EPA STRIVE Programme 2007–2013

Monitoring of Gas Emissions at Landfill Sites Using Autonomous Gas Sensors

(2005-AIC-MS-43-M4)

STRIVE Report

Prepared for the Environmental Protection Agency

by

Dublin City University

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DISCLAIMER

The EPA STRIVE Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Table of Contents

Executive Summary

This report details the work carried out during the Smart Plant project (2005-AIC-MS-43-M4). As part of this research, an autonomous platform for monitoring greenhouse gases (methane (CH_4), carbon dioxide (CO_2)) has been developed, prototyped and field validated. The modular design employed means that the platform can be readily adapted for a variety of applications involving these and other target gases such as hydrogen sulfide (H_2S), ammonia (NH_3) and carbon monoxide (CO) and the authors are in the process of completing several short demonstrator projects to illustrate the potential of the platform for some of these applications. The field validation for the greenhouse gas monitoring platform was carried out at two landfill sites in Ireland. The unit was used to monitor the concentration of CO_2 and CH_4 gas at perimeter borehole wells. The final prototype was deployed for over 4 months and successfully extracted samples from the assigned perimeter borehole well headspace, measured them and sent the data to a database via a global system for mobile (GSM) communications. The data were represented via an updating graph in a web interface. Sampling was carried out twice per day, giving a 60-fold increase on current monitoring procedures which provide one gas concentration measurement per month.

From additional work described in this report, a number of conclusions were drawn regarding lateral landfill gas migration on a landfill site and the management of this migration to the site's perimeter.

To provide frequent, reliable monitoring of landfill gas migration to perimeter borehole wells, the unit needs to:

- Be fully autonomous;
- Be capable of extracting a gas sample from a borehole well independently of personnel;
- Be able to relay the data in near real time to a base station; and
- Have sensors with a range capable of adequately monitoring gas events accurately at all times.

The authors believe that a unit capable of such monitoring has been developed and validated. This unit provides a powerful tool for effective management of landfill site gases. The effectiveness of this unit has been recognised by the site management team at the long-term deployment trial site, and the data gathered have been used to improve the day-to-day operations and gas management system on-site.

The authors make the following recommendations:

1. The dynamics of the landfill gas management system cannot be captured by taking measurements once per month; thus, a minimum sampling rate of once per day is advised.
2. The sampling protocol should be changed:
    (i) Borehole well samples should not be taken from the top of the well but should be extracted at a depth within the headspace (0.5–1.0 m). The measurement depth will be dependent on the water table and headspace depth within the borehole well.
    (ii) The sampling time should be increased to 3 min to obtain a steady-state measurement from the headspace and to take a representative sample; and
    (iii) For continuous monitoring on-site, the extracted sample should be recycled back into the borehole well. However, for compliance monitoring, the sample should not be returned to the borehole well.
3. Devices should be placed at all borehole wells so the balance on the site can be maintained through the gas management system and extraction issues can be quickly recognised and addressed before there are events of high gas migration to the perimeter.
4. A pilot study should be carried out by the EPA using 10 of these autonomous devices over three to five sites to show the need and value for this type of sampling on Irish landfill sites.

1 Introduction

The accurate and reliable monitoring of air quality in our environment is of great importance in modern society, as recognised by the evolving legislation that governs the legally permissible levels of key pollutants. For example, the EU Clean Air for Europe Directive (CAFÉ, 2008/50/EC) "*establishes the need to reduce pollution to levels which minimise harmful effects on human health … and the environment as a whole, to improve the monitoring and assessment of air quality … and to provide information to the public*".

To police adherence to the legislation, accurate and reliable monitoring is essential, in accordance with the following framework:

- Availability of sensors/instruments capable of providing reliable and accurate data at an acceptable cost;
- Good dispersion of devices in the environment so that events can be quickly identified and adequately tracked; and
- Notification to various stakeholder groups in good time so that informed decisions can be made on how to minimise the impact of these events, and facilitate prosecution of polluters in the courts.

This report details the work carried out during the Smart Plant project (2005-AIC-MS-43-M4). As part of this research, an autonomous platform for monitoring greenhouse gases (methane (CH_4), carbon dioxide (CO_2)) has been developed, prototyped and field validated. The modular design employed means that the platform can be readily adapted for a variety of applications involving these and other target gases, such as hydrogen sulfide (H_2S) and carbon monoxide (CO).

