221.475	12958.190
E3	74.893	14221.973	12958.236
E4	74.748	14222.373	12958.422
E5	74.664	14222.873	12958.515
E6	74.537	14223.338	12958.591
E7	74.354	14223.733	12958.735
E8	74.130	14224.242	12958.755
E9	73.884	14224.690	12958.855
E10	73.682	14225.125	12958.973
E11	73.445	14225.547	12959.091
E12	73.250	14226.009	12959.143
E13	72.993	14226.543	12959.286
E14	72.868	14226.909	12959.337
E15	72.713	14227.398	12959.455
E16	72.522	14227.921	12959.512
E17	72.413	14228.368	12959.608
E18	72.361	14228.717	12959.692
E19	72.480	14229.226	12959.735
E20	72.530	14229.803	12959.876
E21	72.572	14230.357	12959.868

Electrode	Z	X	Y
F1	74.802	14220.819	12959.043
F2	74.813	14221.333	12959.194
F3	74.839	14221.817	12959.307
F4	74.772	14222.196	12959.329
F5	74.695	14222.710	12959.420
F6	74.557	14223.156	12959.511
F7	74.420	14223.610	12959.637
F8	74.177	14224.077	12959.720
F9	73.971	14224.538	12959.847
F10	73.701	14224.997	12959.896
F11	73.392	14225.446	12960.082
F12	73.174	14225.831	12960.139
F13	72.988	14226.343	12960.218
F14	72.840	14226.754	12960.241
F15	72.662	14227.217	12960.444
F16	72.507	14227.766	12960.475
F17	72.427	14228.203	12960.565
F18	72.408	14228.595	12960.628
F19	72.513	14229.071	12960.687
F20	72.509	14229.661	12960.769
F21	72.516	14230.163	12960.841

Electrode	Z	X	Y
G1	74.850	14220.690	12960.037
G2	74.763	14221.169	12960.221
G3	74.799	14221.624	12960.225
G4	74.810	14222.044	12960.373
G5	74.738	14222.506	12960.503
G6	74.585	14223.025	12960.595
G7	74.471	14223.449	12960.694
G8	74.219	14223.871	12960.758
G9	73.949	14224.336	12960.858
G10	73.726	14224.812	12961.029
G11	73.413	14225.290	12961.069
G12	73.220	14225.673	12961.116
G13	73.022	14226.137	12961.244
G14	72.891	14226.585	12961.216
G15	72.718	14227.097	12961.403
G16	72.546	14227.567	12961.433
G17	72.447	14228.061	12961.529
G18	72.462	14228.459	12961.613
G19	72.513	14228.946	12961.729
G20	72.475	14229.486	12961.676
G21	72.463	14229.966	12961.737

Electrode	Z	X	Y
H1	74.797	14220.501	12961.007
H2	74.829	14220.968	12961.151
H3	74.813	14221.498	12961.229
H4	74.795	14221.841	12961.338
H5	74.697	14222.343	12961.395
H6	74.576	14222.898	12961.477
H7	74.401	14223.312	12961.601
H8	74.161	14223.759	12961.710
H9	73.881	14224.190	12961.827
H10	73.575	14224.679	12961.908
H11	73.400	14225.187	12962.029
H12	73.187	14225.530	12962.091
H13	72.944	14226.027	12962.212
H14	72.855	14226.420	12962.169
H15	72.686	14226.899	12962.372
H16	72.557	14227.411	12962.401
H17	72.501	14227.874	12962.500
H18	72.503	14228.258	12962.616
H19	72.550	14228.824	12962.650
H20	72.543	14229.320	12962.812
H21	72.530	14229.810	12962.806

Electrode	Z	X	Y
I1	74.694	14220.312	12962.001
I2	74.780	14220.816	12962.071
I3	74.770	14221.303	12962.173
I4	74.729	14221.683	12962.271
I5	74.656	14222.172	12962.371
I6	74.529	14222.636	12962.455
I7	74.333	14223.121	12962.580
I8	74.095	14223.570	12962.703
I9	73.808	14224.092	12962.790
I10	73.558	14224.543	12962.885
I11	73.392	14224.939	12963.052
I12	73.192	14225.379	12963.065
I13	73.044	14225.864	12963.174
I14	73.012	14226.327	12963.261
I15	72.938	14226.783	12963.383
I16	72.781	14227.281	12963.354
I17	72.643	14227.716	12963.489
I18	72.577	14228.150	12963.614
I19	72.596	14228.664	12963.739
I20	72.621	14229.139	12963.804
I21	72.575	14229.680	12963.822

