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LANDFILL GAS MIGRATION—FIELD INVESTIGATIONS AT SKELLINGSTED LANDFILL, DENMARK

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The background for a landfill gas explosion accident which happened at Skellingsted Landfill in Denmark was investigated. To understand the behaviour of the lateral migrating landfill gas in the area where the accident occurred, an intensive investigation was carried out after the explosion accident measuring time-series of gas composition in 30 wells over a 35-day period. The changes in gas composition in selected wells following a decrease in barometric pressure were measured over a 33-h period. The maximal distance for measured methane concentrations above 5% (vol.) in the pore gas was 90 m. The investigations showed that changes in barometric pressure have a great impact on the pore gas composition. Indications of methane oxidation were observed down to 2 m below ground in distances of more than 60 m from the landfill.

Key Words—Landfill gas, migration, explosion accident, field investigation, barometric pressure, methane oxidation, Denmark.

1. Introduction

Organic wastes disposed of in landfills undergo anaerobic degradation, which leads to production of biogas consisting of methane, carbon dioxide and trace gases. The produced biogas is utilized at some larger landfills, but the extraction is never 100% effective. At most landfills, the biogas is not utilized due to low economical profitability, and biogas is only flared at a minor number of landfills. Therefore, at most landfills, biogas is emitted to the atmosphere either directly from uncovered waste, through top covers or by migrating through surrounding soil layers.

The migration and emission of landfill gas potentially leads to different effects in the surroundings, such as fire and explosion hazards and damage to vegetation (Gendebein *et al.* 1992). Emission of methane to the atmosphere is also a source of greenhouse gases implicated in global warming. Methane emitted from landfills makes up 7–20% of the anthropogenic methane (CH_4) emission to the atmosphere (Thorneloe 1991).

Many factors influence gas migration from landfills. Waste composition, construction of the landfill and geological properties of the surrounding strata are important factors, together with permeability and water content of the surrounding unsaturated zone. The importance of the different factors is reviewed in Kjeldsen (1994). Here it is stated that the effect of changing barometric pressures and oxidation of CH_4 are particularly important factors, which have occasionally been overlooked as governing factors to the migration of landfill gas in soils. The oxidation of CH_4 has been studied in landfill

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top covers by several authors (Mancinelli & McCay 1985; Jones & Nedwell 1990, 1993; Whalen *et al.* 1990; Figueroa 1993; Bergman *et al.* 1993). The effect of CH_4 oxidation on the lateral migration of landfill gas, and the relationship between CH_4 oxidation and barometric pressure changes have, however, not been studied.

The objective of this study was to investigate the background for the explosion accident which happened at Skellingsted Landfill in Denmark, and to understand the behaviour of the lateral migrating landfill gas in the area where the accident occurred. This study gives special attention to the importance of barometric pressure changes and methane (CH_4) oxidation.

2. Field location

Skellingsted Landfill is located south of Holbæk, Western Sealand, Denmark (Fig. 1*a*), and received waste between 1971–1990. In total, approximately 300,000 tonnes of waste have been disposed of at this site. The composition of the waste was approximately 60% municipal solid waste and 40% bulky waste, industrial waste and sewage treatment sludge.

The landfill is situated in an abandoned gravel pit located in an area of alluvial sand and gravel sediments. The unsaturated zone in the surrounding areas of the landfill is 10–20 m thick. The landfill is divided into 10 areas as shown in Fig. 1*b*. For each area, the closing year and estimated waste depth are shown. No bottom liner is present in any of the stages. Waste has never been disposed of in area "D". This area contained the entrance area to the landfill and the house of the attendant. The landfill was covered with a soil layer approximately 80 cm thick, at final closure.

3. The gas explosion

The gas explosion accident happened in the early morning of 21 March 1991 in the house located in area "D" (Fig. 1*b*). An analysis of the background for the accident showed that several factors coincided. The house was surrounded on three sides with landfilled waste. The distance to area "E" was less than 30 m.

The meteorological conditions in the time immediately before the accident were of decisive importance. Figure 2 shows the barometric pressure and the precipitation as measured at Niløse Holme (3 km from Skellingsted). A substantial drop in barometric pressure together with heavy rain occurred in the days before the accident. The observed drop in pressure could have led to increased convective gas transport from the landfill since convective gas transport is controlled by gas pressure gradients in the soil. The heavy rain probably filled the pores of the upper soil layer with water, thus decreasing the vertical gas permeability of the layer. The only places where a high vertical gas permeability could be maintained were in the soil layer beneath the house. The gas entrance to the house could also have been enhanced by the new cesspool, which was constructed a few months before the accident. The floor construction of the house consisted of a dry stamped earth floor underlying a wooden floor. This construction serves as a very poor barrier to gas transport. These unfavourable circumstances led to an increased CH_4 concentration inside the house to a level above 5%—the lower explosion limit of CH_4 (Hoather & Wright 1989).

Damage to adjacent vegetation was also observed at Skellingsted Landfill in a 20×120 m area at the eastern border.

