Landfill Gas Formation in Iceland

A study on Landfill Gas Formation in landfills in Iceland,
in relation to the implementation of the Landfill Directive
into the national law

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Foreword

This report represents the study on landfill gas (LFG) formation in landfills in Iceland. The landfills that were studied had in common that they all accept municipal solid waste (MSW) including biodegradable waste.

This study was performed as a training assignment between the Environment and Food Agency of Iceland (Umhverfisstofnun) and the University of Den Bosch in the Netherlands.
The Agency oversees Icelandic food inspection, pollution issues, hazardous substances, and performs lab analysis connected to these matter. The Agency's aims are to protect living conditions connected with clean environment, healthy habitats and safe products under the motto “Healthy people in a clean country”.

The education on the University of Den Bosch in the Netherlands is called Environmental Technology and is a cooperation between the Higher Technical School (HTS) and the Higher Agriculture School (HAS). The HTS is specialized in technical educations such as: road and hydraulic engineering, mechanical engineering, architecture, environmental technology etc.
The HAS is more specialized in biological and agricultural education such as: cattle farming, water and soil purification, food technology, environmental chemistry, micro and cell biology, etc.
Currently this education has 125 students and in total the HTS an HAS have around 3500 students.

Personally, I have great interest in the geology of Iceland. Furthermore I would like to experience the possible differences between the approach on environmental issues between the Netherlands and one of the Nordic countries, for example Iceland.

I have carried out this study in cooperation with Mr. C.A. Meyles B.Sc. scientific officer and my supervisor at the Environment and Food Agency of Iceland in Reykjavik. I would like to thank the Umhverfisstofnun for its cooperation with my University in the Netherlands and furthermore I would like to thank all the operators of the Icelandic landfills who where willing to cooperate with us during this study.

This report is also to be found on the website of Umhverfisstofnun at www.umhverfisstofnun.is or www.ust.is.

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1. Summary

Being a member of the EEA (European Economic Association), Iceland had to implement the Landfill Directive (LFD). The implementation of the LFD took place in 2002 with the adoption of a new national law. The LFD requires a.o. that all landfills accepting municipal solid waste (MSW) including biodegradable waste must collect landfill gas (LFG) and utilize it or where this is not possible, it must be flared.
LFG forms while the degradation of biodegradable waste takes place, especially under anaerobic conditions. The gas consists of a mixture of methane and carbon dioxide (together with various trace components). Only methane is useful for energy generation, provided that the formation of this gas in a landfill is enough to be used.

There are around 25 landfills in Iceland accepting biodegradable waste but most of them are relatively small. In fact, not much is known about LFG production in these smaller landfills under the specific Icelandic climatologic conditions.
Therefore a study on LFG formation in Icelandic landfills, especially the smaller ones, was needed. In this study only the **concentration** of LFG was measured in the landfills that participated, not studied was the **amount** of LFG formed, as this needs different sampling and measuring techniques and is therefore in fact a totally different project.

From the 25 municipalities operating a landfill, 14 where willing to cooperate with this study. For the measuring of the LFG, these municipalities had to place 3 probes on their landfill. The LFG in the probes was measured and the results where evaluated.
It appeared that LFG formation in landfills with a waste layer thickness of less than 4 meters was not substantial (concentration methane lower than 20%) and not possible to utilize or flare the gas itself. It became also clear that on landfills with a waste layer thickness of 4 meters or more, LFG formation starts quite quickly (within a year).

It can be concluded that the smaller landfills in Iceland with a waste layer thickness less than 4 meters, are not suitable for the collection and utilization/flaring of methane gas.
For the landfills that have a reasonable methane production, further study is necessary to estimate the amount of LFG that can be collected and whether it is useful for utilization/flaring.

Key words: waste management/ treatment and disposal, landfill constructions, LFG formation/compounds, methane, utilization/flaring.

2. Introduction

On 16 July 1999 the European Commission (EC) officially adopted the Landfill Directive (LFD) 1999/31/EC (Ref. 3). The LFD aims to improve the standards of landfilling across the EC/EU, through setting specific requirements for the design, operation and aftercare of landfills, and for the different types of waste that can be accepted on landfills.
Because Iceland is a member of the EEA, it has to comply with this LFD and in 2002 the LFD was implemented by adopting a new Icelandic law (nr. 162/2002) on the treatment of waste.

The LFD requires a.o. that all landfills, accepting municipal solid waste (MSW) including biodegradable waste, must collect landfill gas (LFG) that is formed during anaerobic degradation of the waste in the landfill, and utilize it or, when this is not possible, flare is.
Furthermore the amount of biodegradable waste going to landfill must be gradually reduced by 25% (1996), 50% (2009) and 65% (2016) from the total amount of biodegradable waste landfilled in 1995 or in the latest year before 1995 that date are available for.
Countries that landfilled 80% or more of their waste in the reference year may delay these targets by 4 years. This delay applies to Iceland, as 86% of the produced MSW went to landfill in 1995 (Chapter 3).

The main objective for this study has been, to provide an insight in the formation of LFG on landfills in Iceland. Another important reason for this study was to investigate the relevance of the collecting of LFG (article 16 and Annex III of the LFD), especially on the smaller landfills looked at in the study as this is relevant to the question whether an exemption from this provision of the LFD could be applied for those landfills where LFG production proves to be very little?

The formation of LFG on landfills is caused by natural bacterial degradation of organic and biodegradable waste present in MSW under anaerobic conditions (Chapter 4). The gas is primarily a mixture of methane and carbon dioxide (together with various trace components), though it is only the methane that is useful for energy recovery, provided that the produced amounts are substantial enough to make utilization or flaring feasible.
Methane gas with a concentration of 20 % LEL (lower explosive limit) or more can be used for utilization/flaring (Ref. 8/12).

The formation of LFG has earlier been studied on the biggest landfill of Iceland, which is located in the vicinity of Reykjavik (Álfsnes, Chapter 3). The study on this landfill has resulted in the placement of a gas-drainage system, extracting LFG, clean and utilize it. For our study we used the Sorpa landfill at Álfsnes as a reference because this landfill is best comparable with other landfills elsewhere in Europe concerning the LFG formation, and research has shown that there are no significant climatologically effects influencing this landfill.

From 1970 until 1990 the waste management in Iceland changed from open-pit burning to more controlled and sophisticated alternatives such as landfilling, incineration as well as reuse, recovery or recycling. This strategy has led to a waste management system building on the so-called waste hierarchy: prevention/reuse, recycling and recovery with energy generation/recovery without energy generation/landfill, reminding of the Lansink-triangle, the basis for waste management in the Netherlands, where most of the waste is recycled/recovered or incinerated with energy generation and only a few percentage is landfilled.

Today 67% of all produced MSW in Iceland goes to landfills, around 3 % is incinerated with energy recovery and 30% is reused or recycled. Open-pit burning has practically ceased to exist today.
The population of Iceland consists approximately of 280.000 inhabitants and the waste generated in 2002 was around 260.000 tonnes (Chapter 3).

The transportation costs within Iceland are relatively high because of the long distances between municipalities and also due to the harsh meteorological conditions during a significant part of the year. This is the main reason why there are many but relatively small landfills in Iceland.

In Iceland there are around 25 landfills in operating accepting MSW including biodegradable waste. Before measuring the LFG formation on these landfills, an investigation was made on the willingness of the landfill operators to take part in the study.
A letter was sent with the request of participating along with the necessary practical information on this project. 14 of the 25 municipalities operating a landfill were willing to cooperate (almost 60%). Instructions were sent to the participating landfill-operators about how the 3 probes, that were required for the measuring should be manufactured and where they should be placed on the landfill (Chapter 5).
For this study, only the concentration/composition (vol. %) of the LFG was measured, how much LFG is being formed was not studied.

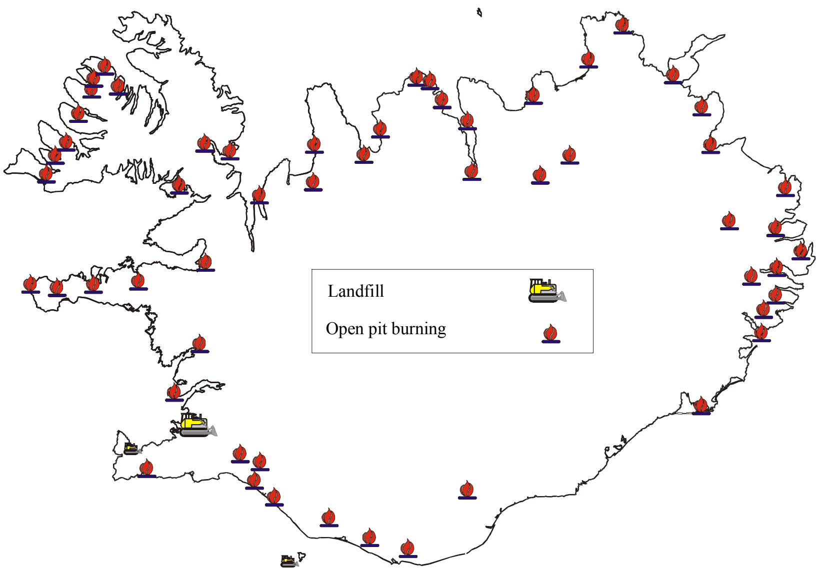
3. Waste management in Iceland

3.1 History of the Icelandic waste management

The Icelandic market is very small both in respect of volume of produced waste materials as for products from recycled waste. The transportation costs within Iceland are relatively high because of the long distances between municipalities and due to the harsh meteorological conditions during a significant part of the year. This is the main reason that there are relatively many but small landfills in Iceland.

Iceland has been working systematically since the early 1970´s on changing their waste treatment and disposal. Around 1970 the main treatment and disposal in Iceland was by burning the waste in open pits. During this time only two locations where used for landfilling (figure 3.1).

Figure 3.1 Waste treatment and disposal in Iceland around 1970

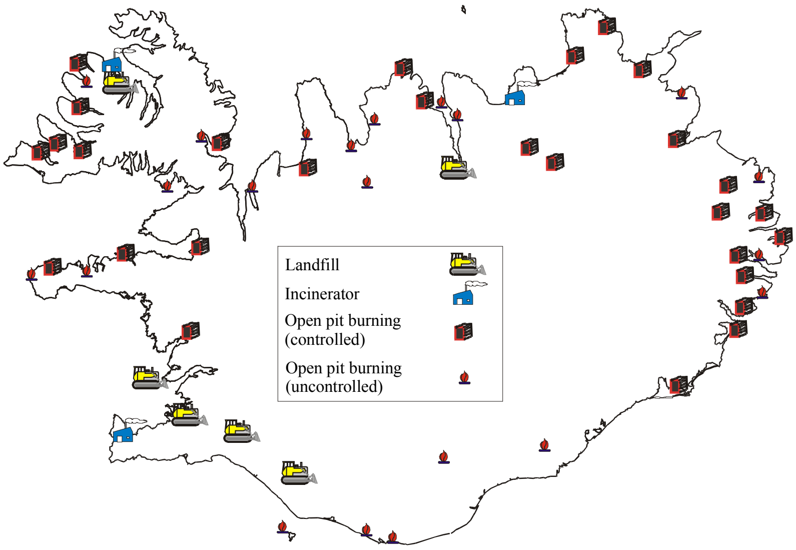


From 1970 until 1990 the waste management changes from mainly open-pit burning to more controlled and sophisticated alternatives. This was partly done to eliminate the formation of the highly dangerous dioxins/furans compounds that are formed by the uncontrolled incineration of the waste in open pits.