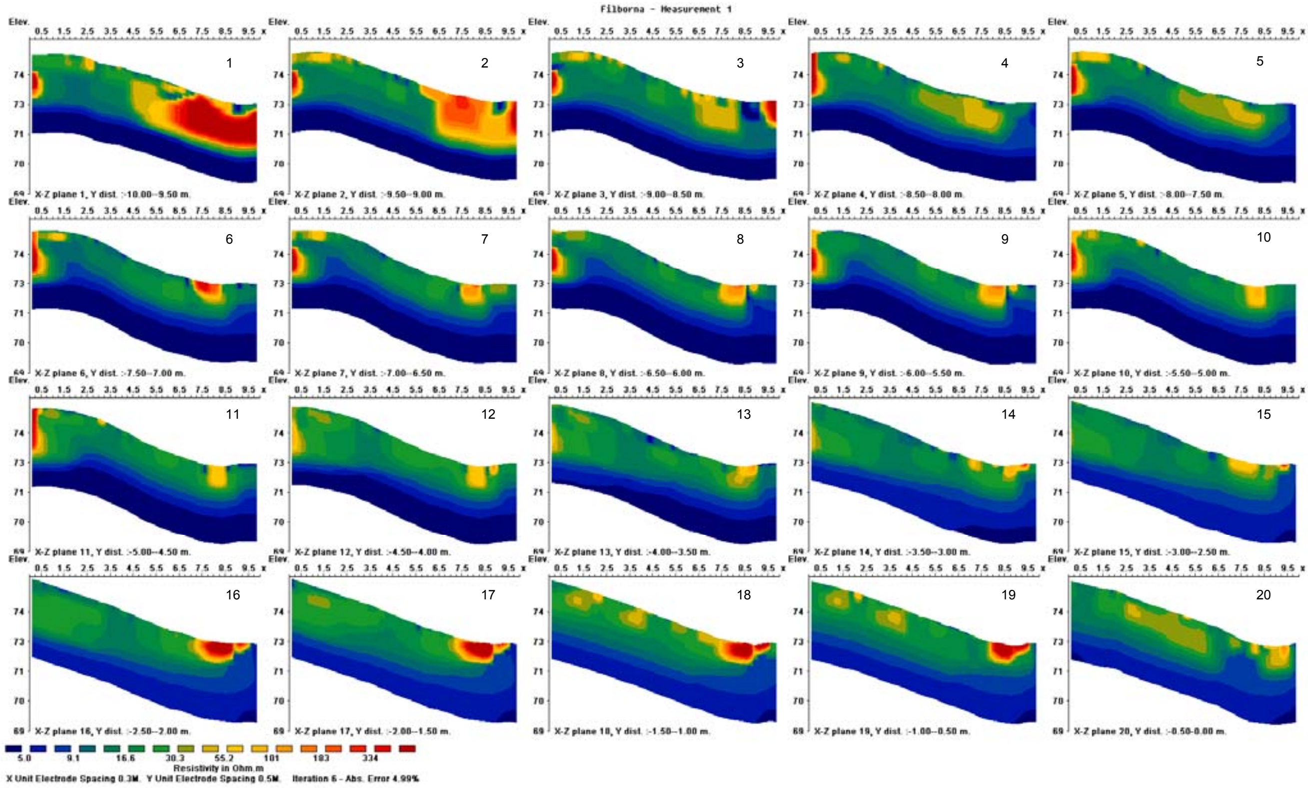
Electrode	Z	X	Y
J1	74.689	14220.151	12963.024
J2	74.750	14220.581	12963.084
J3	74.839	14221.135	12963.168
J4	74.820	14221.498	12963.319
J5	74.749	14221.964	12963.331
J6	74.601	14222.512	12963.493
J7	74.398	14222.945	12963.560
J8	74.200	14223.385	12963.598
J9	73.984	14223.819	12963.797
J10	73.792	14224.317	12963.825
J11	73.652	14224.743	12963.976
J12	73.391	14225.234	12964.026
J13	73.196	14225.713	12964.138
J14	73.024	14226.225	12964.171
J15	72.922	14226.660	12964.303
J16	72.889	14227.109	12964.391
J17	72.817	14227.573	12964.441
J18	72.712	14228.024	12964.626
J19	72.672	14228.545	12964.703
J20	72.743	14229.010	12964.823
J21	72.758	14229.539	12964.824

Electrode	Z	X	Y
K1	74.629	14219.928	12963.882
K2	74.620	14220.395	12964.033
K3	74.650	14220.900	12964.177
K4	74.613	14221.424	12964.244
K5	74.599	14221.914	12964.405
K6	74.496	14222.377	12964.426
K7	74.243	14222.838	12964.557
K8	74.205	14223.254	12964.640
K9	74.166	14223.758	12964.727
K10	74.003	14224.307	12964.842
K11	73.876	14224.724	12964.942
K12	73.765	14225.173	12965.010
K13	73.597	14225.683	12965.133
K14	73.443	14226.085	12965.161
K15	73.179	14226.555	12965.228
K16	72.992	14226.998	12965.342
K17	72.812	14227.504	12965.448
K18	72.654	14227.970	12965.614
K19	72.553	14228.413	12965.684
K20	72.526	14228.819	12965.779
K21	72.553	14229.372	12965.857