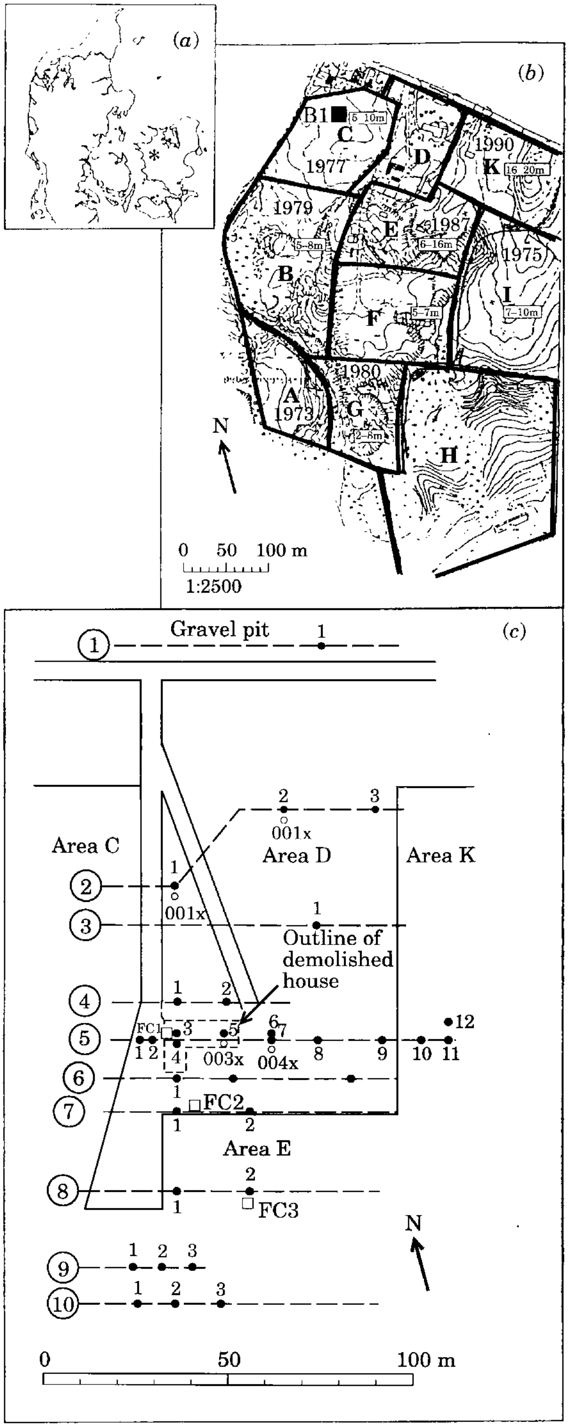

Fig. 1. (*a*) The geographical location of Skellingsted Landfill. (*b*) Map showing the stages of the landfill. The year of closure and estimated waste depth in each stage is given. The house where the explosion occurred is placed in area "D", and is shown with a black signature. ■, gas sampling well. (*c*) Detailed map of area "D" showing permanent piezometers (piezometer 0201 is piezometer 1 in row 2), profile piezometers (001x–004x) and location of flux chambers (FC1–FC3). ●, single well; ⊙, bundle well; □, flux chamber.

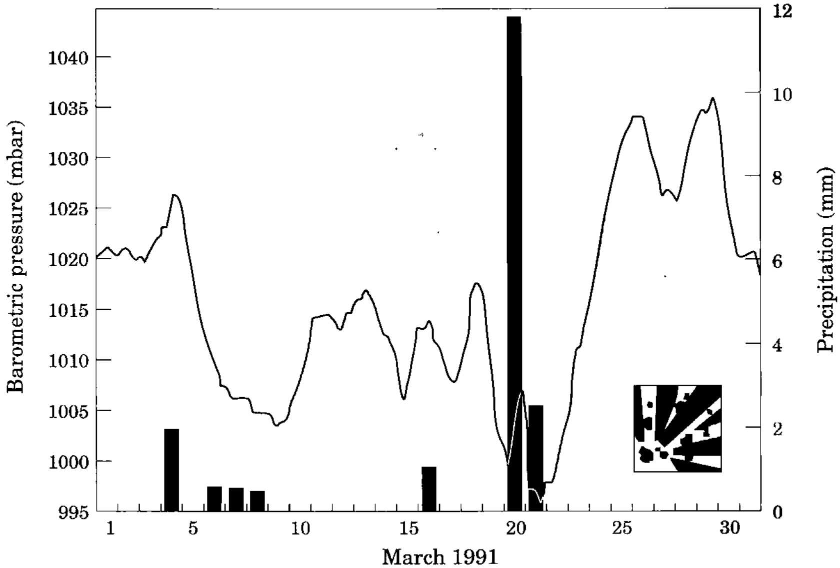

Fig. 2. Daily precipitation (columns) and barometric pressure (line) for March 1991 as measured at climatic stations close to Skellingsted Landfill. The explosion accident happened on 21 March as indicated.

4. Theoretical considerations on landfill gas migration

The migration of CH_4 and carbon dioxide (CO_2), which are the major constituents in landfill gas, is controlled by both convection and diffusion in the soil. Other processes also affect CH_4 and CO_2 concentrations and the CH_4/CO_2 ratio, which is a very useful parameter in the evaluation of landfill gas migration. The following processes are of major importance to the behaviour of CH_4 and CO_2 in landfill gas affected soil:

—Dilution;
—Gas transfer between pore gas and pore water;
—Methane oxidation;
—Differential diffusion.

Dilution of the landfill gas with atmospheric air in the unsaturated zone will lead to a reduced concentration of CH_4 and CO_2 but leaves the CH_4/CO_2 ratio unaffected.

Gas transfer. Carbon dioxide is much more soluble in water than CH_4. Therefore, more CO_2 than CH_4 will be washed out by drain water resulting in an increase in the average CH_4/CH_2 ratio.

Methane oxidation. Methane can be degraded in the presence of oxygen by methanotrophic bacteria. The process leads to generation of CO_2 and water:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

This process leads to a substantial decrease in the CH_4/CO_2 ratio in the soil gas, since the numerator and the denominator in the ratio are changed in opposite directions by the process.

Differential diffusion. The diffusional transport, J, of a landfill gas constituent is governed by Fick's law:

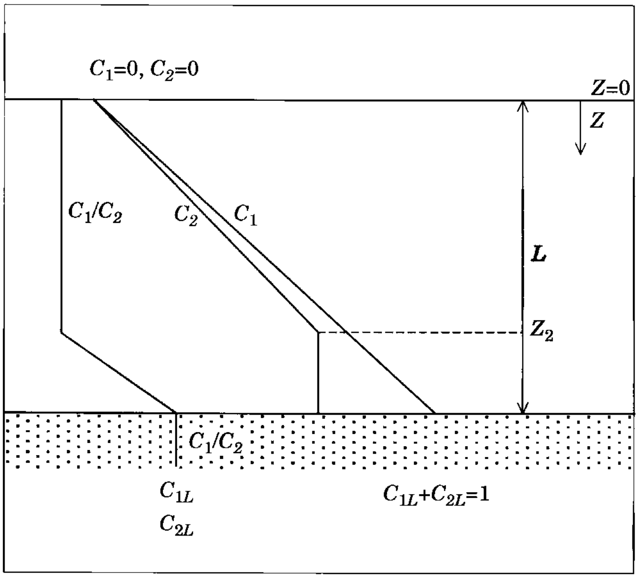

Fig. 3. Model set-up for evaluating the effect of differential diffusion on the CH_4/CO_2-ratio.

$$J = D \cdot \frac{\partial C}{\partial Z}$$

where D is the diffusion coefficient and $\partial C/\partial Z$ is the concentration gradient in the soil. Since the diffusion coefficient of CH_4 is slightly higher than for CO_2, differences in the diffusional transport of the two constituents are expected. These differences could affect the CH_4/CO_2 ratio.