Around 1990 most of the open-pit burnings where changed to more controlled burning sites and 3 incinerators were built. Also the landfilling of waste was making progress as 5 new landfills were built (figure 3.2).

An important improvement in waste treatment has been the separating of hazardous waste from other waste, which started during this period, and the initiative has proved to be successful in many ways.

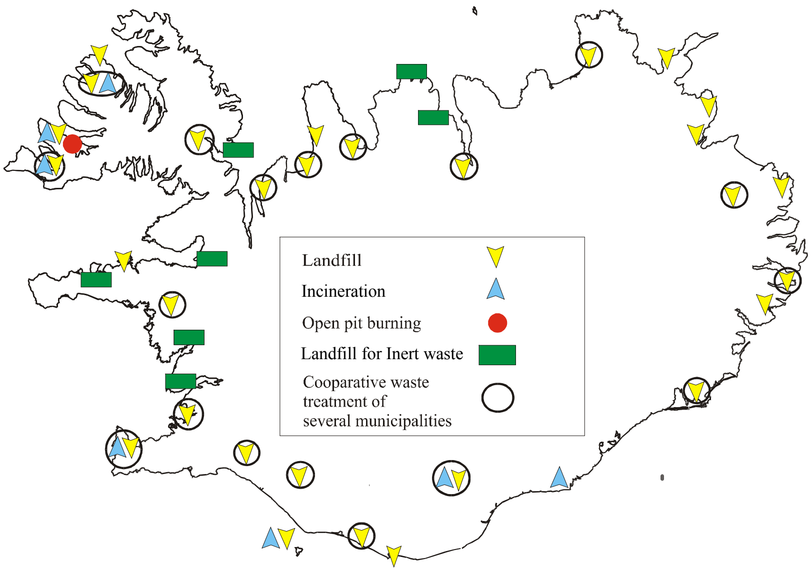
Figure 3.2 Waste treatment and disposal in Iceland around 1990



The strategy mentioned above has led to a waste management system building on the so-called waste hierarchy: prevention/reuse, recycling/recovery with energy generation/recovery without energy generation/landfill, reminding of the Lansink-triangle, the basis for waste management in the Netherlands. Open-pit burning has practically ceased to exist today.

During the last few years, municipalities started to work together forming corporations between municipalities using one larger treatment facility together, instead of separate smaller ones (figure 3.3).

Figure 3.3 Waste treatment and disposal in Iceland in 2003



In Iceland only landfills that accept inert waste [(1)] and non-hazardous waste [(2)] are to be found. No landfills are operated for hazardous waste [(3)]. Waste oil is incinerated with energy recovery in two bigger plants (a cement kiln and a heating plant), all other collected hazardous waste is sent abroad for treatment, mainly to Komuniké in Denmark.

Since the year 2001 Iceland distinguished four categories of landfills. The first category of landfill accepts non-hazardous waste with a capacity exceeding more than 5000 tonnes of waste per year. The second and third category are also accepting non-hazardous waste but respectively with a capacity between 500 and 5000 tonnes per year or less than 500 tonnes per year. The fourth category accepts inert waste up to 20.000 tonnes per year (table 3.1).
A landfill may not be operational without a permit issued by the Environmental and Food Agency.

Table 3.1 Landfill categories in Iceland

	Category of landfill	***Capacity*** *(tonnes/year)*
1	Landfill for non-hazardous waste	> 5.000
2	Landfill for non-hazardous waste	500 – 5.000
3	Landfill for non-hazardous waste	< 500
4	Landfill for inert waste	20.000

From the current 32 registered landfills in Iceland with an operating permit, 7 are in category 4 and 25 landfills accept MSW including biodegradable waste. 14 out of the 25 landfills are in category 3, 7 landfills are in category 2 and 4 landfills are in category 1 accepting approximately 10-20.000 tonnes per year, except for the landfill in Álfsnes with a capacity of over 100.000 tonnes a year.
Recent numbers on waste generated in Iceland in 2002 show that 260.000 tones of waste was generated, of which 80% (208.000 tonnes) consists of MSW and the other 20% (52.000 tonnes) consists of scrap metals and slaughterhouse waste, as can be seen in table 3.2.

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(1) Inert waste means waste that does not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm human health (Art. 2(e), LFD 1999/31/EC).

(2) Non-hazardous waste contains: *municipal, biodegradable and stable non-reactive hazardous waste*
- *Municipal waste* means waste from households, as well as other waste, which because of its natural or composition, is similar to waste from households (Art. 2(b), LFD 1999/31/EC).
- *Biodegradable waste* means any waste that is capable of undergoing anaerobic or aerobic degradation, such as food and garden waste, paper and paperboard (Art. 2(m) of the LFD 1999/31/EC)
- *Stable, non-reactive hazardous waste* means that the leaching behaviour if the waste will not change adversely in the long-term, under landfill design conditions or foreseeable accidents: in the waste alone (for example, by biodegradation), under the impact of long-term ambient conditions (for example, water, air, temperature, mechanical constraints), by impact of other wastes (including waste products such as leachate and gas)
(Annex, section 2.3, LFD 2002/33/EC)

(3) Hazardous waste means a waste which because of its quantity, concentration, or physical, chemical or infectious characteristics may cause or significantly contribute to an increase in serious irreversible, or incapacitating reversible illness or pose a substantial present or potential hazard to human health, safety, welfare or to the environment. This when improperly treated, stored, transported, used or disposed of, or otherwise managed
(Art. 14 of Council Directive 91/689/EEC of 12 December 1991 on hazardous waste)

Table 3.2 Generated waste in Iceland from 1992 until 2002

x 1.000 tonnes	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Total waste	199	201	203	206	209	216	224	233	245	252	260
Total municipal waste (MSW)	159	161	162	165	168	173	179	187	197	202	208
Household waste	63	64	64	64	65	67	68	71	74	75	76
Non-household	96	97	98	101	103	106	111	116	123	127	132
Other waste	40	40	41	41	41	43	45	46	48	50	52
Scrap metals	30	30	31	31	31	33	35	36	38	40	40
Slaughterhouse waste	10	10	10	10	10	10	10	10	10	10	12
Power intensive industries and cement production	-	-	-	-	-	-	-	-	-	-	-

- *The table does not include wastes from **power-intensive industries, cement production**, construction (earth-moving and demolition) and agricultural waste other than slaughterhouse waste.*
- *The numbers in the table has to be multiplied with 1000 tonnes.*

In 2002, 67% (172.000 tonnes) of the waste was going to landfills and 33% (81.000 tonnes) was recycled or recovered with energy recovery, as can be seen in table 3.3.

Table 3.3 Waste treatment and disposal in Iceland from 1992 until 2002

x 1.000 tonnes	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Total waste	199	201	203	206	209	216	224	233	245	252	260
Recovery (incl. energy recovery)	40	41	45	47	52	52	60	64	69	73	81
of which with energy recovery	0	1	2	2	2	2	4	4	6	6	7
Incineration	13	13	13	13	13	13	11	11	11	11	7
Landfill (total)	136	137	135	136	139	148	151	157	165	168	172
Landfill with permit (1)	80	85	90	99	104	114	129	140	163	167	171
Landfill without permit	56	52	45	37	35	34	22	17	2	1	1
Others (2)	10	10	10	10	5	3	2	1	0	0	0

(1) Landfill on sites with permit according to regulation no 785/1999
(2) Open-pit burning at dump sites
- *The numbers in the table has to be multiplied with 1000 tonnes.*

3.2 Construction of landfills in Iceland

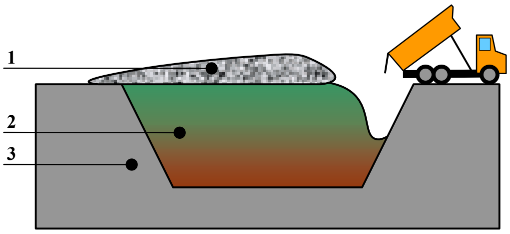
Within the current waste management in Iceland there are three different types of landfill construction: landfills where the waste is being landfilled in one waste layer, landfills where the waste is lifted in separate (mostly 2 or 3) waste layers and landfills where the waste is landfilled in cells. Most Icelandic landfills are located in low landscapes and outside the urbanized areas and on all locations ground- and surface water protection has been taken into account for, mainly by situating them far away from all water protection or water supply areas, typically near the sea or on massive sands.
The landfills in Iceland (except the 4 larger landfills in: Álfsnes, Akureyri, Borgarnes and Kirkjuferjuhjáleiga) have no additional bottom-lining system or specific leachate-collection system. However, where applicable, separation of rainwater and leachate is required in the permit, making treatment of leachate possible if needed.

Landfill type I
For this type of landfill, a lane is excavated with a depth varying from 2 until 30 meters, a wideness varying from 1 until 40 meters and a length varying from 15 until 300 meters. The waste is then landfilled in just one layer and finally covered with peat soil or gravel as seen in figure 3.4.
A typical landfill of this type is the Sorpa landfill at Álfsnes. On this landfill a study on LFG formation has already been done earlier, resulting in placing a gas-drainage, collection and cleaning-system to extract and use the LFG for electricity production and as fuel for cars and city-buses.
As we used the landfill at Álfsnes as a reference a short description of this landfill will be given below.

Sorpa landfill at Álfsnes

This is the largest landfill of Iceland and was opened in 1991 and nowadays is accepting ca. 110.000 tonnes of waste yearly containing non-hazardous and inert waste. After sorting the waste in the sorting centre (in Gufunes) most MSW going to the landfill at Álfsnes is baled, each unit weighing around 1 tonne. At Álfsnes the bales are stacked up to approximately 26m height and 40m wide before the lane is covered with a topsoil layer.
Most of the waste landfilled at Álfsnes is coming from households, firms and institutions in the capital area of Reykjavik but also some waste from other municipalities is landfilled at Álfsnes.
The lanes of the landfill are realized by excavating peat soil and clay down to the bedrock underground.
The excavated clay is then placed at the bottom again and compacted. On top of this layer, drainage pipes are placed, which are used to collect the leachate. A layer of gravel is placed over this drainage layer and after that the lane is ready for use.
After one lane is completely filled and the waste is covered with topsoil (typically peat soil), drainage pipes to collect the LFG are placed vertically. The gas formed in the landfill is extracted collected and cleaned. Methane is used for electricity production and as fuel for cars and city-buses.
The extraction of the LFG started 2 years after the landfill was opened. The concentration of the gas is approximately 50-60% for methane and 35-40% for carbon dioxide, typical for landfills in the methanogenesis-phase. The temperature measured inside the probes on this landfill ranges from 12-26 °C.
In 1998, there the landfill produced approximately 1300 tonnes of methane gas (97-98% methane after purification) and Sorpa expects that the production of methane gas will reach a maximum of 4000 tonnes/year in 2012 (Sorpa Álfsnes, 2003, Ref. 6/10).
It is not known yet how long exactly LFG will be produced in amounts that make usage economically and environmentally interesting for this landfill.