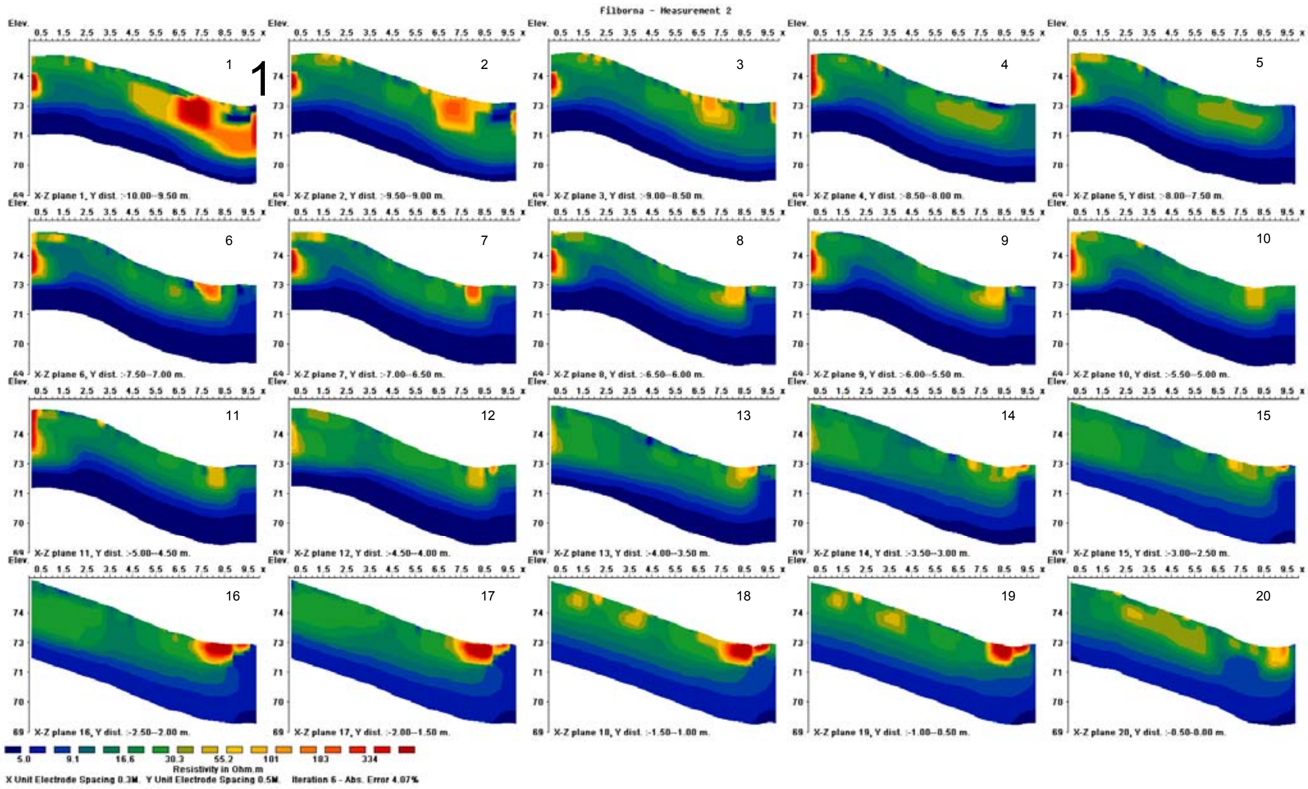
Appendix 10

Georesistivity measurements

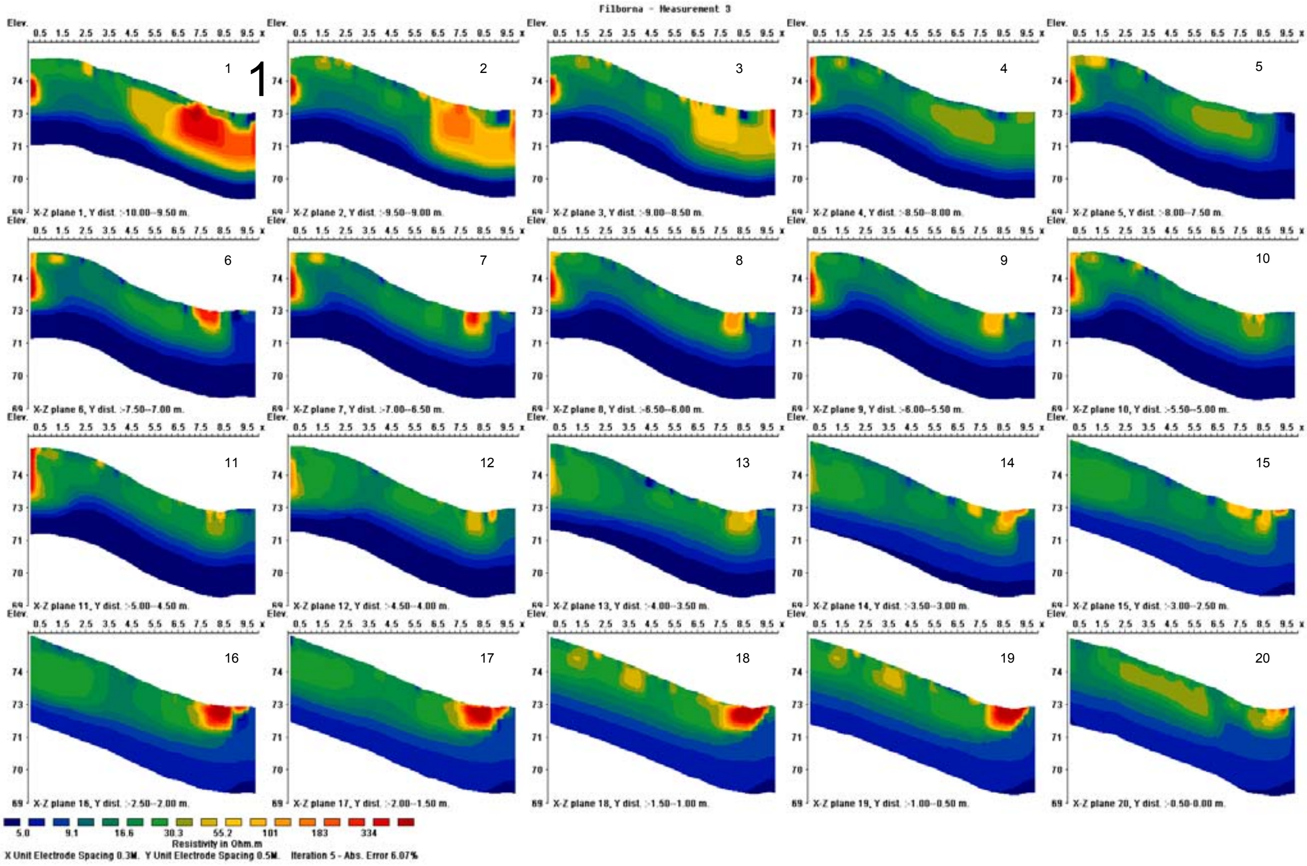
Timelap 1



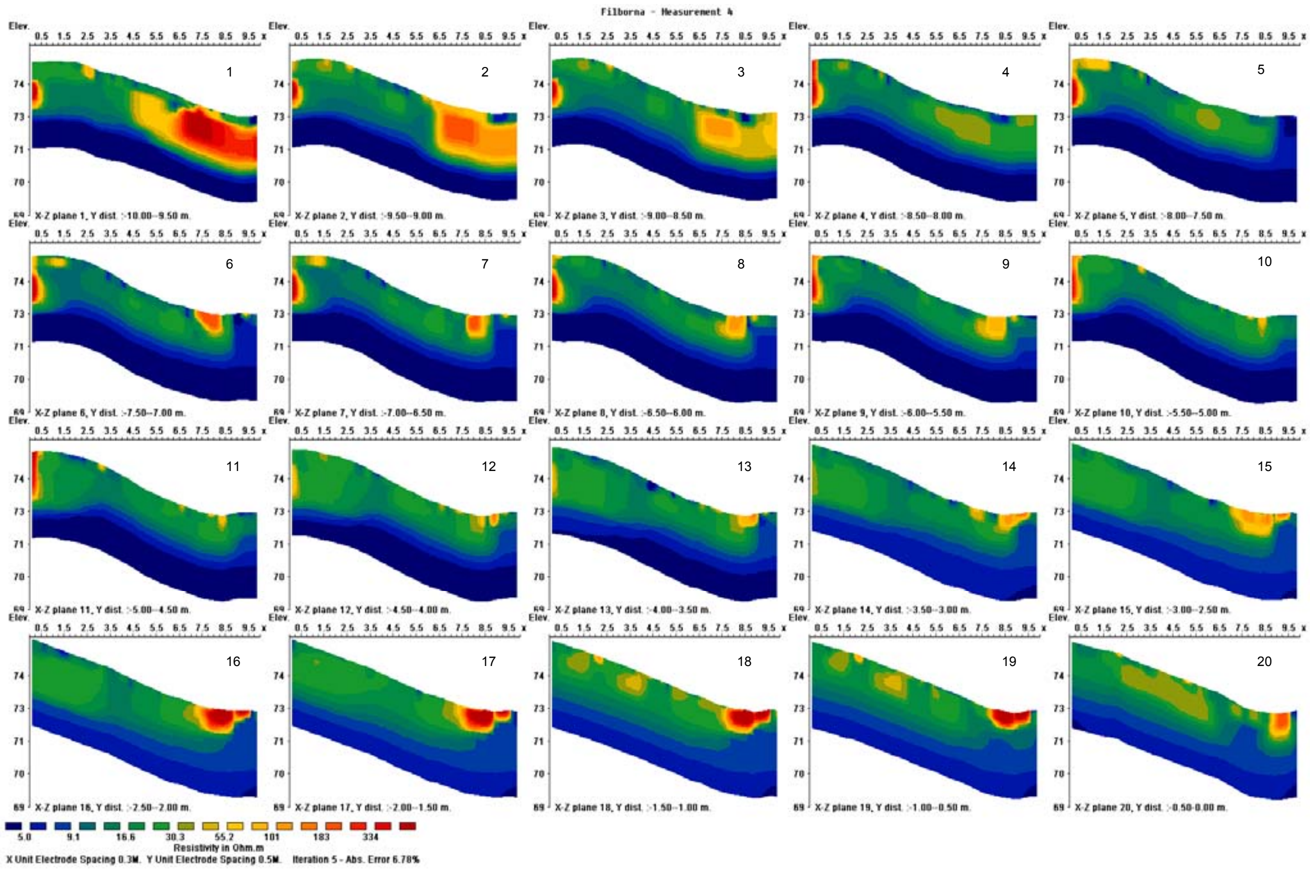
Timelap 2



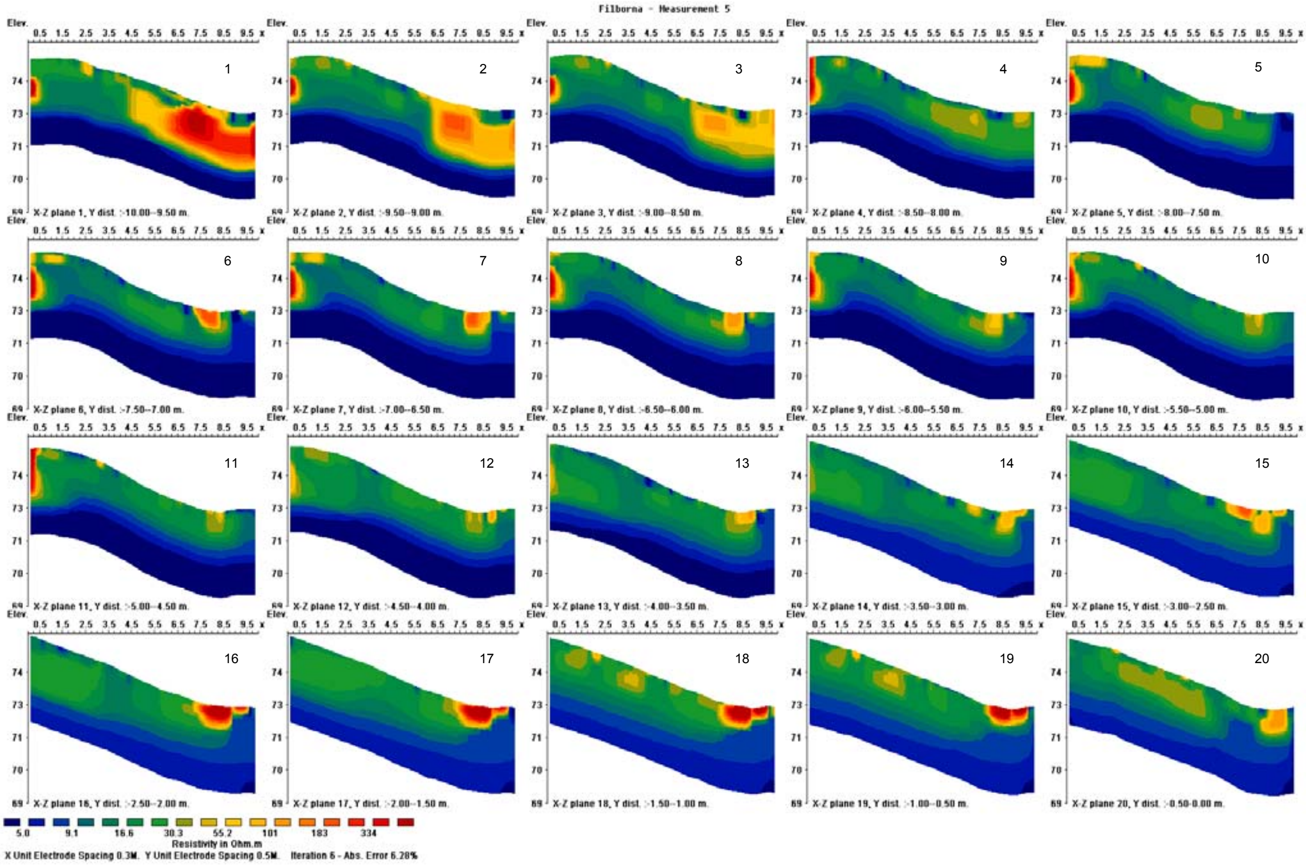
Timelap 3



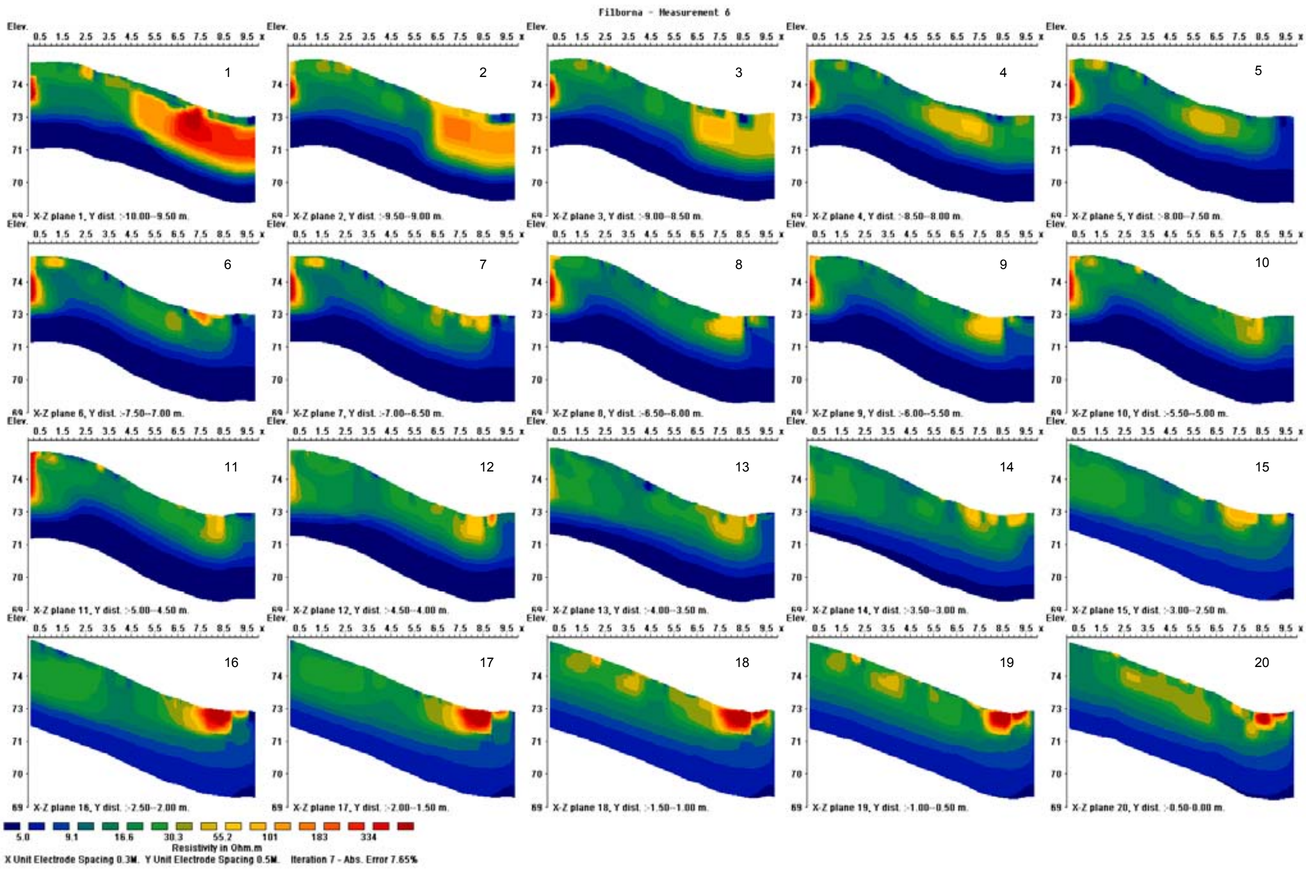
Timelap 4



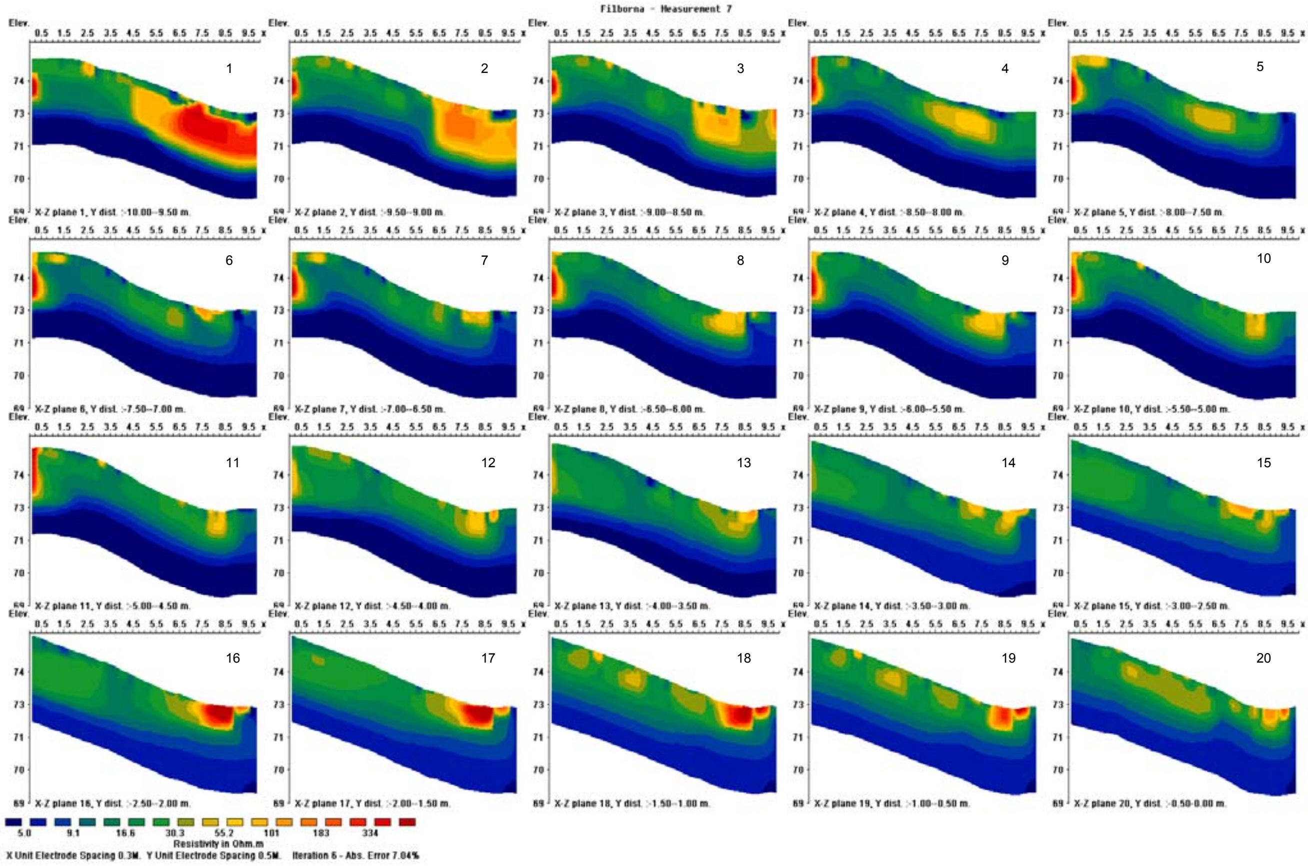
Timelap 5



Timelap 6



Timelap 7


Filborna - Measurement 7
X-Z plane 1, Y dist. :-10.00--9.50 m.
X-Z plane 2, Y dist. :-9.50--9.00 m.
X-Z plane 3, Y dist. :-9.00--8.50 m.