To evaluate the importance of differential diffusion on the CH_4/CO_2 ratio, a simple model of diffusional transport of landfill gas was set up. Only diffusional transport is considered, since the effect from differential diffusion will be lower if a significant proportion of the transport is controlled by pressure differences (convective transport). Other processes like gas-transfer to pore water and degradation are also ignored. Figure 3 presents the simple model used. A landfill top cover of depth, L, is considered. The landfill gas contains only CH_4 and CO_2. The concentrations of CH_4 (C_1) and CO_2 (C_2) are set to zero in the atmosphere above the top cover. Below $Z = L$ the concentrations are constant and $C_{L1} + C_{L2} = 1$. Methane and CO_2 are assumed to be produced in a fixed proportion ($= C_{L1}/C_{L2}$), and in the steady state situation, fluxes must equal productions:

$$\frac{J_1}{J_2} = \frac{C_{L1}}{C_{L2}} = \frac{C_{L1}}{1 - C_{L1}} \qquad [1]$$

When diffusion is considered alone, and steady state is assumed:

$$J_1 = D_1 \frac{\partial C_1}{\partial Z} \qquad [2]$$

$$J_2 = D_2 \frac{\partial C_2}{\partial Z} \qquad [3]$$

4.1 Boundary conditions

$$Z=0\colon\ C_1=C_2=0$$

$$Z=L\colon\ C_1=C_{L1};\ C_2=C_{L2}$$

The following two assumptions are set up:

$$C_{L1}>C_{L2} \text{ and } D_1>D_2$$

This meant that the C_1 concentration will decrease linearly from $Z=L$ to $Z=0$, and the flux is:

$$J_1=D_1\frac{C_{L1}}{L} \qquad [4]$$

From Equation 1, the following is obtained:

$$J_2=\frac{1-C_{L1}}{C_{L1}}\cdot J_1=\frac{1-C_{L1}}{C_{L1}}\cdot D_1\frac{C_{L1}}{L}=(1-C_{L1})D_1/L \qquad [5]$$

Since the proportion of the fluxes J_1 and J_2 is determined by the C_{L1}/C_{L2} proportion, C_2 is linearly decreasing (in the steady state) from a depth less than L, namely, Z_2 (Fig. 3). Equation 3 gives:

$$J_2=D_2\frac{C_{L2}-0}{Z_2-0}=D_2\frac{C_{L2}}{Z_2}=D_2\frac{1-C_{L1}}{Z_2} \qquad [6]$$

Equation 5 is set equal to Equation 6:

$$D_2(1-C_{L1})/Z_2=D_1(1-C_{L1}/L\Rightarrow Z_2=\frac{D_2}{D_1}\cdot L \qquad [7]$$

For $Z_2<Z<L$, the concentrations are (Fig. 3):

$$C_1=C_{L1}\frac{Z}{L}$$

$$C_2=C_{L2}=1-C_{L1}$$

The C_1/C_2 ratio is:

$$\frac{C_1}{C_2}=\frac{C_{L1}}{1-C_{L1}}\frac{Z}{L} \qquad [8]$$

For $Z<Z_2$ the concentrations are (Fig. 3):

$$C_1=C_{L1}\frac{Z}{L}$$

$$C_2 = C_{L2}\frac{Z}{Z_2} = (1 - C_{L1})\frac{Z}{Z_2}$$

The C_1/C_2 ratio is:

$$\frac{C_1}{C_2} = \frac{C_{L1}}{1 - C_{L1}}\frac{Z_2}{L} \qquad [9]$$

Equations 7 and 9 give:

$$\frac{C_1}{C_2} = \frac{C_{L1}}{1 - C_{L1}}\frac{D_2}{D_1} \qquad [10]$$

The result of the differential diffusion is that the fixed C_1/C_2-ratio valid within the landfill ($Z > L$) is reduced for depths above $Z = Z_2$ by the proportion D_2/D_1. From Kjeldsen (1994), the diffusion coefficients are:

$$\frac{D_2}{D_1} = \frac{1.5 \cdot 10^{-5}\,\mathrm{m^2\,s^{-1}}}{2.0 \cdot 10^{-5}\,\mathrm{m^2\,s^{-1}}} = 0.75$$

This means that the C_1/C_2 ratio is decreased to 75% of the ratio given in the landfill gas (LFG). If C_1/C_2 in LFG is 2.0, the C_1/C_2 in the top soil above $Z = 0.75L$ is 1.5. The differential diffusion therefore has only a minor effect on the CH_4/CO_2-ratio, and CH_4 oxidation is the only process which can lead to significant changes in the CH_4/CO_2 ratio.

5. Material and methods

5.1 Wells and piezometers

One well (Well B1H) was placed in the landfill area in area "C" (Fig. 1*b*). The well was made in connection to an earlier investigation run by the Western Sealand County. This well consisted of a 63 mm PVC tube with a 1 m long screen. The well screen was placed in the upper waste layer. The well was plugged with bentonite at ground level to prevent entrance of atmospheric air while sampling.

Thirty piezometers were placed in the area surrounding the house where the gas explosion occurred (the house was demolished after the accident). The piezometers were driven into the ground by use of the MACHO SYSTEM 14 (KVA Analytical Systems, Falmouth, MA, U.S.A.). The final construction of a piezometer is shown in Fig. 4*a*. As shown, bentonite slurry was placed over the slotted drive point, and at ground level to ensure that gas sampled from the piezometer originated from the screened depth. The piezometers were screened in different depths (between 0.8 3.0 m below ground surface). Figure 1*c* shows the location of the driven piezometers in area "D" and the northern part of area "E". Also, four bundle piezometers were constructed. At each of the four locations, piezometer screens were placed 10, 20, 30, 50, and 80 cm below ground surface. The location of these piezometers designated 001x–004x is also shown in Fig. 1*c*.