***Figure 3.4 Landfill type I** (using one waste layer)*

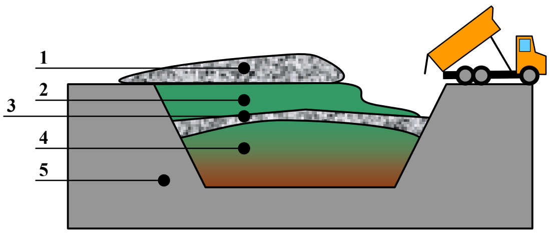


1) *Soil or gravel to cover the waste,*
2) *Landfilled waste layer,*
3) *Bedrock underground.*

Landfill type II

This landfill type is made the same way as type I by excavating a lane. But the waste on this type of landfill is landfilled in separate lifts or waste layers separated by a sub-layer.
After the waste is landfilled for approximately 2 or 3 meters, it is covered with timber cuttings, soil or gravel and on top of that layer a new similar waste layer is placed as seen in figure 3.5.
In some places (Akureyri, Sauðákrókur, Fíflholt, Kirkjuferhjáleiga) the waste is compressed after disposal in the lane by driving over it several times with a heavy compactor.
This reduces significantly the space that is needed for landfilling, as well as the spreading of waste materials by wind.

***Figure 3.5 Landfill type II** (using separate waste layer)*

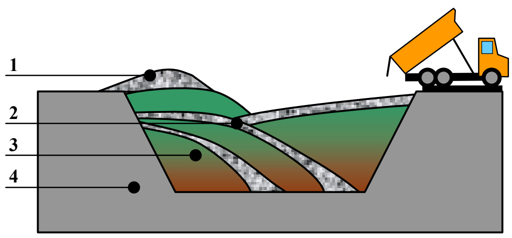


1) *Soil or gravel to cover the second waste layer,*
2) *Second landfilled waste layer,*
3) *Sub-layer of soil or gravel to cover the first waste layer,*
4) *First landfilled waste layer,*
5) *Bedrock underground*

Landfill type III

This type is a bit similar to landfill type II, but instead of landfilling the waste in separate lifts (layers), the waste is landfilled in separate cells. These cells are forming when relatively small amounts of waste (one or a few truckloads) are separately covered with soil or gravel as seen in figure 3.6.

***Figure 3.6 Landfill type III** (using separate waste cells)*



1) *Peat soil or gravel to cover the waste,*
2) *Sub-layer of soil or gravel to cover the waste cells,*
3) *Landfilled waste cell,*
4) *Bedrock underground*

4. Landfill gas

4.1 The formation of LFG

LFG is formed while organic and biodegradable waste in a landfill is degrading because of bacterial activity under anaerobic conditions. The gas is primarily a mixture of methane and carbon dioxide (together with various trace components), though it is only the methane that is useful for energy generation.

Gasses in landfills move through the subsurface into the atmosphere, under the influence of both concentration and pressure gradients that is both diffusion and convection. Usually one process is dominant in near-surface soils, while convection dominates near gas recovery wells, which are subject to partial vacuum in order to abstract the gas from the landfill. Once they reach the atmosphere, their movement is dominated principally by convection and turbulent transfer processes.

Gas formation depends on a number of factors, such as: the amount and type of waste, e.g. how the waste is landfilled (thickness and amount of the waste layers), the moisture content and climate (Ref. 1/9). Under temperate conditions, gas-formation begins within a few months, rising to a maximum within a few years and may persist for several decades.

The degradation of biodegradable matter caused by bacterial action can be put out in this simplified chemical reaction.

$$\underset{\text{(cellulose)}}{n\ C_6H_{10}O} + \underset{\text{(water)}}{n\ H_2O} \xrightarrow{\text{(Bacteria)}} \underset{\text{(methane)}}{3n\ CH_4} + \underset{\text{(carbon dioxide)}}{3n\ CO_2}$$

LFG temperatures typically range from 30 to 40° C within the landfill. But because of relatively low soil temperature in Iceland with an average of 4°C as is a proper refrigerator, the concentration of the formed LFG at Icelandic landfills could be expected to be significantly lower than in other EU countries, especially in the smaller landfills, where climatologic effects can be expected to have significant impact on the biological, physical and chemical processes within the landfill.

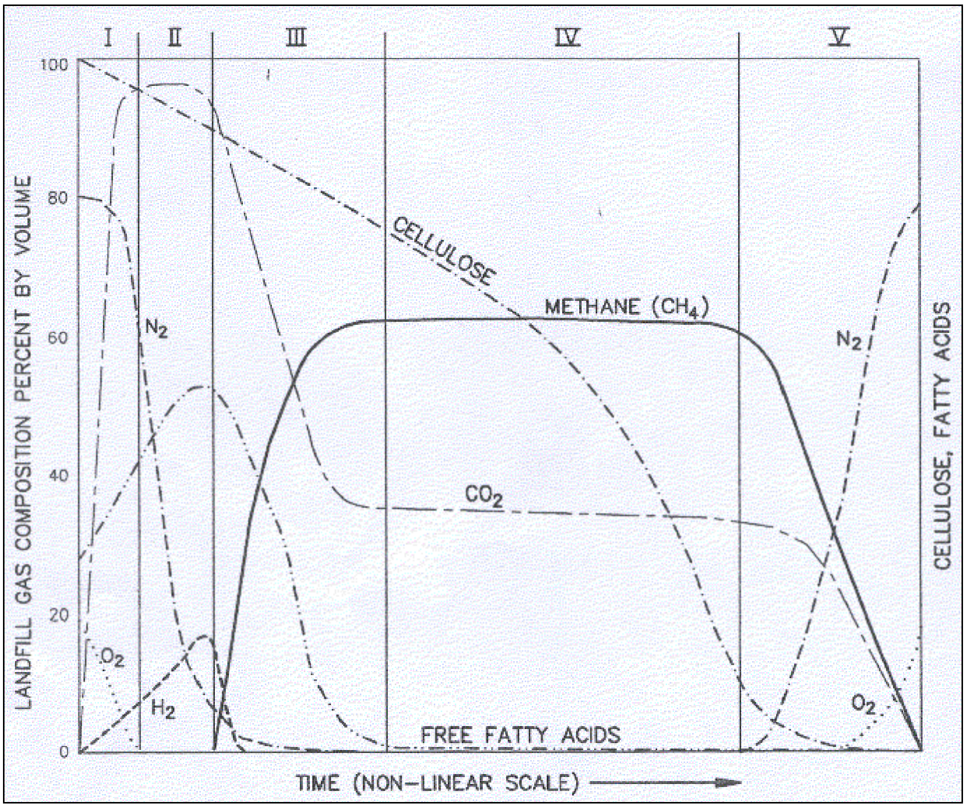
Figure 7.1 gives the typical LFG production pattern (Ref. 7). The first four phases shown in this figure are referred to as the aerobic phase, the anaerobic acid phase, the methanogenic unsteady phase and the methanogenic steady phase. Subsequent phases of decomposition, in which the waste layer or cell begins to turn aerobic are based on theory and are somewhat speculative because no field data are available to document the onset of aerobic conditions. This is due to the fact that most well monitored landfills are less than 30 years old and are still in stable methanogenic phase (Christensen and Kjeldsen, 1995)

During the initial aerobic phase, oxygen present in the void spaces of the freshly buried waste is rapidly consumed, resulting in the production of CO_2 and maybe an increase in waste temperature. The aerobic phase in a landfill lasts only a few days because oxygen is not replenished once the waste is covered. As oxygen sources are depleted, the waste becomes anaerobic, which supports fermentation reactions. Cellulose and hemicellulose comprise 45 to 60% of the dry weight of MSW and are its major biodegradable constituents (Barlaz et al., 1989, Ref. 9).
The decomposition of these compounds to methane and carbon dioxide in landfills under anaerobic conditions is well documented (Barlaz et al., 1990; Pohland and Harper, 1986; Bookter and Ham, 1982).

Cellulose and hemicellulose biodegradation is carried out by three groups of bacteria: (1) the hydrolytic and fermentative bacteria that hydrolyse polymers and ferment the resulting monosaccharides to carboxylic acids and alcohols; (2) the acetogenic bacteria that convert these acids and alcohols to acetate, hydrogen and carbon dioxide; and (3) the methanogens that convert the end products of the acetogenic reactions to methane and carbon dioxide (Zehnder, 1982).

For landfills where the waste is landfilled in different cells or waste layers, it is common that the waste in the different parts, are in different phases of decomposition (Kjeldsen *et al.,* 2002).
It is expected that the time of LFG production it the longest on landfills with one waste layer and that there is a little chance of LFG emissions into the atmosphere on landfills with separate layers or cells.

Figure 4.1 Typical LFG production pattern



I	*Aerobic phase,*
II	*Anaerobic acid phase,*
III	*Anaerobic, methanogenic phase (unsteady),*
IV	*Anaerobic, methanogenic phase (steady),*
V	*Anaerobic, methanogenic phase (declining),*

4.2 The LFG-compounds

LFG contains a large variety of compounds. This paragraph will describe the following LFG compounds:

- Methane (CH_4)
- Carbon Dioxide (CO_2)
- Hydrogen (H_2)
- Non Methane Organic Compounds (NMOC´s)
- Hydrogen Sulphide (H_2S) and organosulphur compounds
- Ammonia and Nitrogen
- Carbon Monoxide (CO)
- Mercury (Hg)
- Silicon (Si)

4.2.1 Methane (CH_4)

Methane is the first of the two main compounds of LFG, which is generated during the anaerobic degradation of the waste. Its concentration typically ranges between 30 and 60 % of the gas, under stable methanogenic conditions. The methane emissions from MSW landfills will last for decades. If seen in figure 4.1, the start of methanogenesis and thus methane emission may be retarded due the excessive accumulation of free fatty acids (Lagerkvist *et al.,* 1999).

Methane is an important greenhouse gas. Despite its relatively low atmospheric concentration compared to carbon dioxide (currently 1.75 ppm as opposed to 358 ppm), the higher infrared absorption potential of methane makes its global warming potential around 25 times higher than that of carbon dioxide (Dlugokencky & Masarie, 1998).

Methane is generally not considered toxic to plants or other organisms. The major effect of methane in soil is believed to be due to methane oxidation, which depletes the oxygen present increases the carbon dioxide levels and may also raise the soil temperature. This may lead to plants death by enhanced asphyxiation.