X-Z plane 4, Y dist. :-8.50--8.00 m.
X-Z plane 5, Y dist. :-8.00--7.50 m.
X-Z plane 6, Y dist. :-7.50--7.00 m.
X-Z plane 7, Y dist. :-7.00--6.50 m.
X-Z plane 8, Y dist. :-6.50--6.00 m.
X-Z plane 9, Y dist. :-6.00--5.50 m.
X-Z plane 10, Y dist. :-5.50--5.00 m.
X-Z plane 11, Y dist. :-5.00--4.50 m.
X-Z plane 12, Y dist. :-4.50--4.00 m.
X-Z plane 13, Y dist. :-4.00--3.50 m.
X-Z plane 14, Y dist. :-3.50--3.00 m.
X-Z plane 15, Y dist. :-3.00--2.50 m.
X-Z plane 16, Y dist. :-2.50--2.00 m.
X-Z plane 17, Y dist. :-2.00--1.50 m.
X-Z plane 18, Y dist. :-1.50--1.00 m.
X-Z plane 19, Y dist. :-1.00--0.50 m.
X-Z plane 20, Y dist. :-0.50-0.00 m.
5.0 9.1 16.6 30.3 55.2 101 183 334
Resistivity in Ohm.m
X Unit Electrode Spacing 0.3M. Y Unit Electrode Spacing 0.5M. Iteration 6 - Abs. Error 7.04%

APPENDIX 11

HiG-ITB
Sven-Åke Ljungberg
NSR
Jan-Erik Meijer

14-2-2005
31-3-2006 (rev.)

RVF_appendix_060404.doc)

The use of remote sensing to determine the status of waste facilities – applications relating to energy and environment

A research project aimed at developing techniques and methods for determining the status of waste facilities, emissions of methane, energy- and environment-related status is presented. The project is a continuation of a recently-completed EU project (the VOGUE project, NNES-1999-20031). The aim of the VOGUE project was to develop a laser system for detecting methane, and to study the behaviour of methane under realistic conditions.

A final report from the VOGUE project was submitted to, and approved by, the EU Commission in August 2004. The different parts of the VOGUE project were aimed at developing technical systems (remote sensing) and methods to remotely detect and visualise leakage of methane from piped systems placed below and above ground. The VOGUE project was a research and development project carried out by an international working group of researchers, engineers and end users. The end users represented companies that produce and distribute methane gas.