This project is an example of an innovative systems integration whereby existing commercial sensors and communications technology are married using in-house expertise to develop a completely autonomous all-in-one platform for gas monitoring where gases are sampled, accurately measured and the data communicated to stakeholders and decision makers in near real time. This monitoring platform can be made application specific by changing the sensors used and modifying the sampling regime and frequency.

The field validation for this platform was carried out at two landfill sites. The unit was used to monitor the concentration of CO_2 and CH_4 gas at perimeter borehole wells. The final prototype was deployed for over 4 months and successfully extracted samples from the assigned perimeter borehole well headspace, measured them and sent the data to an internal web page via a global system for mobile (GSM) communications. Sampling was carried out twice per day, giving a 60-fold increase on current monitoring procedures which provide one measurement per month.

During the development phase of the prototype, a number of issues were identified relating to the factors influencing landfill gas generation and landfill site design and their impact on the effective monitoring of landfill gas. Therefore, a number of studies were carried out to better understand these issues and find routes to use them or circumvent them to successfully monitor the lateral landfill gas migration on the site.

Finally, the recommendations made and conclusions drawn for policy makers based on the research work carried out are described.

All project outputs (reports, papers, presentations, etc.) are listed in Appendix 1.

1.1 Landfill Gas Generation

Landfill is defined as a waste disposal site for the deposit of the waste onto or into land. Accordingly, landfill gas is defined as all the gases generated from the landfill waste (Council Directive 1999/31/EC). It is generated by the decomposition of biodegradable waste. Additionally, a liquid known as leachate is also generated. Landfill gas comprises approximately 100 different components, though the main components are CO_2 and CH_4 gas (~99% v/v) (Bridges et al., 2000).

Methane and carbon dioxide are both greenhouse gases and, therefore, need monitoring to ensure compliance with EU directives regarding greenhouse gas emissions to the atmosphere. Additionally, CH_4 is flammable and a build-up of this gas can contribute to explosions and fires near the perimeter of landfill sites (Christophersen and Kjeldsen, 2000a). Landfill gas is formed by the anaerobic decomposition of organic waste in the landfill. Equation 1.1 describes this breakdown (Tchobanoglaus et al., 1993; Aitchinson, 1996).

$$C_aH_bO_cN_d + nH_2O = xCH_4 + yCO_2 + wNH_3 + zC_5H_7O_2N + \text{energy} \quad \text{(Eqn 1.1)}$$

where $C_aH_bO_cN_d$ is the empirical formula of the biodegradable organic matter and $C_5H_7O_2N$ is the chemical formula of the microbial mass.

Waste starts to generate landfill gas about 3–6 months after being deposited, depending on the amount of decomposition undergone by the waste before landfilling (John Gibbons, Office of Environmental Enforcement, EPA, 2010, personal communication), and this conversion takes place over five phases. Initially, the environment is aerobic and mainly CO_2 gas is produced (Aitchison, 1996). In the transition phase, the air is consumed with the generation of CO_2, leading to an anaerobic environment which produces both CH_4 and CO_2 gases (Kumar et al., 2004). As the landfill matures and the waste stabilises, the quality and quantity of gas produced decreases, although viable amounts of gas can be produced for 20–50 years after the site has been inactive, again depending on the rate of degradation and extraction. Continuous monitoring should not be required for this length of time.

1.2 Factors Influencing Landfill Gas Emissions and Diffusion to the Perimeter

A study by Young and Aspinwall identified a number of facts about the nature of landfill gas. Sharp drops in air pressure can lead to surges of the gas, depending on the geology of the site and the type of waste found in the site, i.e. household or industrial. The geology is dependent on the porosity of the cover material, moisture content, temperature gradients and the engineering of the landfill (Young, 1992). Additionally, whether the landfill site is lined or unlined will have an effect on the gas emissions and its rate of diffusion.

Scharff and Jacobs (2006) have noted high variability in emissions data reported in the literature. Landfill gas emissions in a single landfill can vary by three orders of magnitude. These factors include atmospheric pressure around the landfill site, the soil type, moisture content and temperature of the landfill, the presence of gas extraction within the site and the age of the landfill.