A mixture of 5% to 15% methane in air will explode if ignited. A concentration of 5% methane in air, is the “lower explosive limit” (LEL), and concentrations equal to or greater than the LEL are considered hazardous. To add a margin of safety, it is considers that concentrations greater than 20% LEL may be associated with still higher concentrations, exceeding the LEL. Therefore, methane concentrations greater than 20% LEL warn of conditions which could be potentially hazardous, and gas control systems should be designed to maintain concentrations below this level. Methane gas with a concentration of 20 % LEL or more can be used for utilization/flaring (Ref. 8/12).
The flammability range is lower than the normal concentrations of methane in pure landfill gas. However, during migration, landfill gas will mix with air and becomes depleted in methane, through dilution and/or oxidation, and therefore fall within the flammability range (Christensen *et al.,* 1996; Gendebien *et al.,* 1992).

Methane constitutes both a very short term and acute explosion hazards and has a much more far-reaching and long-term effect on global warming. This is one of the reasons why we especially looked at the methane compound in this study.

4.2.2 Carbon dioxide (CO_2)

Carbon dioxide is the second main compound of the gas generated in MSW landfills, where it typically makes up between 20 and 50% of the gas. It arises as one of the waste products of the biodegradation of organic compounds, both aerobic and anaerobic.

Atmospheric, carbon dioxide is a limiting factor in photosynthesis and is essential to plants. However, when present at high concentrations in soil, it can result in asphyxia due the oxygen displacement and can be directly toxic to plants.
The normal carbon dioxide concentration in soils varies between 0.04 and 2 %. An elevated concentration of carbon dioxide in a soil, a situation typical for landfill cover soils, is directly toxic to the plant roots, even if there is enough oxygen available. An indirect effect of carbon dioxide could be a lowering of the soil pH and the consequent changes in soil composition (Maurice, 1998).

Carbon dioxide is classified as an intermediary between toxic and non-toxic substances. It acts by displacing oxygen in the respiratory system. It ambient concentration lies around 250 – 350 ppm. Several deaths due to carbon dioxide asphyxia have occurred on or near landfills (in recent years), in underground or closed environments such as drains or culverts, where LFG had accumulated, carbon dioxide must therefore be considered a serious safety threat in landfill environments.
This hazard is generally treated in far less detail than the explosion and fire hazards due to methane formation (Christensen *et al.,* 1996).

4.2.3 Other LFG-compounds

Hydrogen (H_2)
Hydrogen is a non-poisonous, odourless and colourless, but highly inflammable gas.
In MSW landfills, it is produced both by the fermentative and acetogenic bacteria and consumed by the methanogens. As this last group of micro-organisms are the slowest to develop in the metabolic succession of anaerobic degradation, molecular hydrogen may accumulate during the initial stages of waste degradation and be transiently present at high levels (up to 20%) in the gas phase of young landfills, well above its LEL(4%).

Hydrogen is also produced in ash and slag deposits: elemental aluminium, which is the fifth most abundant element in bottom ash, reacts with water to form aluminium hydroxide and gaseous hydrogen (Chandler et al., 1997). A variety of industrial wastes may have a potential of hydrogen formation on wetting. There are no reports of accidents involving hydrogen on landfills. It is relatively easily oxidized in soils by micro-organisms and this has been documented experimentally in landfill top covers (Nozhevnikova *et al.,* 1993).

Non-Methane Organic Compounds (NMOC´s)
The gas from MSW landfills usually contains a variety of trace organics that may make up to 1% volume of the gas. Many research studies have generally detected between 100 and 200 different compounds. These compounds are either the sub-products of the biological and chemical processes occurring in the waste (Genebien *et al.,* 1992).

Examples are oxidised carbon compounds: alcohols, ketones, esters, organic acids, furans and sulphur compounds. The concentrations of these compounds are extremely variable from one site to another.
The nature of waste deposited and the rates and mechanisms of degradation occurring will have a decisive influence on the types of compounds and concentrations. The presence of these compounds in the gas phase will depend on their polarity: more polar compounds will tend to solubilize in the leachate, while the more apolar ones will be found in a higher proportion in the gas phase.

Hydrogen Sulphide (H_2S) and organosulphur compounds
Hydrogen sulphide and organosulphur compounds may all represent the most critical group of LFG compounds encountered to date, due to their toxicity, odour potential and corrosiveness.

Hydrogen sulphide is highly toxic and affects the nervous system. It also has a repugnant odour and is highly flammable. Its odour threshold is comprised between 5 and 40 ppm. Above 50 ppm it paralyses the olfactory system, which makes it a particularly pernicious intoxicant. Concentrations above 400 ppm affect the nervous system and above 700 ppm there is risk of death by respiratory failure.
When in contact with water, hydrogen sulphide gives rise to sulphuric acid, which may corrode gas utilization facilities. It may also result in high SO_2 emissions after LFG combustion (Rettenberger, 1996).

Organosulphur compounds, i.e. mercaptans and carbon or methyl sulphides, are important contributors to the foul smell of LFG formed on MSW landfills. They most probably arise from the degradation of proteins, which typically forms 6% of food wastes (Genebien *et al.,* 1992).

Generally, the levels of sulphur compounds are lower in LFG than in other biogases.
Sulphur is abundant in bottom ash and has been found in concentrations ranging from 1000 to 5000 mg/kg. Most of the sulphur is in the form of sulphate. The most toxic of organosulphur compounds is methyl mercaptan, which affects the central nervous system (Rettenberger, 1996).

Ammonia and Nitrogen
Like the organically bound sulphur, ammonia and nitrogen compounds arise from the degradation of proteins. Because of the very low odour threshold for ammonia (1ppm), landfill workers could be exposed to above limit levels and therefore can be considered a security factor.
Ammonia may be released during leachate treatment, for example during aeration. Ammonia stripping is an effective way to reduce the nitrogen load of the leachate.

Oxidised forms of nitrogen are unwanted products of the combustion of LFG and are largely influenced by the combustion technology and by parameters such as temperature, reaction time and oxygen supply. Nitrous oxide (N_2O) emissions in particular are environmentally relevant as it is a greenhouse gas with a global warming potential 300 times that of carbon dioxide. Numbers say that nitrous oxide contributes for 9% to the greenhouse effect.

Carbon Monoxide (CO)
Carbon monoxide has been found in LFG of MSW landfills with concentrations between 0 and 3% volume. If higher concentrations are present, this may be a sign of oxygen-starved burning of the refuse. Research shows that concentrations up to 1600 ppm of carbon monoxide can be found inside the burning waste mass. The highest levels of carbon monoxide can be found during the extinguishing of fire on landfills. It may also be emitted during combustion of LFG, as a result of incomplete combustion. It is a highly toxic gas, which binds with hemoglobin in the blood and thus causing respiratory failure and death above 5000 ppm. Carbon monoxide can be oxidised by bacteria to carbon dioxide, mostly occur in landfill top covers (Nozhevnikova *et al.,* 1993).

Mercury (Hg)
Municipal solid waste has been identified as a potentially source of mercury. MSW contains mercury due to the disposal of a variety of products, which contain this metal. Mercury is found in varying amounts in batteries, fluorescent and high intensity light bulbs, thermometers, thermostats, light switches, with batteries as the most important contributor. During incineration, most of the mercury passes into gas.

Once released to the environment, mercury is distributed to the earth's surface including soils, wetlands, lakes and oceans. It can undergo chemical transformations, predominantly oxidation-reduction and methylation-demethylation. Biological processes play an important part in these transformations. Methylation, the addition of ($-CH_3$) to ionised mercury has been documented in water, sediments and soil. It is a microbial process and is in particular affected by dissolved oxygen, sulphur, organic matter or clay and by the pH. More methylated mercury is formed in the oxygen-limited environments and sulphate-dependant bacteria are thought to be involved in the process. These conditions are characteristics for MSW landfills, so it is probable that methylation may occur there.
Clay particles and organic matter bind the mercury, thus decreasing its bioavailibilty for methylation. Methyl mercury is toxic and fairly soluble in water. Dimethyl mercury is much less soluble, so it is less toxic. In anaerobic environments mercury may also be converted into the insoluble mercury sulphide.

Silicon (Si)
Siloxanes, or silicones are commercially produced compounds containing carbon, silicon, oxygen and hydrogen and must be distinguished from inorganic silicon which contains no carbon, but only SiO_2 units. When combusted however, the product will be inorganic, regardless of its original form and the impact is believed to be the same. The increasing utilization of LFG in reciprocating engines or turbines for energy recovery has sparked awareness of technical problems due to corrosion and fouling form residues generated by the combustion of trace impurities in the gas. The identification of the sources of Si deposits in gas utilization equipment is complicated by several factors.

Firstly, a large variety of siloxanes compounds exist, due to their polymeric nature. Not only low molecular weight volatile siloxanes are entrained, but also high molecular weight siloxanes have been shown to aerosolise and thus be transported in gas streams. Secondly, naturally occurring silicon compounds are very common in landfill environments. Though they are exclusively non-volatile mineral species they may be transported with the gas as particulate matter or as solutes in water droplets (Niemann *et al.,* 1997).

Table 4.1 on the next page, shows a technical overview of the described LFG compound and their concentration range, scale of impact, type of impact, relevance and expected trend of emissions within the next years (Ref. 5).

Table 4.1 Technical overview of the LFG-compounds

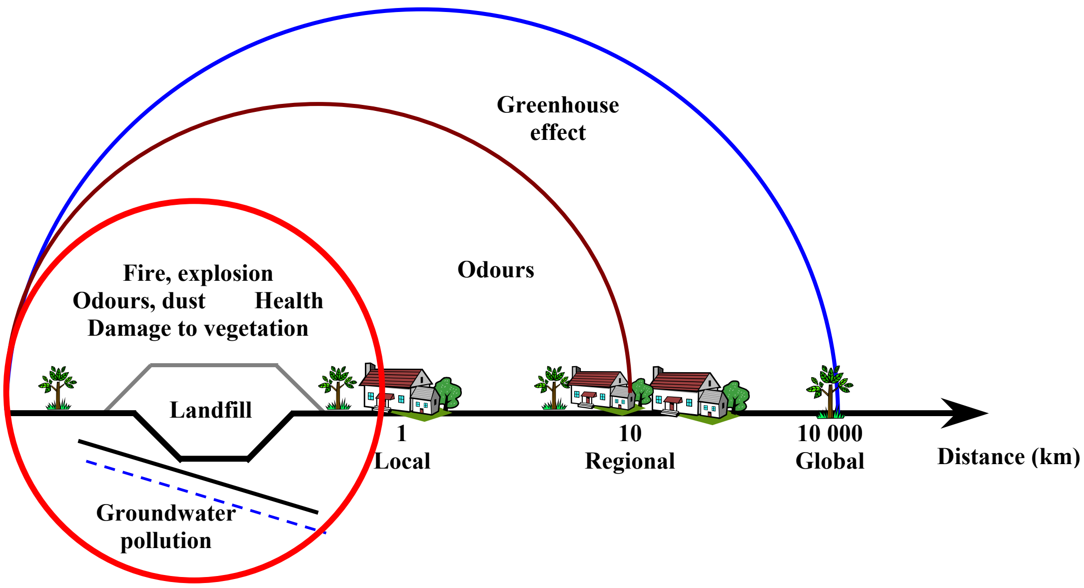
Compound		Concentration range	Scale of impacts	Type of impacts	Relevance	Expected trend of emissions
Methane	CH_4	30 - 60%	Global Local	Global warming Vegetation, asphyxia, explosion and fire hazard	High High	↘ (slow)
Carbon dioxide	CO_2	20 - 50%	Global Local	Global warming Vegetation, asphyxia	High High	↗
Hydrogen	H_2	0 - 20%	Local	Explosion	Low	→
Non Methane Organic Compounds	NMOC´s	mg/m^3	Local	Odours, vegetation	Low	↘ (slow)
Hydrogen sulphide	H_2S	0 - 20 g/m^3	Local	Health hazard, odours, corrosion	High	→
Organosulphides		mg/m^3	Local Local	Health hazard, odours, corrosion Odours, corrosion	High Low	→
Ammonia	NH_3	mg/m^3	Global Local	No_x formation Odours, health hazard	Low Low	↘
Nitrogen	N_2	mg/m^3	Global	Global warming	Low	↗
Carbon monoxide	CO	0 - 3%	Local	Asphyxia, explosion	Low	↘
Mercury	Hg	10 - 25 ng/m^3	Global Local	Dispersion and bio-Accumulation Health hazard	Unknown Unknown	↘
Silicon	Si	mg/m^3	Local	Wearing of equipment	Unknown	↗