The final product of the VOGUE project was six laser systems (prototypes) for detecting methane. The prototypes were tested under controllable conditions at a specially designed field laboratory at Malmö Fire Service's gas testing facility, BARBARA, Spillepeng, and at the field laboratories of ADVANTICA (formerly British Gas). The end users carried out comparative tests of the prototypes using traditional technology (sniffers) for detecting methane. The test was carried out under realistic field conditions for a selection of distribution networks in Europe. The purpose of the test was to determine the accuracy of the laser systems, the operative usability, and limitations for detection of leakage of methane from piped systems above and below ground.

The laser systems developed in the VOGUE project (active gas detection) measure the concentration of methane in ppm x m. Data from the measurements with the laser systems are presented as a concentration profile on a display in the field, and can be stored on a laptop for later presentation and analysis. Methane cannot be visualised with the current laser systems, so a high-resolution IR system (passive gas imaging) was used in the VOGUE project to detect and visualise controlled gas leakage simulated from gas pipes. The aim was to used the image-generating IR technology to study and increase knowledge about the behaviour of methane under different conditions in terms of flow, pressure, size of leakage from gas pipes, filling material, weather and radiation conditions.

The results of the VOGUE project indicate that the laser systems developed in the project, in addition to their use for mapping methane leakage from pipes below and above ground, can also be used for environmental applications, such as mapping leakage of biogas and determining the status of landfills.

Preliminary tests with the VOGUE laser system and image-generating IR systems for mapping of biogas leakage were carried out at Filborna landfill, NSR, Helsingborg, in September 2004. Filborna landfill is one of the first landfills in Sweden with a facility for active treatment of biogas for energy production. In order to maximise the recovery of biogas from the landfill, and to minimise the emission of methane to the atmosphere, the landfill has been covered with different layers with varying covering material with low permeability.

Results from the pilot tests indicate the occurrence of low concentrations of methane (10-20 ppm x m) for sections with a thick covering layer with low permeability, higher concentration of methane in sections with covering material with higher permeability (200-400 ppm x m), and high concentration of methane on slopes with little or no covering material (600-1,000 ppm x m). The results indicate that gas detection with an active gas laser system can be an efficient tool for measuring leakage of methane from landfills, and for control and maintenance of a landfill with the aim of using the energy from the biogas and reducing the emission of methane to the atmosphere. However, the VOGUE laser system used in the experiments has a limited range (≤ 30 m) and should be regarded as a 'spotmeter'. For greater ranges, more powerful lasers are required.

The range of laser systems that are to be used in the field is normally limited because of safety regulations to prevent eye injuries. If a laser system is combined with a high-resolution, image-generating IR system, it should be possible to use the IR system to detect and visualise leakage of biogas from landfills and, at the same time, use the laser system to measure the gas concentration at the leakage source.

On the basis of results from the VOGUE project, and from the field experiments carried out at Filborna landfill, an R&D project is proposed, divided into three parts, with a continual evaluation of the results to be used as a basis for subsequent parts. The proposed parts are described below.

Part 1.
Repeated, simultaneous and comparative measurements should be made using a gas laser system and a passive, high-resolution IR system for a selection of sections of Filborna landfill with different layers in the covering material representing known low to high permeability. The field measurements should preferably be carried out under different weather and radiation conditions in order to map the systems' advantages and disadvantages when used for measurement under realistic field conditions. The landfill type, the type and thickness of the different layers of covering material at Filborna landfill are well known and documented for the different sections of the landfill. Filborna landfill could be used as a test area for field laboratory research, and is a landfill with well-known and verified field data.

The results from Stage 1 are to be evaluated and used as a basis for planning and implementing a more detailed study, Stage 2.

Stage 2.
Similar measurements using the laser and IR systems as in Stage 1 should be planned for Stage 2, but at four different landfills, some with sections with known covering material, other sections less known, some that are unknown and some that completely lack cover. The four landfills that should be included in the study will be located in different parts of the country, in different climate zones, primarily from Malmö in the south to Gävle in the north.

The results from the measurements in Stage 2 will be evaluated, and comprise part of the basis for an international R&D project with the emphasis on both energy-related and environment-related aspects of emissions of methane from landfills.

Stage 3.
The international R&D project in Stage 3 should be planned to include research into the behaviour of biogas in landfills, and upgrading of existing laser and IR technology and field methods, adapted to the needs of end users. Preparation of guidelines for use of remote sensing technology and knowledge transfer between industrial and developing countries will be prioritised.

The interested parties/countries, in the form of an international working and reference group, will jointly plan the final design of the R&D project in Stage 3.

Potential partners/countries that have declared an interest in participating in the international R&D project are Sweden, UK, Russia, Germany and Finland. Stage 3 has not yet been actively presented for the landfills' end users, either nationally or internationally.

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