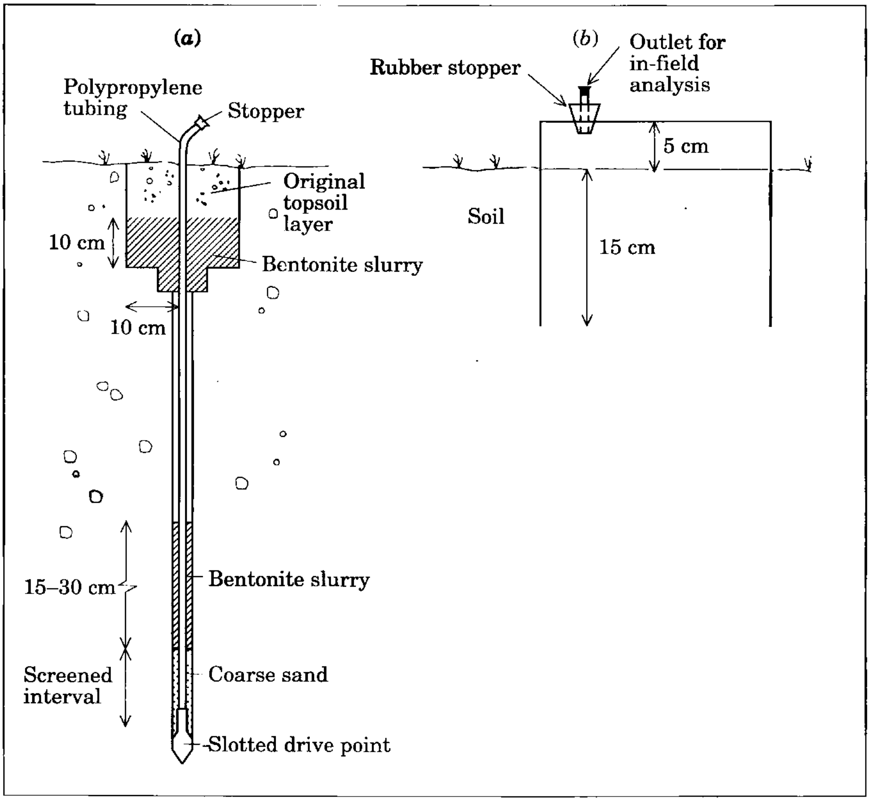

Fig. 4. (*a*) Construction of the piezometers in area "D". (*b*) Construction and placement of the flux chamber in the upper soil layer.

5.2 Flux chambers

The flux of landfill gas through the ground surface can be measured by either static closed flux chambers or dynamic flux chambers (Rolston 1986). Reinhart & Cooper (1992) reported that the measured flux depends on the chamber pressure, sweep air flow rate etc., when using dynamic flux chambers. In order to see relative spatial differences in landfill gas flux through the ground surface, a simple static closed flux chamber was used. The flux chamber consisted of the top 20 cm of a metal drum (57 cm inner diameter, i.d.). The top 5 cm of the soil was removed and the sides of the drum were pressed into the ground leaving a space 5 cm in height between the lid and the ground surface (Fig. 4*b*). Three chambers were placed on the ground. The locations are shown in Fig. 1*c*. Gas composition in the chamber was analysed immediately after installation and after 24 h. If the flux into the chamber is controlled by pressure differences, a build-up of pressure above barometric pressure will occur in the chamber, and the flux will decrease with time (Rolston 1986). Also the diffusional flux will decrease due to increased concentrations in the air space above the soil surface in the chamber. Due to these reasons, the chambers can only be used for relative comparison of fluxes from place to place.

TABLE 1
Landfill gas composition and pressure above barometric pressure as measured in 5 piezometers screened in the waste layers. The average composition is given together with the observed range (in parentheses)

Piezometer	No. of samples	Gas concentration (%)			Pressure a.b.p. (mbar)
		CH_4	CO_2	O_2	
0801	14	61 (42–64)	33 (29–35)	1.9 (1.8–2.0)	n.a.
0802	5	59 (54–66)	35 (33–36)	1.7 (1.6–1.9)	n.a.
1003	13	63 (52–68)	33 (28–35)	1.9 (1.8–2.1)	2 (0.9–3)
B1H	13	58 (56–70)	35 (18–41)	1.7 (1.4–3.8)	20 (18–32)
Average	45	60	34	1.8	

n.a., Not analysed; a.b.p., above barometric pressure.

5.3 Sampling and measurements

Gas sampling and in-field analysis for CH_4, CO_2 and O_2 was carried out with an infrared Gasanalyser GA90 (Geotechnical Instruments, Warwickshire, U.K.). The instrument is equipped with a gas pump sampling approximately 240 ml min^{-1}. The instrument was calibrated each day in the field by use of a calibration gas containing 2% v/v CH_4 and 2% v/v CO_2.

Gas composition was intensively measured in the piezometers located in area "D" over a 1.5-month period (15–20 samples from each piezometer) starting on 21 March 1992. For selected piezometers, gas compositions were measured between 4–10 times within a very short period from 21 April 8.30 p.m. to 23 April 6.40 a.m. The selection of this measuring period was based upon a forecast of decreasing barometric pressure.

The gas pressure in the piezometers was measured with a manometer (water filled 8 mm i.d. U-shaped tube). The manometer was connected to the piezometer through an air-tight rubber stopper and the pressure difference was measured after the reading stabilized. The precision of the reading was ± 2 mm $\sim \pm 0.2$ mbar. Pressures in the piezometers in area "D" were measured 8–10 times in the 1.5-month period.

Data for the barometric pressure and precipitation were obtained from the Danish Meteorological Institute. Barometric pressure was measured at Tyvelse (15 km southwest of Skellingsted) and precipitation at Niløse Holme (3 km southeast of Skellingsted).

6. Results and discussion

6.1 Landfill gas composition

In Table 1, the landfill gas composition is shown. The values are based on measurements from the well B1 placed in the western part of the landfill (area "C"), and on measurements in the driven wells placed in area "E" close to area "D". The table shows that the composition was rather stable with an average CH_4 concentration of 62%, CO_2 concentration of 32% and a minor residual (<7%), probably consisting primarily of N_2. The CH_4/CO_2 ratio was, on average, 1.8. The CH_4 concentration was similar to measurements from other landfills in the high range, indicating that significant CH_4 production was taking place in the landfill (Ham & Barlaz 1989).