4.3 The environmental impact of LFG-emission

A landfill constitutes a number of potential risks to the environment but one of the most common and important is the uncontrolled release of LFG. These emissions constitute one of the major environmental concerns regarding landfills as methane gas is widely accepted to contribute to global warming effects by around 25 times more than CO_2 (Dlugokencky & Masarie, 1998).

The gaseous compounds emitted from landfills have various environmental impacts on their surroundings and act on different scales, as illustrated by figure 4.2. In addition to having impacts over a large spatial scale, gaseous emissions also act on different time scales. Compared to most other processes used in waste treatment, those occurring inside the landfill and the emissions they generate extend over a very long period of time after the waste has been disposed: from tens to hundreds of years.
Not only is the period of significant emissions long, but also the compounds emitted will themselves have effect and life-spans of varying duration.
Odours and dust, for example, are mainly transient phenomena, while some of the anthropogenic trace compounds in LFG may persist and accumulate in organisms or natural ecosystems over very long periods of time (Kjeldsen, 1996).

Figure 4.2 Different scales of environmental impact caused by LFG emission



(Kjeldsen, 1996)

5. Fieldwork and study methods

In Iceland there are around 25 landfills (table/figure 5.1) operating, accepting MSW including biodegradable waste. Before measuring the LFG formation on these landfills, an investigation was made on the willingness of the landfill operators to take part in the study.

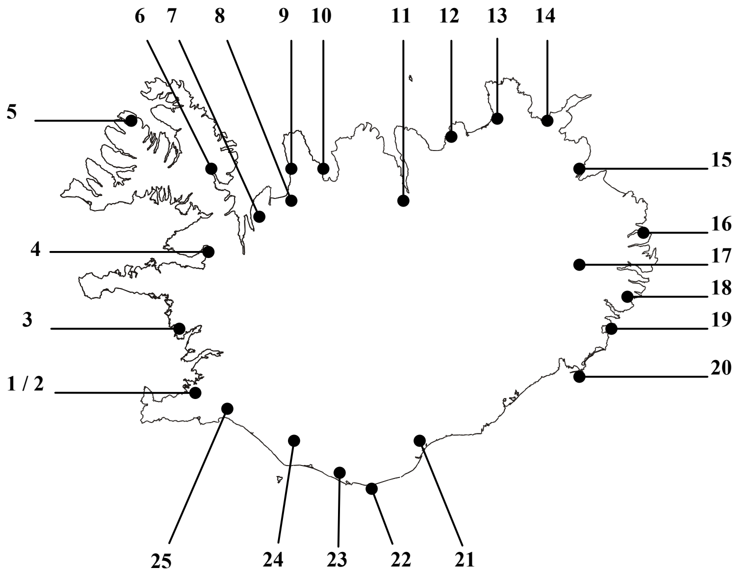
A letter was sent to all landfill operators in Iceland, with the request of participating along with the necessary practical information on this project. 14 of the 25 landfills operators were willing to cooperate. Instructions were sent to the participating landfill operator about how the 3 probes, that were required for the measuring should be manufactured and where they should be placed on the landfill (see figure 5.2).
For this study, only the concentration and composition (vol. %) of the LFG was measured, how much LFG is being formed was not studied

Table 5.1 Operational landfills in Iceland accepting MSW containing biodegradable waste

	Landfill	
1	Reykjavik *(Álfsnes)*	
2	Reykjavik *(Gufunes)(sorting plant)*	
3	Borgarnes *(Fíflholt)*	LFG
4	Dalabyggð *(Buðardalur)*	
5	Bólungarvík	
6	Hólmavík *(Skeljavík)*	LFG
7	Hvammstangi *(Kárastaðir)*	LFG
8	Blönduós *(Draugagil)*	
9	Skagaströnd *(Neðri-Harrastaðir)*	LFG
10	Sauðárkrókur	
11	Akureyri *(Glerárdalur)*	LFG
12	Húsavík *(Saltvik)*	
13	Kópasker *(fyrrv. Flugvöllur)*	
14	Þórshöfn	LFG
15	Vopnafjörður *(Búðaröxl)*	LFG
16	Borgarfjörður eystra *(Brandsbalir)*	
17	Egilsstaðir *(Tjarnaland)*	LFG
18	Miðausturland *(Þernunes)*	
19	Breiðdalsvík *(Melar)*	LFG
20	Höfn *(Lón)*	LFG
21	Kirkjubæjarklaustur, *(Stjórnarsandur)*	
22	A-Eyjafjalla hreppi, *(Skógasandur)*	LFG
23	Myrdalssandur *(Uxarfótarlæk)*	
24	Rangárvallassýsla, *(Strönd)*	LFG
25	Suðurland, *(Kirkjufurhjáleiga)*	LFG

- *LFG = Landfill gas measuring on this landfill*

Figure 5.1 Locations of operational landfills in Iceland accepting MSW containing biodegradable waste



For this study, each landfill taking part in this project had to place 3 probes on the landfill. The locations of the probes where determined by the age of the landfilled waste.
Where possible, one probe was placed in the oldest part of the landfill, one probe in the newest part of the landfill and one probe was placed in the mid part, as seen in figure 5.2.

The length of the probe was determined by the thickness of the waste layer, but was typically 3-4 meters, unless different stated in the results. The probes that we used for this project had the purpose of collecting LFG, although on some landfills water was also collected inside these probes.
We used metal probes and they can be divided in separate parts. The probe exists of pieces of normal iron pipe, a piece of pipe that has holes drilled in it to allow the gas (or water) to enter the probe, and one part with a sharp point to penetrate the material more easily. A technical drawing of a probe and an example of the placing of a probe can be found in appendix I and II.

With the cooperating landfill operators we arranged a date to come to measure the LFG.
Not on each landfill we measured 3 probes, on some landfills there where only one or two probes placed and in some cases, a probe was simply missing, broken or run over by one of the trucks.

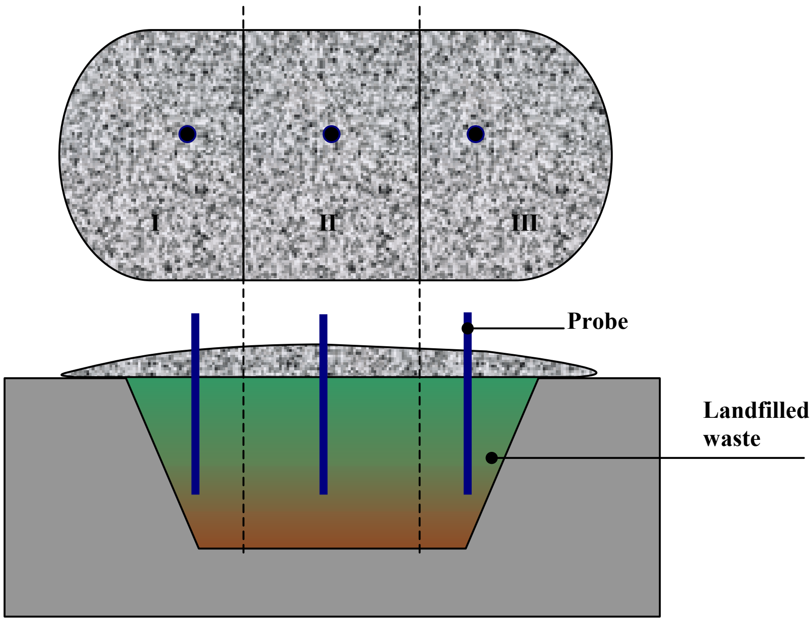
To measure the LFG we used a *GA94A* gas-analyzer that was specially rented for this study from *Geotechnical Instruments Ltd*. in the UK. This analyzer is especially used for LFG measuring and this is the same type of analyzer used at the Sorpa landfill in Álfsnes. We checked the working of the gas analyzer at Sorpa landfill in Álfsnes to be sure about its calibration before the measurements were done. The parameters, which we where able to measure with this analyzer where:

- Time of measuring,
- Air-pressure,
- Concentration (vol. %) of methane, carbon dioxide and oxygen.

The parameters that we had to measure with other equipment where:

- Depth of the probe (tape measure),
- Temperature (thermometer),
- Coordinates of the probes (GPS).

Figure 5.2 Locations of probes on landfill



I) Oldest part of the landfill,
II) Mid part of the landfill,
III) Newest part of the landfill.

We will give a short example on how the measuring of the probes was done:

Example: First after the probes were located, we opened all probes to allow the probe to adjust to the surrounding air-pressure. Then the depth of the probe and/or the water level of the probe were measured. After this, a small silicone tube of approximately 1 meter long, which was attached to the analyzer, was hung into the probe together with the thermometer. The probe was then closed with a piece of foam, preventing the analyser from pumping up air from outside causing, obviously, an inaccurate reading. The concentrations of the 3 main gas-compounds (methane, carbon dioxide and oxygen) were measured in volume percentages (vol. %) with one decimal.
Each probe was measured until the measurement values had stabilized, typically for approximately 5 minutes in which ca. 5 times the volume of the probe was pumped up by the inbuilt pump of the analyzer.
The time and date of the measuring, the atmospheric pressure, gas concentrations, temperature inside and outside the probe and the coordinates (GPS) were written down on a special form that was made for this study. An example of the measuring of a probe can be found in appendix II of this report.

During the measurements we talked with the landfill operators and asked if they knew some specific details about the landfill, such as: the type of landfilled waste, the age of the landfilled waste, when it was last used, etc. All this information about the landfill was noted and pictures of the landfill were taken.