Atmospheric pressure: A drop in atmospheric pressure can lead to an increase in the amount of gas vented from the landfill (Christophersen and Kjeldsen, 2000b; Environment Agency, UK, 2004). The initial drop in pressure leads to the oxygen in the surface layers of the site being expelled and gases from lower layers of the site diffusing upwards to compensate for the vacancies in the layers.

Soil type: The soil type in which the landfill site is situated is of importance when monitoring gas emissions. Areas near peat or coal soils can have a background CH_4 content in the soil. This background content should be identified before landfilling begins (Young, 1992).

Moisture: The moisture content of the landfill is also a factor (Haubrichs and Widmann, 2006; Scharff and Jacobs, 2006). If the surface soils and clay capping are waterlogged, the flow of gas will not be able to reach the surface and this will decrease the amount of emitted landfill gas.

Age of landfill: The age of the landfill also results in changes in the rate of landfill emissions. Generation of landfill gas begins 3–12 months after deposition of the waste in the landfill and usually continues for 20–50 years, once the landfill has closed (Aitchison, 1996), though some traces of landfill gas production can continue for up to 100 years depending on the rate of degradation and gas production and extraction (Environment Agency, UK, 2002). The older the landfill, the more the gas emissions will fluctuate (Young, 1992). This results from the fact that the older sites did not have gas management and recovery systems put in before filling began. The sites are retrofitted and, therefore, not as effective. The state of the landfill, whether closed or active, lined or unlined, using gas recovery or not, causes great differences in the amount of CH_4 produced and eventually emitted from the landfill. Fluxes in CH_4 can be more than 10 times greater for an active site without gas recovery compared with a closed site using gas recovery. The emissions are greatest in active sites without gas recovery, as one would expect. Active sites with gas recovery have lesser gas emissions, as little as a third, while closed sites with active gas recovery have as little as a tenth of the emissions of the active sites with no gas recovery (Mosher et al., 1999).

Gas extraction: There is evidence that by extracting CH_4 gas from a landfill, gas production is promoted, just as removing the product in a chemical reaction speeds up the rate of the reaction (Czepiel et al., 2000). The extraction of landfill gas also means that there are lower levels of gas diffusing through the soil to the upper layers, making CH_4 oxidation by the bacteria in the soil more efficient and leading to less CH_4 gas emission.

1.3 Landfill Monitoring Regulation in Ireland

There are currently 79 licensed landfill sites in Ireland, but only 29 municipal sites are active (EPA, 2009). Active landfill sites are regulated with waste licences provided by the Environmental Protection Agency (EPA) to sites conforming to the EU regulations (EPA, 2003). New landfills are designed with polyethylene lining preventing leachate from migrating through the landfill. There are areas for the leachate to be collected before being treated. Similarly, landfills are designed with gas extraction systems so that large volumes of landfill gas can be used to generate power (when composition is >50% CH_4) or can be burned off using an on-site enclosed flare system. This prevents the release of potentially dangerous amounts of landfill gas to migrate from the landfill site. Collection wells have been fashioned around the perimeter of the landfill site to monitor the lateral migration of landfill gas to the perimeter. A threshold limit of 1.0% v/v for CH_4 gas and 1.5% v/v for CO_2 gas has been set for these wells and an increase in gas beyond the threshold limit leads to the generation of an incident report to the EPA (EPA, 2003). Compliance monitoring takes place on a monthly basis by on-site personnel using a hand-held monitoring device. This sampling is labour intensive, operator dependent and not frequent enough to gather adequate information regarding events on the site and landfill gas leaks or increased emissions.

A number of detailed handbooks have been produced by regulatory agencies dealing with landfills and the inherent problems associated with the control of landfill gas emissions (Environment Agency, UK, 2002, 2004). Perimeter borehole wells are placed at intervals (~50 m) around the site, more frequently if nearer building developments. The well should be placed approximately 20 m from the waste body and should be installed to the maximum depth of the waste in the waste body (EPA, 2003).

However, issues such as waterlogged landfill pipes, crushed/blocked pipes, unexpected increase in gas volume or extraction pump breakdown can arise, all of which affect the efficiency of the site management. Any of these can lead to a build-up of lateral or vertical gas migration, and, therefore, protocols are necessary to deal with these issues and make personnel aware of them. The prototype devices described in this report fulfil this role: monitoring and communicating the data to on-site personnel in near real time, so that events can be identified and dealt with, thereby facilitating much improved management of the overall facility.