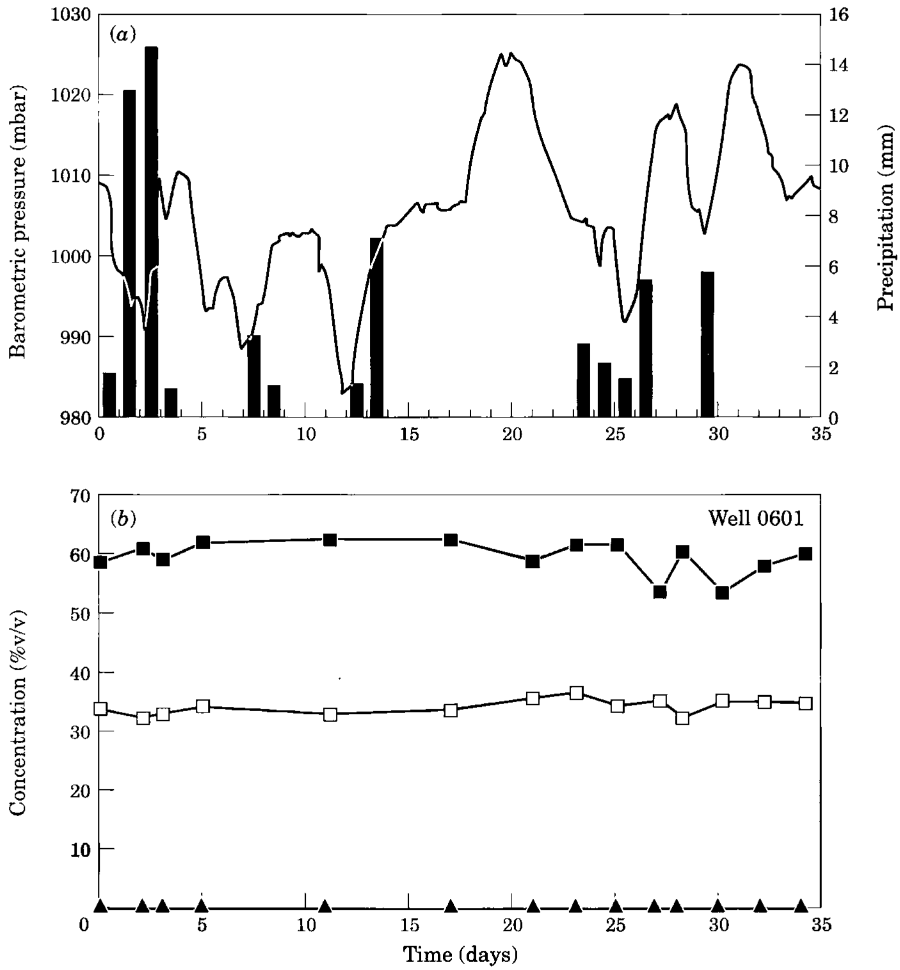

Fig. 5. (a) Daily precipitation (columns) and barometric pressure (line) for the measuring period (Day 1 is 21 March 1992) as measured at climatic stations close to Skellingsted Landfill. (b) Measured concentrations of methane (■), carbon dioxide (□) and oxygen (▲) in piezometer 0601, 0201, and 0101, respectively over the measuring period.

6.2 Influence from barometric pressure changes

Figure 5*a* shows the barometric pressure measured over the 35-day investigation period together with precipitation measurements. The figure shows that a large variation in barometric pressure was observed in the 35-day period.

Figures 5*b*–*d* show the soil gas composition as a function of time in the three piezometers 0601 (filter depth 1.3–1.5 m below surface (m.b.s.), 10 m from landfill border), 0201 (filter depth 1.0–1.2 m.b.s., 60 m from landfill border) and 0101 (filter depth 2.3–2.5 m.b.s., 120 m from landfill border). In piezometer 0601, very stable concentrations of CH_4 and CO_2 were found, indicating no effect from pressure changes. The concentration levels were similar to levels found in piezometers placed in the waste layers (Table 1). No O_2 was found at any time. Pressures above barometric pressure have been measured (from 0.1–0.2 mbar). In piezometer 0201, a distinct relationship

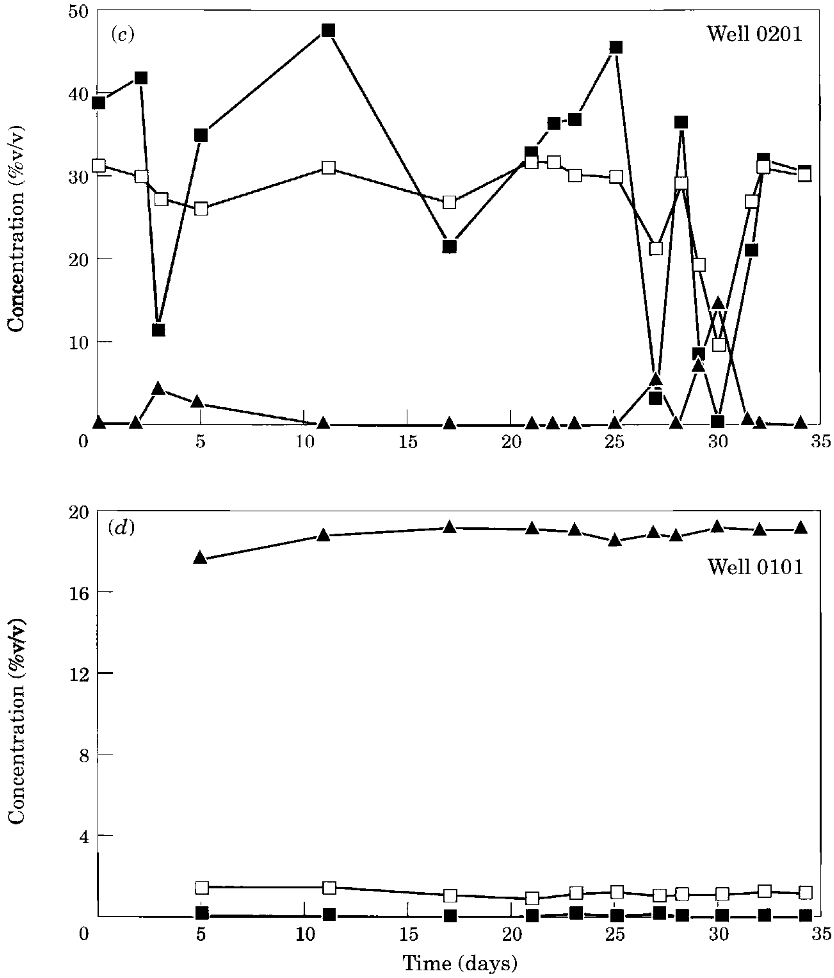

Fig. 5. (*c*–*d*) Measured concentrations of methane (■), carbon dioxide (□) and oxygen (▲) in piezometer 0601, 0201, and 0101, respectively over the measuring period.

between CH_4 concentration and barometric pressure changes was observed in intensively monitored periods (Days 0–5 and 20–35): the highest CH_4 concentrations were observed with decreasing barometric pressure and vice versa. For O_2, the opposite occurs. In piezometer 0101, which was located at the border of the gravel pit (Fig. 1*c*), no elevated CH_4 concentrations were observed. The CO_2 concentrations were similar to average soil pore concentrations at that specific depth.