6 Results and evaluation

6.1 Results

The results from the LFG measuring on the Icelandic Landfills accepting MSW including biodegradable waste are shown in table 6.1, more detailed information about the measuring can be found in appendix III of this report. This table shows the landfills where LFG was measured, the category and type (Chapter 3) of the landfill, age of the landfilled waste, the thickness of the waste layer(s), concentration of methane, carbon dioxide and oxygen and the type of landfilled waste.

Table 6.1 Results from LFG measuring on Icelandic landfills accepting MSW including biodegradable waste

Landfill *(Date of measuring)*	**Landfill category and type**	**Age of landfilled waste** *(Years)*	**Total thickness of waste layer** *(m)*	**CH_4** *(vol.%)*	**CO_2** *(vol. %)*	**O_2** *(vol. %)*	**Type of landfilled waste**
Borgarnes	Cat.1 / type I	4	5,0	63,0	37,1	0,0	MSW incl. biodeg.
(Fiflholt)		3	5,0	0,0	0,0	20,8	" "
(19.5.2003)		2	5,0	2,5	1,7	19,7	" "
Hólmavík	Cat.3 / type II	4	5,0	36,0	30,8	0,1	MSW incl. biodeg.
(Skeljavik)		2	5,0	0,7	0,7	20,7	" "
(22.5.2003)		1	5,0	54,8	38,3	1,3	" "
Skagaströnd	Cat.3 / type I	13	2,0	0,0	3,2	18,1	MSW incl. biodeg.
(Neðri-Harrastaðir)		6	2,0	0,0	6,8	14,1	" "
(2.6.2003)		1	2,0	0,0	1,2	20,1	" "
Akureyri	Cat.1 / type I	5	15,0	61,4	34,7	0,0	MSW incl. biodeg.
(Glerardalur)		4	15,0	66,9	34,1	0,0	" "
(3.5.2003)		3	15,0	62,8	36,8	0,0	" "
Þórshöfn	Cat.1 / type I	5	2,0	0,0	0,3	20,7	MSW incl. biodeg.
(10.6.2003)		3	2,0	0,0	0,0	20,9	" "
Vopnafjörður	Cat.3 / type I	4	4,0	5,8	9,7	5,5	MSW incl. biodeg.
(Búðaröxl)		3	4,0	41,1	20,8	1,6	" "
(10.6.2003)		1	4,0	17,4	18,8	0,0	" "
Egilsstaðir	Cat.2 / type I	11	3,0	22,0	19,3	1,7	MSW incl. biodeg.
(Tjarnaland)		11	3,0	22,2	21,0	0,1	" "
(10.6.2003)		4	3,0	6,0	10,4	9,1	" "
		1	3,0	0,4	13,0	7,0	" "
Breiðdalsvík	Cat.3 / type III	15	2,0	0,0	2,4	17,8	MSW incl. biodeg.
(Melar)		2	2,0	0,0	3,0	17,0	" "
(23.6.2003)							
Höfn	Cat. 3 / type II	9	4,0	21,1	21,8	0,0	MSW incl. biodeg.
(Lón)		8	4,0	37,6	30,3	0,0	" "
(23.6.2003)		6	4,0	36,3	26,2	0,0	" "
		6	4,0	36,5	26,5	0,0	" "
A-Eyjafj.hr,	Cat. 3 / type II	6	4,0	0,0	2,3	17,8	MSW incl. biodeg.
(Skógasandur)		4	4,0	0,0	2,8	17,1	" "
(2.7.2003)		2	4,0	0,0	2,4	16,7	" "
Suðurland	Cat. 1 / type II	7	10,0	15,1	14,5	9,9	MSW incl. biodeg. +
(Kirkjufurhjáleiga)		5	10,0	39,8	28,4	0,0	Slaughterhouse
(2.7.2003)							
Selfoss	Cat. 2 / type I	9	4,0	50,1	28,8	0,0	MSW incl. biodeg.
(2.7.2003)							

Table 6.2 shows the results of the gas measuring on landfills where slaughterhouse waste was landfilled as such, i.e. not mixed with other MSW, and is evaluated separately from the other results.

Table 6.2 Results from LFG measuring on Icelandic landfills accepting slaughterhouse waste

Landfill *(Date of measuring)*	**Landfill category and type**	**Age of landfilled waste** *(Years)*	**Total thickness of waste layer** *(m)*	**CH_4** *(vol.%)*	**CO_2** *(vol. %)*	**O_2** *(vol. %)*	**Type of landfilled waste**
Rangárvallassýsla	Cat. 3 / type I	8	5,0	8,6	12,3	3,0	Slaughterhouse
(Strönd)		5	5,0	0,0	0,0	20,8	“ “
(2.7.2003)		3	5,0	0,0	6,3	8,2	“ “
Hvammstangi	Cat. 2 / type II	20	2,0	0,7	3,6	18,6	Slaughterhouse
(Kárastaðir)		2	2,0	0,0	0,1	20,8	“ “
(2.6.2003)		1	2,0	3,9	17,3	0,4	“ “

6.2 Evaluation

6.2.1 Landfills accepting MSW including biodegradable waste

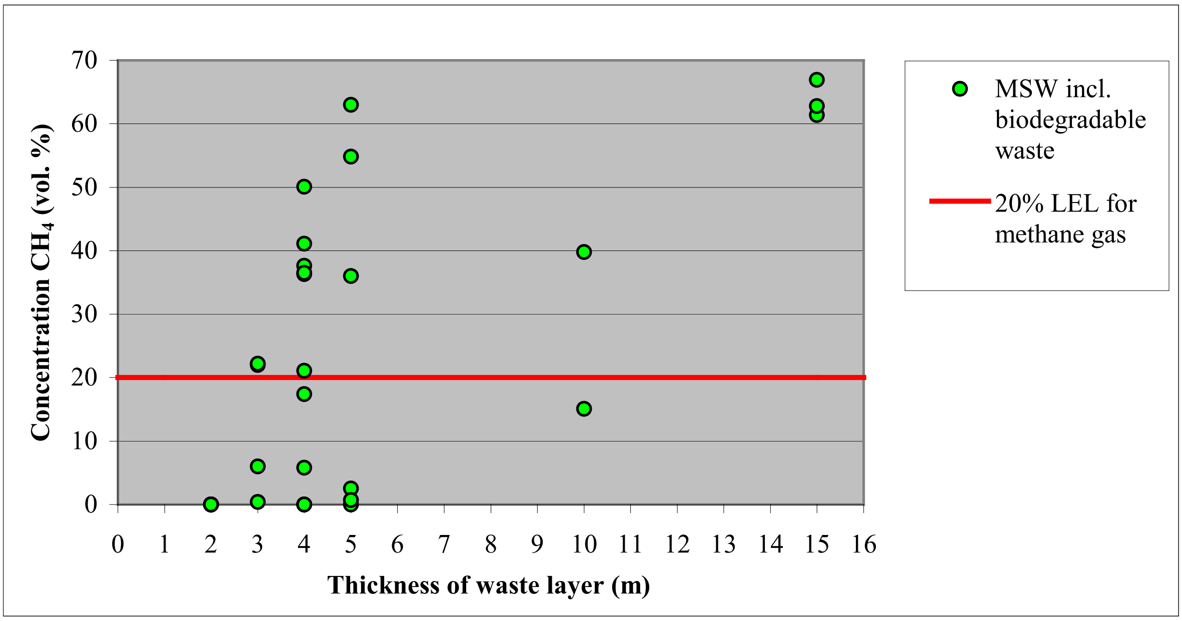
As described in paragraph 3.2, we used the Sorpa landfill at Álfsnes as a reference for this study. Research and LFG measuring on this landfill have shown that the depth of a landfill and the thickness of the waste layer are very important for the formation of LFG. It shows that the thickness of the waste layer at least has to be 4 meters to get formation of methane gas with a concentration that is useful for utilization/flaring (above 20%).

Knowing that the measured landfills have a waste layer thickness varying from 3 until 15 meters, we first needed to determine which depth at least is necessary for LFG formation with a concentration that is useful for utilization/flaring.
Determining the critical waste layer thickness we regarded all the measured landfills as being homogeneous, i.e. with only one waste layer, assuming that a landfill with separate waste layers is acting the same as a landfill with one waste layer. Further we related the methane concentrations to the lower explosive limit (LEL) of 20%.
Methane gas with a concentration of 20 % LEL or more can be used for utilization/flaring (Ref. 8/12).

When the formation of methane gas in relation to the thickness of the waste layer (without taking the age of the waste into account nor the technique of landfilling) is put in one figure, it relates into figure 6.1. This figure shows that the thickness of the waste layer on Icelandic landfills, to get any significant formation of methane gas with a concentration that is useful for utilization/flaring, is approximately 4 meters.

Thus, we determined that the limit for the thickness of the waste layer to get formation of methane gas (useful for utilization/flaring) has to be 4 meters or more, under Icelandic conditions, to expect any significant LFG formations.

Figure 6.1 Formation of methane gas in relation to the thickness of the waste layer
(without taking the age of the waste into account nor the technique of landfilling)



There are four measurements on landfills with a waste layer thickness exceeding 4 meters that are lower than 20%. Three of the deviant measurements were caused by the misplacing of probes (Hólmavík and Borgarnes) or because a probe was broken (Borgarnes). It was not possible to determine at which depth the probe was broken.
The fourth deviant measuring (Suðurland) was probably caused by the mixed composition of the waste. The waste was a mixture of MSW and slaughterhouse waste and this second type of waste has probably a large influence on the LFG formation.
The influence of slaughterhouse waste on the formation of LFG will be explained under the evaluation of landfills for slaughterhouse waste (paragraph 6.2.2).

The next step we took, was to look at the landfills with a waste layer thickness of 4 meters or more, and to see when the methane gas-formation is starting on those landfills. We did this to determine which landfills are possibly feasible for the collection of LFG and to utilize/flare the gas.

When the formation of methane gas in relation to the age of the landfilled waste (for landfills with a waste layer thickness of 4 meters or more) is put in one figure, we get figure 6.2.
This figure shows that anaerobic conditions are already established in these landfills within one year after landfilling.

Figure 6.2 Formation of methane gas in relation to the age of the landfilled waste
(for landfills with a waste layer thickness ≥ 4 meters)

Because there are landfills with separate waste layers (or cells) from 2 until 5 meters each, it is not known if the production of LFG behaves in the same way as on landfills with one waste layer. Generally it is expected that the production of LFG on landfills with separate waste layers is less than on landfills with one waste layer, as the degradation of biodegradable matter by anaerobic bacteria in the landfill – and therefore the forming of LFG – is expected to depend on a certain “critical mass”. How big this critical mass has to be is however not easy to determine, but it may be clear that in between layers of covering materials has significant impact on the forming of LFG.