Lateral gas migration can increase for a number of reasons on a site. A problem with gas extraction (such as a rich source of gas or a blocked extraction pipe) in the main waste body can lead to an increase in gas migration to the perimeter. Additionally, seasonal and barometric pressure changes can play a role in migration (Christophersen and Kjeldsen, 2000a). If there is a consistent leaking of landfill gas to the perimeter, evidence of this will be seen in the death of vegetation in the migration area (Jones and Elgy, 1994). Because of the hazard of this gas if it builds up and the potential for harm to individuals and to property, the monitoring and tracking of lateral migration of the gas is very important so that the source of the gas leak can be found.

1.4 Methods of Landfill Gas Monitoring

There are four possible approaches to monitoring gaseous emissions at landfill sites. These are passive sampling, active sampling, continuous monitoring and remote monitoring (McGettigan et al., 2000).

1. **Passive monitoring** involves the adsorption of a pollutant onto a chemical agent in a tube over the period of a few weeks, followed by subsequent quantitation in the laboratory and averaging of the pollutant concentration over the time period. This gives results of average concentration of the pollutant but will not effectively identify events, as the results are averaged.

2. **Active sampling** involves passing a known volume of gas through a filter or chemical solution over a specific time interval and then analysing the filter or the solution in the laboratory. As in passive monitoring, this will not effectively identify events, as the results are averaged over the sampling period.

3. **Continuous monitoring** involves using automatic analysers which give average concentrations over short periods of time, usually less than an hour. In this fashion, the sample is analysed in real time.

4. **Remote monitoring** also provides real-time measurements using long-path detection methods such as long-path infrared (IR) spectroscopy.

The extent of sampling and the most appropriate method of sampling change from site to site and are dependent on factors such as landfill design, the type of waste deposited in the landfill and the age of the landfill. Other methods of gas monitoring in the literature will now be discussed briefly.

There are numerous approaches to CH_4 gas detection, including hand-held devices based on flame ionisation detection (FID), photo ionisation detection and IR spectroscopy, and larger lab-based off-line detection systems based on infrared spectroscopy and gas chromatography–mass spectrometry (GC-MS). Most detection methods, especially where quantitative results are given, are not in real time but require a sample to be 'grabbed' and then analysed at another location. Methods of analysis for the 'grabbed' sample include IR spectroscopy, GC-MS and GC-FID (Griffin and Rutherford, 1994; Bogner et al., 1995; Ward et al., 1996; Diot et al., 2000; Oonk and Boom, 2000; Environment Agency, 2004; Haubrichs and Widmann, 2006).

For the device described in this report, it was decided to develop a small, energy-efficient sensor module for greenhouse gases with the goal of providing an autonomous landfill gas monitoring platform. The types of sensors identified for potential use are described in Table 1.1. The sensors were compared in terms of accuracy, cost, range and power. In the end, IR sensors were chosen because of their range of detection and their selectivity. While they use more power and are more expensive than electrochemical sensors, they have appropriate sensitivity and linear range for this particular application, as well as superior

Table 1.1. Comparison of gas sensors for use in an autonomous monitoring device for greenhouse gases.

	Selectivity	Range	Expense	Response time	Power consumption	Poisoning
Semiconductor sensors	Not good	Good	Inexpensive (c. €10–20)	Good (<1 min)	High	Possible
Pellistor sensors	Not good (combustible gases only)	Good	Inexpensive (c. €20–30)	Good (<1 min)	High	Possible
Electrochemical sensors	Good	Good	Inexpensive (c. €80–100)	Good	Low	Possible
Infrared gas sensors	Excellent	Excellent	Expensive (c. €200)	Fast (1 s)	High	N/A

selectivity for each target gas, and excellent lifespan as there is no active sensing surface employed that can be poisoned by the sample matrix. Therefore, for this particular application, IR sensors were deemed to be the best choice.

However, in the case of passive monitoring of toxic and odorant gases (Chapter 6, End of Project Report), it was found that electrochemical sensors were currently the best choice because of their better range of target species and their lower power.

1.5 Development of Autonomous Environmental Monitoring Devices

Autonomous sensing systems, such as that developed under this project, must meet a number of key operational requirements if they are to be ultimately successful. These are:

1. **Power**
   The most successful autonomous system will have a low inherent power consumption supplemented by a capability to scavenge energy from its immediate environment, e.g. solar panels. This will make the system completely autonomous in terms of power, and capable of long periods of deployment (6–12 months), and, therefore, scalable if the cost base can be kept low. The power consumption of the system is dependent on factors such as the number, and type, of sensors used, the frequency of sampling, and the communications technology employed.