Results from the short intensive measuring period are shown in Fig. 6 for the profile piezometers 001x and 003x. Over the study period, barometric pressure gradually decreased from 1022 mbar at time $t = 0$ to 1010 mbar at $t = 33$ h. The pressure decrease occurred immediately after an increase in barometric pressure (from 1003 mbar to 1023 mbar in 2 days). In profile piezometer 003x, which was located 20 m from the landfill border, no significant differences with time were observed for CH_4, CO_2 or O_2. This is in accordance with observations from piezometer 0601 (Fig. 5*b*), which was

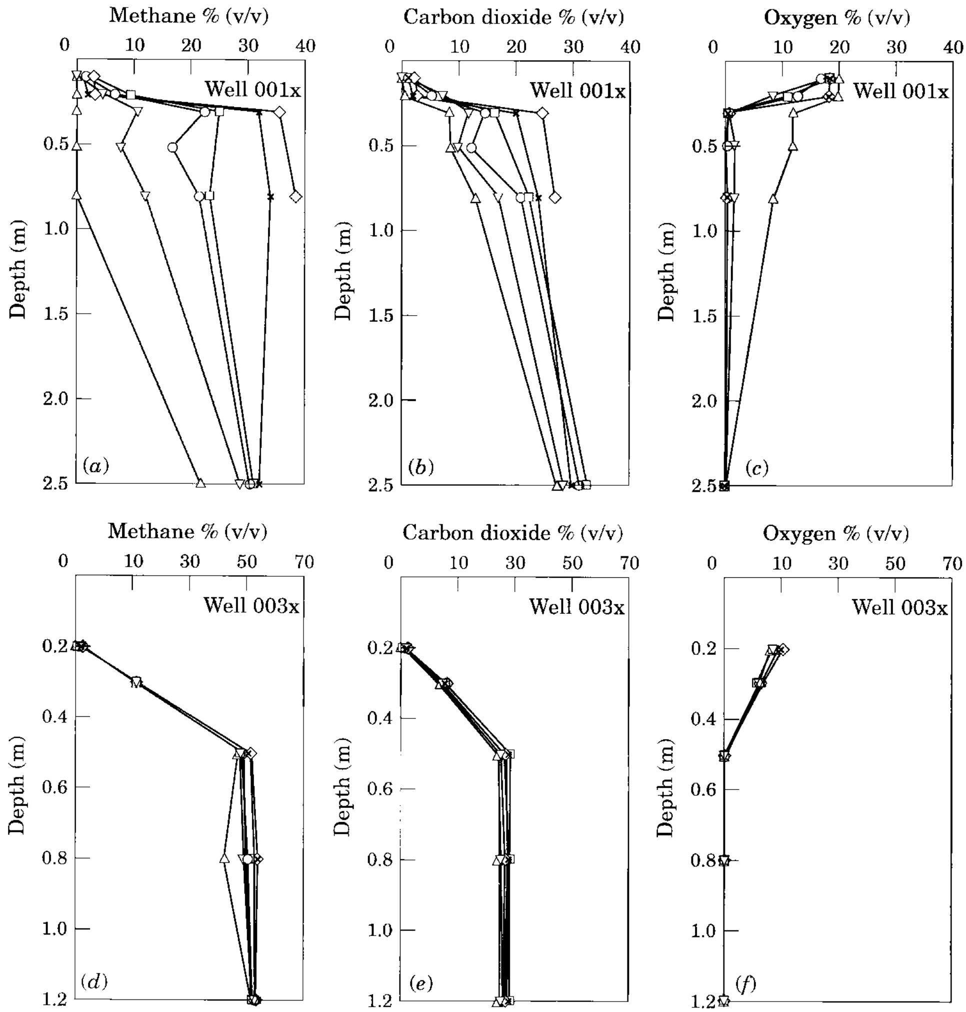

Fig. 6. Gas composition in profile piezometer 001x (*a–c*) and 003x (*d–f*) at different times. $t=0$ h is 21 April 1992 8.30 p.m. △, $t=0$ h; ▽, $t=8.5$ h; ○, $t=13.5$ h; □, $t=16$ h; ×, $t=24$ h; ◇, $t=33.5$ h.

located less than 15 m away. In profile piezometer 001x, the effect of the decreasing barometric pressure was very distinct. The pressure decrease led to vertical transport of CH_4. Figure 6*a* shows, for instance, that the CH_4 concentration increased at 80 cm depth from below 1% at $t=0$ to near 40% at $t=33$ h. At 250 cm depth, the changes were less and a constant value was reached much faster. The reduced influence of barometric pressure changes with increasing depth has also been observed in other investigations (Ward *et al.* 1992; Latham & Young 1993). Figure 6*c* shows that O_2 in the lower layers was pushed out by the up-flowing landfill gas and concentrations close to zero are reached after 8 h.

6.3 Methane oxidation

Figure 7 presents concentrations of CH_4, CO_2 and O_2 as a function of depth in profile piezometer 001x and 004x. The measurements were carried out on Day 3 after an increase

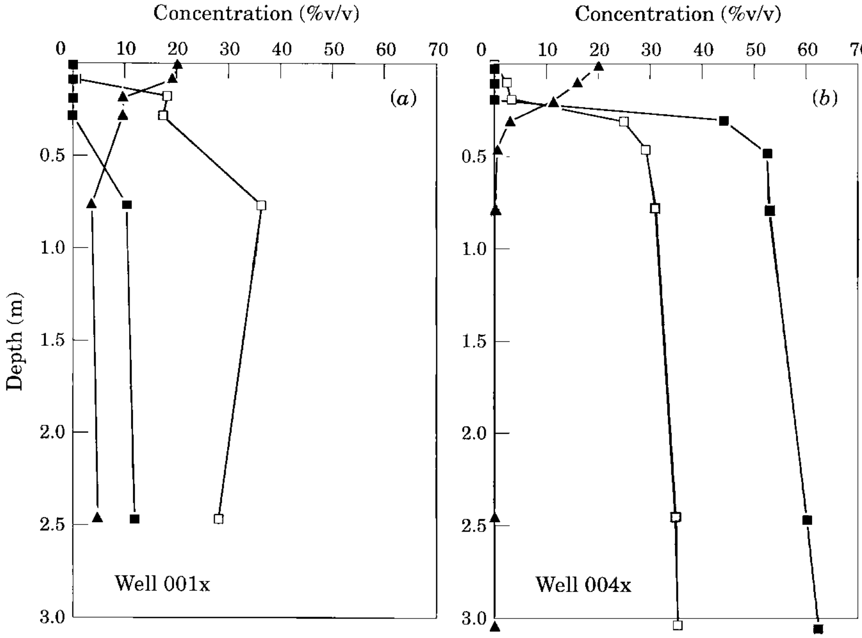

Fig. 7. Gas concentrations of methane, carbon dioxide, and oxygen as a function of depth in profile piezometer 001x and 004x measured on Day 3. ■, methane; □, carbon dioxide; ▲, oxygen.