6.2.2 Landfills accepting slaughterhouse waste

As shown in table 6.2 there is a very low concentration (not exceeding 9 %) of methane gas being formed on landfills that accept slaughterhouse waste.
A possible explanation for this might be that this type of waste does no decompose quickly at all, if ever under Icelandic conditions!
This compares to some experience with digging up old slaughterhouse waste in different places in Iceland, where the waste was still more or less the same after 30 years of landfilling.
Even after 10 years, workers from Sorpa found bones within an old lane that were still red outside.
It is however well known that slaughterhouse waste is very active right after landfilling, because of quick rotting processes as fermentation, leading even to explosion on some places, but after that the decomposition seems to go very slowly.
Based on this study and mentioned experiences it is recommended that the landfilling of slaughterhouse waste as such is re-examined, as the long term effects of this form of disposal might be unwanted from an environmental point of view.

7. Conclusions and recommendations

It can be concluded that on the landfills with a waste layer thickness less then 4 meters, the LFG formation is not suitable for collection and utilization/flaring of the gas. It appeared that the methane gas on these landfills does not exceed the 20%, which is at least needed to utilize/flare the gas without the use of fossil fuels.
But because we only measured 56 % of the landfills that accept biodegradable waste and the construction of these landfills (in relation to the type of landfilled waste and thickness of waste layers (cells)) are not always the same, this conclusion might therefore only count fore the measured landfills and not for all MSW landfills in Iceland.
The landfills that might not qualify for the collection and utilization/flaring of methane gas are:

- Hvammstangi *(Kárastaðir)**
- Skagaströnd *(Neðri-Harrastaðir)*
- Þórshöfn
- Egilsstaðir *(Tjarnaland)*
- Breiðdalsvík *(Melar)*
- A-Eyjafjalla hreppi *(Skógasandur)*
- Rangárvallassýsla, *(Strönd)**
  (Landfill accepting slaughterhouse waste)*

This study shows that LFG production on Icelandic landfills in general, and the smaller ones particularly, might not be a realistic option, both from an economic and environmental point of view. It is therefore to be seen whether a further exemption for article 4 and Annex III is not needed for those landfills in Iceland where LFG production is not significant or a threat to environment.

For those landfills that have a waste layer thickness of 4 meters or more and shown methane gas-formation with a concentration exceeding 20%, it is recommended to carry out a further study, observing the amount of LFG that can be extracted during a longer period, and determining whether LFG collection at those landfills is needed.
The landfills that might be suitable for the further study on collection and utilization/flaring of LFG are:

- Borgarnes *(Fíflholt)*
- Akureyri *(Glerardalur)*
- Suðurland *(Kirkjuf.hjáleiga)*

Also we conclude that the degradation of waste on the smaller landfills in Iceland stops somewhere in the third phase of the gas production pattern (figure 4.1), producing some amounts of LFG, but not significant, and maybe over a very long period.
On most of the landfills, the degradation process only reaches an anaerobic, methanogenic unsteady phase. The conditions of these smaller landfills, such as the amount of waste and thickness of waste layers, are not optimal for a steady methanogenic phase.

It is recommended to repeat this study and to measuring the LFG on the landfills in Iceland after e.g. 3 years, and to see how the formation of LFG has changed.

Personal recommendations
My personal experience in regard to the approach of environmental issues (generally about landfills) in Iceland is, that it is not very different from the approach in the Netherlands. The only significant difference that I could see very clearly was the long period of time that it takes to establish solutions and the low contribution to new ideas, to solve environmental problems.
My personal recommendation for the landfills operators in Iceland is to look closely to the Landfill Directive and to implement it as quickly as possible (at least before 2009). This is not only the best for their own benefit, but also to preserve this beautiful and clean country for its future generations.

8. References

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4. **Environmental Technology University of Den Bosch, Netherlands**
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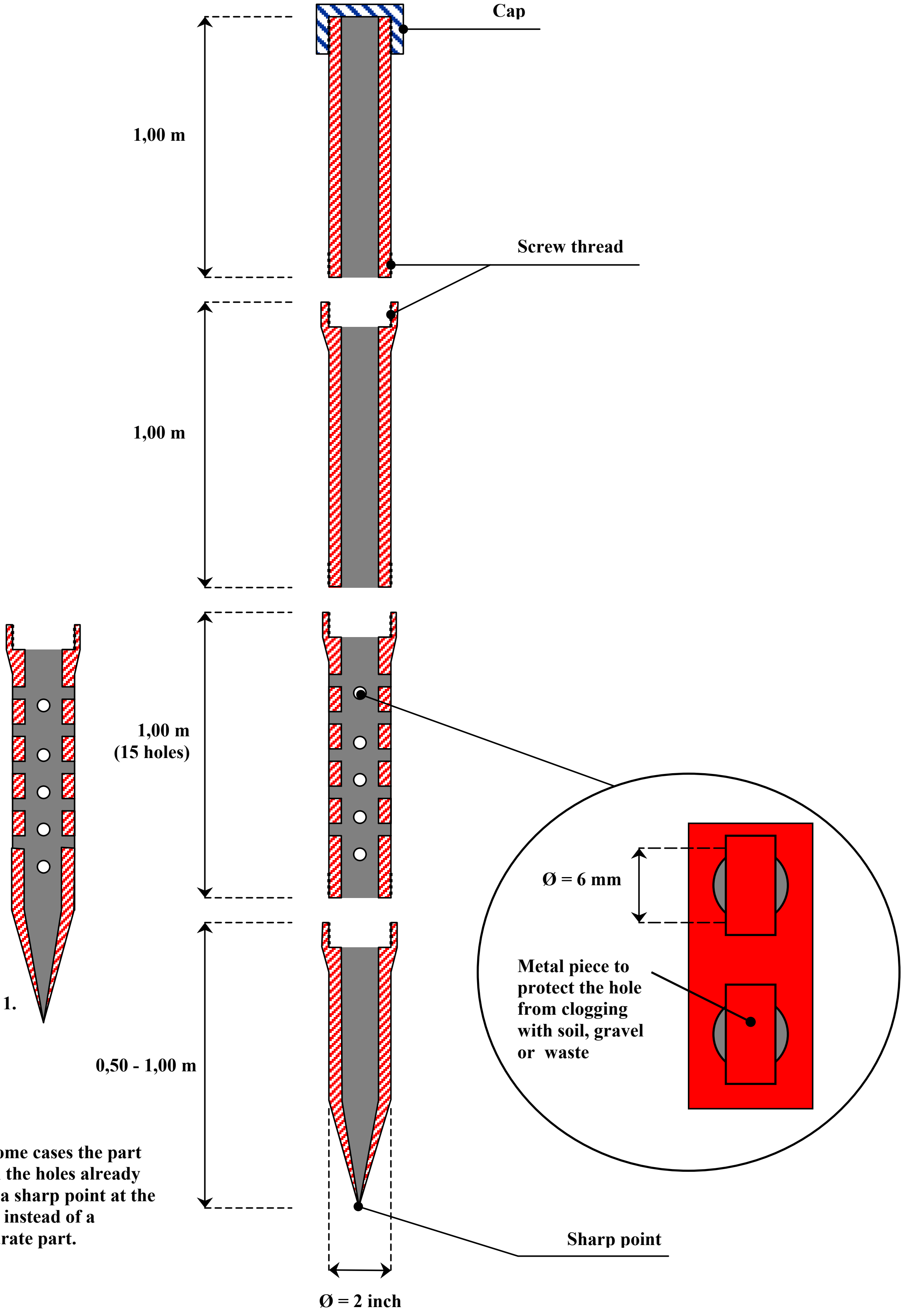
9. **Present and Long-Term Composition of MSW Landfill Leachate: A Review**
Peter Kjeldsen[(1)], Morton A. Barlaz[(2)], Alix P. Rooker[(2)],Anders Baun [(1)],Anna Ledin[(1)], Thomas H. Christensen [(1)].
[(1)] Environment & Resources DTU, Technical University of Denmark,Bldg. 115, DK-2800 Kgs. Lyngby,Denmark; [(2)] Department of Civil Engineering, North Carolina Sates University, Box 7908, Raleigh, NC 27695-7908

10. **SORPA General description, operation at Sorpa´s Landfill at Álfsnes.**
Björn Halldórsson, MSc., Chief engineer, bjorn@sorpa.is
Guðmar Gudmundsson, gudmar@sorpa.is

11. **Umhverfisstofnun, Environment and Food Agency of Iceland**
Cornelis A. Meyles B.Sc. scientific officer on the Environment and Food Agency of Iceland in Reykjavik, cees@ust.is, tel. +354 591 2015

12. **15 Years of experience in the field of landfill gas disposal standards, problems, solutions and procedures.** *Wolfgang H. Stachowitz Dipl. Ing.*

Appendix I Technical drawing of a probe



1. In some cases the part with the holes already had a sharp point at the end, instead of a separate part.

Appendix II Placing and measuring of the probes


1.


2.


3.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6.


7.

1) Placing of the probe with the help of a crane,
2) Drilling machine used to drill the probe in the ground,
3) Example of a probe,
4) Example of a placed probe, in the background is the second probe,
5) Carrying out of gas measuring by a fieldworker (Rob Kamsma),
6) Example of gas measuring with the gas analyser,
7) Equipment used for the measuring of the gas.

Appendix III Results of the LFG measuring

ed = end depth of probe
wl = water level in probe

Landfill location Borgarnes, *(Fíflholt)*
Date of measuring 19.5.2003
Air pressure 999 mb
Fieldworker Rob Kamsma
Air temperature 11 °C
Category 1(> 5000 tonnes/year) ***Type*** I

Probe	**Depth** *(m)*	**Start**	**End**	**CH4** *(%)*	**CO2** *(%)*	**O2** *(%)*	**Temp.** *(°C)*	**North Latitude**	**Western Longitude**	***Comment / Remarks***
1	4,00 ed	11:33	11:38	63,0	37,1	0,0	-	-	-	Landfill from 1999
2	4,00 ed	11:39	11:44	0,0	0,0	20,8	-	-	-	Probe is not standing correctly in the ground, probably the probe is broken, and therefore the measuring is not accurate. Landfill from 2000
3	2,40 wl	11:50	11:55	2,5	1,7	19,7	-	-	-	Landfill from 2001
				0,0	0,0	21,1				Composition of outside air

Landfill location Hólmavík, *(Skeljavík)*
Date of measuring 22.5.2003
Air pressure 1019 mb
Fieldworker Rob Kamsma
Air temperature 8 °C
Category 3 (< 500 tonnes/year) ***Type*** II

Probe	**Depth** *(m)*	**Start**	**End**	**CH4** *(%)*	**CO2** *(%)*	**O2** *(%)*	**Temp.** *(°C)*	**North Latitude**	**Western Longitude**	***Comment / Remarks***
1	2,80 wl	09:00	09:05	36,0	30,8	0,1	8,3	-	-	Landfill from 1999
2	2,00 wl	08:50	08:55	0,7	0,7	20,7	10,0	-	-	No measuring of LFG is probably caused by the misplacing of the probe, the probe does not stand in the part where the gas is formed. Landfill from 2001
3	4,00 ed	08:40	08:45	54,8	38,3	1,3	12,3	-	-	Landfill from 2002
				0,0	0,1	20,4				Composition of outside air