TABLE 2
Average CH_4/CO_2 ratios measured in the three profile piezometers

	Profile piezometers		
Depth (cm)	001x	003x	004x
5–10	0.38	—	0.79
15–20	0.61	0.69	0.91
25–30	0.86	1.49	1.61
40–50	0.85	1.62	1.62
70–80	0.90	1.60	1.69
230–250	0.97	—	—

in barometric pressure (Fig. 5*a*). In piezometer 001x, measurable O_2 concentrations were observed through the whole profile. CH_4/CO_2 ratios were lower than 0.4, which is much lower than the 1.7–1.8 valid for gas sampled within the waste layers. In piezometer 004x, near constant composition was observed below 40 cm depth, with CH_4/CO_2 ratios from 1.7–1.8, which are almost similar to the range found within the waste. The results presented in Fig. 7 and similar observations for 15 other days are the basis for the average CH_4/CO_2 ratios in the three profile piezometers given in Table 2. This table shows that CH_4 oxidation is generally observed in profile piezometer 001x through the whole measuring period. For the two other profile piezometers, no significant CH_4 oxidation was observed below 30 cm depth. For the upper layers, measured CH_4

TABLE 3
Final concentrations in % (v/v) of CH_4, CO_2, and O_2 in the three flux chambers (FC1–FC3) after a 1-day collection period. Composition at the start was similar to composition in atmospheric air. The difference in barometric pressure from start to stop is also given for each day

	Difference in barometric pressure (mbar)	Component		
		CH_4	CO_2	O_2
Day 27–28	−2			
FC1		20	11	4
FC2		38	20	1
FC3		2	2	16
Day 28–29	−12			
FC1		13	12	1
FC2		36	21	1
FC3		1	1	13
Day 29–30	+15			
FC1		0	0	16
FC2		0	5	14
FC3		0	0	19

concentrations were low (typical below 3%). This meant that the soil respiration generating CO_2 in the root zone (typically in the range of 2–5%) was decreasing the observed CH_4/CO_2 ratios. The low CH_4/CO_2 ratios in the upper layer of the profiles were therefore not proving that CH_4 oxidation was actually taking place.

Methane oxidation together with CO_2 transfer between the gas and water phase led to an attenuation of the fluctuations in CO_2 concentrations as seen in several piezometers: when barometric pressure decreased, O_2 in pore gas was pushed out by the up-flowing landfill gas and the pore gas composition reflected the general composition in landfill gas (CH_4/CO_2 ratios in the range of 1.7–1.9) (Fig. 5*c*). Perhaps some CO_2 was also transferred to the pore water by this method, and reached equilibrium with the higher CO_2 concentration of the pore gas, this increasing the CH_4/CO_2 ratio. When barometric pressure increased, atmospheric air was pushed back into the pore gas. This led to dilution of the CH_4 and CO_2 concentrations and at the same time, decreased CH_4 concentration further due to CH_4 oxidation. The CO_2 concentration was increased by both CH_4 oxidation and gas to water transfer. The result was that significant fluctuations in CH_4 concentrations occurred, while CO_2 fluctuations dampened out (Fig. 5*c*). This phenomena was also seen in piezometer 001x through the intensive measuring period (Figs 6*a* & *b*). The phenomena has also been predicted by Latham & Young (1993) in model calculations solely as a result of gas/water transfer (no CH_4 oxidation was assumed).

6.4 Evaluation of gas migration

The results of the flux chambers are shown in Table 3. The final gas composition in the chamber after a 1-day collection period is shown for three locations and three measuring days. The gas compositions at the start were also measured, but were similar to the composition in atmospheric air at all locations. The locations are shown in Fig. 1*c*. In Table 3, the barometric pressure changes from start to end of the collection

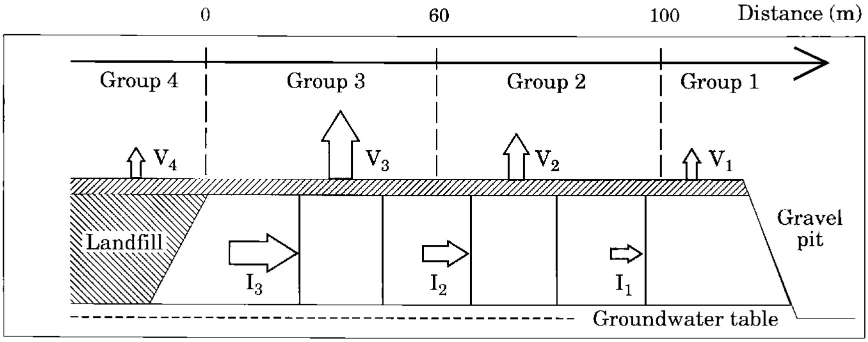

Fig. 8. Cross-section through area "D" from south to north. The area is divided into four groups (1–4). The magnitude of the vertical and horizontal gas fluxes are indicated with arrows.

period are also given. The table shows that for the third measuring day (days 29–30), no flux of landfill gas was observed in any of the three locations, due to the pressure increase of 15 mbar over the day. For the two other days where barometric pressure drops were observed, significant accumulation of landfill gas was observed for Flux Chamber 1 and 2, especially in Chamber 2 located just outside the border of the landfill. In Flux Chamber 3, only traces of landfill gas were accumulated. The general low flux through the soil cover of the landfill was probably due to low permeability of the cover soil. Several diggings of the soil cover in the area of Flux Chamber 3 showed that both the clay content and the water content were much higher than in the original top soil surrounding the landfill. Much reduced CH_4 emissions in landfill top covers in the winter season due to higher water content has been observed by Jones & Nedwell (1990, 1993).

The use of clay soil for landfill cover in combination with the lack of any landfill gas venting installations has, in many cases, led to a higher lateral gas migration away from the landfill (Kjeldsen 1994).

In order to further evaluate gas migration from the landfill, the measurements in the piezometers were grouped into four groups according to distance from landfill area "E" (Fig. 8). The averages and coefficients of variation (CV) for CH_4, CO_2, and CH_4/CO_2 ratio for all piezometers are given in Table 4 classified after the groups shown in Fig. 8. The numbers are calculated on the basis of 15–20 single measurements in each piezometer. The measured pressure above barometric pressure in the piezometers is also presented in the table.

On the basis of Table 4 and the flux chamber measurements, the four groups of piezometers are described as follows. For each group, all measured concentration data was pooled and statistical testing on differences in variance (*F*-test) and mean (*t*-test) between the groups was carried out. Obvious statistical outliers have been omitted in the tests. All tests were carried out using a 5% confidence level. The following characteristics of the groups were found:

6.4.1 Group 4 (landfill top cover)

High and stable values (low CVs) were observed for CH_4, CO_2, and CH_4/CO_2 ratios. Piezometer pressures were significantly above barometric pressure. Low vertical landfill gas flow was probably due to low permeable clay soil cover.

TABLE 4
Average values and coefficients of variance (CV) for CH_4, CO_2, and CH_4/CO_2 ratio as calculated for all piezometers. The piezometers are grouped in four groups (see text). The piezometer pressure above barometric pressure as measured at Day 12 is also given

Piezometer	Depth (cm)	CH_4		CO_2		CH_4/CO_2 ratio		Pressure a.b.p. (mbar)
		Average	CV	Average	CV	Average	CV	
Group 1								
101	120	<0.05	1.4	1.1	0.1	0.03	1.4	n.a.
Group 2								
11	10	0.7	1.3	1.3	0.7	0.38	1	n.a.
12	20	5	2.2	5.7	1.5	0.61	0.9	n.a.
13	30	21	0.7	19	0.35	0.87	0.7	n.a.
14	50	19	0.8	19	0.46	0.85	0.7	n.a.
15	80	25	0.7	24	0.3	0.9	0.6	n.a.
201	250	29	0.5	28	0.2	0.97	0.5	−0.2
202	100	0.7	1.3	14	0.3	0.06	1.2	0.0
203	120	21	0.6	24	0.36	0.83	0.38	0.0
301	120	41	0.08	36	0.06	1.17	0.07	0.0
Group 3								
401	250	54	0.08	33	0.08	1.63	0.09	0.0
402	250	59	0.05	35	0.06	1.68	0.06	0.2
501	250	60	0.04	34	0.06	1.76	0.04	0.3
502	100	60	0.05	34	0.06	1.78	0.04	0.3
503	150	58	0.08	34	0.05	1.69	0.09	0.1
504	250	59	0.05	34	0.06	1.72	0.06	0.3
505	120	56	0.16	33	0.18	1.68	0.08	1.1
506	250	60	0.05	36	0.04	1.68	0.06	0.4
507	310	61	0.04	36	0.03	1.68	0.06	0.5
508	150	59	0.06	35	0.04	1.67	0.07	0.0
509	100	61	0.03	36	0.04	1.69	0.06	0.2
601	150	60	0.05	34	0.04	1.74	0.07	0.2
602	150	62	0.03	33	0.05	1.88	0.12	0.1
603	150	55	0.16	32	0.12	1.69	0.1	n.a.
701	150	59	0.18	32	0.13	1.9	0.3	0.1
702	150	56	0.21	29	0.31	1.85	0.44	0.3
Group 4								
801	150	61	0.1	33	0.12	1.86	0.06	n.a.
802	150	59	0.07	35	0.04	1.70	0.08	n.a.
1002	100	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.5
1003	120	63	0.06	33	0.06	1.94	0.07	2.4

n.a., not analysed; a.b.p., above barometric pressure.

6.4.2 Group 3 (0–60 m from landfill border)

High and stable values (low CVs) were observed for CH_4, CO_2, and CH_4/CO_2 ratios. The variance of the three parameters were not statistically different from the observed variances in Group 4. The mean values for CH_4, CO_2, and CH_4/CO_2 ratios were all statistically significantly different from the corresponding mean values for Group 4. The mean values for CH_4 and CH_4/CO_2 ratios were respectively 4 and 6% lower than in Group 4, while the mean value for CO_2 was 3% higher. Piezometer pressures were slightly above barometric pressure. High vertical landfill gas flow was due to a gas pressure gradient between the landfill and the atmosphere.

6.4.3 Group 2 (60–100 m from landfill border)
Lower and more unstable values (higher CVs) were observed for CH_4, CO_2, and CH_4/CO_2 ratios. Both mean values and variances were significantly different from the corresponding values in Group 3 for all three parameters. Piezometer pressures were not measurable above barometric pressure. Presumably moderate vertical landfill gas flow was due to a low vertical gas pressure gradient. Significant CH_4 oxidation occurred (mean CH_4/CO_2 ratio in Group 2 was 0.93).

6.4.4 Group 1 (more than 100 m from landfill border)
Methane concentrations were close to or below detection limit, and CO_2 concentrations were below 1.5%. No significant vertical landfill gas flow occurred.

The maximal distance for CH_4 concentrations over 5%, which is the lower explosion limit, was 90 m.

7. Conclusions

The gas explosion accident at Skellingsted Landfill was a result of several unfavourable factors in combination. A house surrounded by landfill on three sides with decreasing barometric pressure and heavy rain probably leading to low vertical permeability of the top soil and an open, unsealed floor construction in the house.

The investigations at Skellingsted Landfill showed that the vertical gas flow through the soil cover of the landfill was low, probably due to the low permeability of the soil used (clay soil).

Changes in barometric pressure have a great impact on the pore gas composition in distances more than 60 m from the landfill. Closer to the landfill (less than 40 m) the effects from pressure changes are insignificant due to a steady advective flow driven by the higher pressure in the landfill.

Indications of CH_4 oxidation were observed down to 120 cm (and in one case down to 250 cm) below ground in distances more than 60 m from the landfill. Close to the landfill, CH_4 oxidation was probably observed in the top 10–20 cm of the soil profile. The CH_4 oxidation together with transfer between pore gas and pore water dampen out the fluctuations in CO_2 concentrations created by the barometric pressure changes.

Pore gas concentrations above 5% (vol.) CH_4 (the lower explosion limit) were not observed at distances from the landfill exceeding 90 m.

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