Landfill location Hvammstangi, *(Kárastaðir)*
Date of measuring 2.6.2003
Air pressure 1003 mb
Fieldworker Rob Kamsma
Air temperature 8 °C
Category 2 (500 to 5000 tonnes/year) ***Type*** II

Probe	**Depth** *(m)*	**Start**	**End**	**CH4** *(%)*	**CO2** *(%)*	**O2** *(%)*	**Temp.** *(°C)*	**North Latitude**	**Western Longitude**	***Comment / Remarks***
1	4,50 ed	13:30	13:35	0,7	3,6	18,6	-	65° 25 830	20° 57 994	Landfill from1983
2	2,50 wl	13:15	13:20	0,0	0,1	20,8	-	65° 25 931	20° 58 060	Slaughterhouse waste, 2001
3	3,20 wl	13:05	13:10	3,9	17,3	0,4	9	65° 25 975	20° 58 028	Slaughterhouse waste, 2002
										Probe 2 and 3, mixed waste from 2001 and 2002
				0,0	0,0	20,9				Composition of outside air

Landfill location Skagaströnd, *(Neðri-Harrastaðir)*
Date of measuring 2.6.2003
Air pressure 1006 mb
Fieldworker Rob Kamsma
Air temperature 8 °C
Category 3 (< 500 tonnes/year) ***Type*** I

Probe	**Depth** *(m)*	**Start**	**End**	**CH4** *(%)*	**CO2** *(%)*	**O2** *(%)*	**Temp.** *(°C)*	**North Latitude**	**Western Longitude**	***Comment / Remarks***
1	2,00 wl	17:45	17:50	0,0	3,2	18,1	11	65° 52 870	20° 18 560	Landfill from 1990
2	1,75 wl	17:35	17:40	0,0	6,8	14,1	11	65° 52 857	20° 18 564	Landfill from 1997
3	2,00 ed	17:25	17:30	0,0	1,2	20,1	11	65° 52 840	20° 18 528	Landfill from 2002
				0,0	0,0	20,8				Composition of outside air

Landfill location Akureyri, *(Glerárdalur)*
Date of measuring 3.6.2003
Air pressure 980 mb
Fieldworker Rob Kamsma
Air temperature 6 °C
Category 1 (> 5000 tonnes/year) ***Type*** I

Probe	**Depth** *(m)*	**Start**	**End**	**CH4** *(%)*	**CO2** *(%)*	**O2** *(%)*	**Temp.** *(°C)*	**North Latitude**	**Western Longitude**	***Comment / Remarks***
1	4,50 ed	08:45	09:00	61,4	34,7	0,0	7	65° 36 371	18° 09 888	Landfill from 1998-1999
2	4,50 wl	09:05	09:10	66,9	34,1	0,0	7	65° 36 386	18° 09 944	Landfill form 1999
3	5,30 ed	09:15	09:20	62,8	36,8	0,0	7	65° 36 358	18° 09 938	Landfill from 1999-2000
				0,1	0,2	20,5				Composition of outside air

Landfill location Þórshöfn
Date of measuring 10.6.2003
Air pressure 1004 mb
Fieldworker Rob Kamsma
Air temperature 9 °C
Category 3 (< 500 tonnes/year) **Type** I

Probe	Depth *(m)*	Start	End	CH4 *(%)*	CO2 *(%)*	O2 *(%)*	Temp. *(°C)*	North Latitude	Western Longitude	*Comment / Remarks*
1	2,20 ed	19:20	19:25	0,0	0,3	20,7	10,0	66° 11 597	15° 17 630	Landfill from 1998-1999
2	1,20 wl	19:10	19:15	0,0	0,0	20,9	10,1	66° 11 605	15° 17 712	Landfill from 2000-2001
										A lot of waste is illegally burned on this landfill. The waste is covered with shells.
				0,0	0,0	20,9				Composition of outside air

Landfill location Vopnafjörður, *(Búðaröxl)*
Date of measuring 10.6.2003
Air pressure 1012 mb
Fieldworker Rob Kamsma
Air temperature 10 °C
Category 3 (< 500 tonnes/year) **Type** I

Probe	Depth *(m)*	Start	End	CH4 *(%)*	CO2 *(%)*	O2 *(%)*	Temp. *(°C)*	North Latitude	Western Longitude	*Comment / Remarks*
1	2,20 ed	16:55	17:00	5,8	9,7	5,5	12,1	65° 45 355	14° 51 005	Landfill from 1999
2	2,10 ed	17:05	17:10	41,1	20,8	1,6	14,6	65° 45 355	14° 51 050	Landfill from 2000-2001
3	1,80 wl	17:15	17:20	17,4	18,8	0,0	12,0	65° 45 381	14° 51 072	Landfill from 2002-2003
				0,0	0,0	20,5				Composition of outside air

Landfill location Egilsstaðir, *(Tjarnaland)*
Date of measuring 10.6.2003
Air pressure 1010 mb
Fieldworker Rob Kamsma
Air temperature 10 °C
Category 2 (500 to 5000 tonnes/year) **Type** I

Probe	Depth *(m)*	Start	End	CH4 *(%)*	CO2 *(%)*	O2 *(%)*	Temp. *(°C)*	North Latitude	Western Longitude	*Comment / Remarks*
1	3,50 ed	13:30	13:35	22,0	19,3	1,7	10,9	65° 27 566	14° 20 519	Landfill from 1992
1	3,50 ed	14:00	14:05	22,2	21,0	0,1	12,9	65° 27 566	14° 20 519	Landfill from 1992
2	1,80 ed	13:45	13:55	6,0	10,4	9,1	12,3	65° 27 544	14° 20 540	Landfill from 1999
3	2,00 wl	13:35	13:40	0,5	13,0	7,0	10,2	65° 27 537	14° 20 577	Landfill from 2002
				0,0	0,0	20,2				Composition of outside air

Landfill location Breiðdalsvík, *(Melar)*
Date of measuring 23.6.2003
Air pressure 1007 mb
Fieldworker Rob Kamsma
Air temperature 17 °C
Category 3 (< 500 tonnes/year) ***Type*** III

Probe	Depth *(m)*	Start	End	CH4 *(%)*	CO2 *(%)*	O2 *(%)*	Temp. *(°C)*	North Latitude	Western Longitude	*Comment / Remarks*
1	3,15 ed	13:30	13:35	0,0	2,4	17,8	11,5	64° 48 463	14° 09 824	Landfill from 1988
2	3,15 ed	13:55	14:00	0,0	3,0	17,0	13,5	64° 48 469	14° 09 786	Landfill from 2001
										There is a lot of scrape metal landfilled on this location.
				0,0	0,0	20,5				Composition of outside air

Landfill location Höfn, *(Lón)*
Date of measuring 23.6.2003
Air pressure 1006 mb
Fieldworker Rob Kamsma
Air temperature 13 °C
Category 3 (< 500 tonnes/year) ***Type*** II

Probe	Depth *(m)*	Start	End	CH4 *(%)*	CO2 *(%)*	O2 *(%)*	Temp. *(°C)*	North Latitude	Western Longitude	*Comment / Remarks*
1	3,30 ed	16:50	16:55	21,1	21,8	0,0	11,9	64° 18 477	15° 00 618	Landfill from 1994
2	2,85 wl	16:55	17:00	37,6	30,3	0,0	12,2	64° 18 463	15° 00 660	Landfill from 1995
3	3,30 wl	16:45	16:50	36,3	26,2	0,0	11,5	64° 18 473	15° 00 581	Landfill from 1997
4	3,15 ed	17:00	17:05	36,5	26,5	0,0	10,8	64° 18 460	15° 00 624	Landfill from 1997
				0,0	0,0	20,4				Composition of outside air

Landfill location A.-Eyjafjalla hreppi, *(Skógasandur)*
Date of measuring 2.7.2003
Air pressure 1016 mb
Fieldworker Rob Kamsma
Air temperature 16 °C
Category 3 (< 500 tonnes/year) ***Type*** II

Probe	Depth *(m)*	Start	End	CH4 *(%)*	CO2 *(%)*	O2 *(%)*	Temp. *(°C)*	North Latitude	Western Longitude	*Comment / Remarks*
1	3,60 ed	10:30	10:35	0,0	2,3	17,8	11,5	-	-	Landfill from 1997
2	3,60 ed	10:40	10:45	0,0	2,8	17,1	14,1	-	-	Landfill from 1999
3	3,60 ed	10:45	10:50	0,0	2,4	16,7	14,1	-	-	Landfill from 2001
										Waste is landfilled in 2 separate layers of 2 m.
				0	0	20,4				Composition of outside air

Landfill location Rángarvallasýsla, *(Strönd)*
Date of measuring 2.7.2003
Air pressure 1013 mb
Fieldworker Rob Kamsma
Air temperature 16 °C
Category 3 (< 500 tonnes/year) ***Type*** I

Probe	Depth *(m)*	Start	End	CH4 *(%)*	CO2 *(%)*	O2 *(%)*	Temp. *(°C)*	North Latitude	Western Longitude	*Comment / Remarks*
1	2,50 ed	12:30	12:35	8,6	12,3	3,0	13	-	-	Landfill from 1995, Slaughterhouse waste from Horses and cows
2	2,50 ed.	12:20	12:25	0,0	0,0	20,8	12	-	-	Landfill from 1998, " "
3	2,00 ed	12:35	12:40	0,0	6,3	8,2	13	-	-	Landfill from 2000, Slaughterhouse waste from chickens
										Waste landfilled in one layer of 5 m thick
				0	0	20,4				Composition of outside air

Landfill location Suðurland, *(Kirkjuf.hjáleiga)*
Date of measuring 2.7.2003
Air pressure 1015 mb
Fieldworker Rob Kamsma
Air temperature 16 °C
Category 1 (>5000 tonnes/year) ***Type*** II

Probe	Depth *(m)*	Start	End	CH4 *(%)*	CO2 *(%)*	O2 *(%)*	Temp. *(°C)*	North Latitude	Western Longitude	*Comment / Remarks*
1	5,00 wl 10,00 ed	14:50	14:55	15,1	14,5	9,9	18,4	-	-	Landfill from 1996
2	5,00 wl 10,00 ed	14:45	14:50	39,8	28,4	0,0	18,3	-	-	Landfill from 1998
										Waste landfilled in 2 separate layers of 5 - 6 m thick.
				0	0	20,4				Composition of outside air

Landfill location Selfoss
Date of measuring 2.7.2003
Air pressure 1010 mb
Fieldworker Rob Kamsma
Air temperature 16 °C
Category 2 (500 to 5000 tonnes/year) ***Type*** I

Probe	Depth *(m)*	Start	End	CH4 *(%)*	CO2 *(%)*	O2 *(%)*	Temp. *(°C)*	North Latitude	Western Longitude	*Comment / Remarks*
1	3,50 wl 7,00 ed	15:35	15:40	50,1	28,8	0,0	15,9	-	-	Landfill from 1994
										This landfill is closed and is not in use anymore, waste layer of 4 m thick.
				0	0	20,1				Composition of outside air