2. **Robustness**
   The system will need to be resistant to the elements through encapsulation in a rugged casing that will ensure that it is resistant to shattering, water ingress and vandalisation. A means for securing the system at the site is also necessary, as theft is an ever-increasing problem for environmental monitoring systems.

3. **Data retrieval**
   Data can be collected in real time, but in order to capitalise on this capability, events must also be rapidly defined and detected. Therefore, analytical measurements must be queried at the device level or transmitted to more powerful computation systems for decision making. Wireless communications, such as Bluetooth, ZigBee and GSM, mean that data can be retrieved in real time from a remote location and any problems on-site flagged to various stakeholders and rectified before they become serious.

4. **Sampling**
   Samples must be representative, and the sampling procedure ideally should not disturb the sample. A high sampling rate inevitably drains the system power much quicker, while a low sampling rate means that events of interest can be missed, e.g. gas surges or fluctuations. Therefore, the sampling rate is usually a compromise between conflicting demands. The ability to dynamically adjust the sampling rate according to other contextual information (e.g. weather forecasts) would consequently be very attractive (e.g. slow sampling rate under ‘normal’ conditions to conserve power and faster sampling rate when ‘an event’ is suspected).

2 Studies of Landfill Gas Migration and Dynamics in the Borehole Well Headspace

Preliminary field validation trials with some sensing devices led to a number of issues being identified regarding the dynamics of concentration changes in the gas concentration of landfill gas components present in the perimeter borehole wells on the chosen landfill sites. From initial studies, whereby three samples of gas from borehole well headspaces were taken in close succession, measurements showed significant differences in gas component concentrations. Therefore, it is evident that the gas sampling dynamics within the borehole well headspace have a significant effect on the measured values obtained, as has been noted in other studies in the literature (Boltze and de Freitas, 1997; Martin et al., 1997). Consequently, it has been suggested that for the landfill gas present in the borehole well the composition and relative concentrations of the components can and do change at different depths within the well (Ward et al., 1996; Boltze and de Freitas, 1997; Kim et al., 2009). Evidence of this was seen in studies where multiple samplings took place at one borehole well headspace over a short duration, e.g. 30 min. Borehole well gas samples were sequentially extracted from the top of the borehole well and measured by the prototypes described in this report, leading to varying component concentration measurements where replicates were taken over a short time.

Before proceeding into these studies, some understanding of the complexities of landfill gas migration is needed. A brief description of landfill gas generation and migration was given in Section 1.2. However, some of the points are worth reiterating and expanding on at this point.

1. The ratio of CH_4/CO_2 is dependent on a number of factors such as the season, the soil type, moisture content, temperature and the activity of methanogenic bacteria. Most of the landfill gas is extracted from the main waste body and flared off, but a small amount of this gas will diffuse through the soil by vertical and/or lateral migration over time, preferring the path of least resistance. The soil type and porosity can affect the path taken and can also affect the CH_4/CO_2 ratio. In areas of high porosity and particle size distribution, CH_4 can have a longer residence time leading to conversion to CO_2 in the presence of methanogenic bacteria, thus decreasing the CH_4/CO_2 ratio in this area (Xiaoli et al., 2009). The temperature affects the activity of the methanogenic bacteria, with most activity occurring in the summer months. In areas of higher moisture, the CO_2 content can decrease as it is more soluble in water, thus increasing the CH_4/CO_2 ratio (Kjeldsen and Fischer, 1995; Ward *et al.*, 1996).

   It is the change in this ratio that causes most of the non-homogeneity in the landfill gas extracted from the perimeter borehole well headspace. The pathways for migration to the perimeter will change with changing weather or soil type, etc., and the CH_4/CO_2 ratio will frequently change based on the factors described above. Therefore, when studying the gas samples extracted for the borehole well headspace over a depth of a number of metres, differences in the component concentrations are to be expected. The borehole well inner pipe is porous, so landfill gas migrating through the soil can diffuse into the pipe for extraction. This movement into the pipe is accelerated when extraction takes place and the quasi-steady-state CH_4/CO_2 ratios that have been established in areas in the soil are disturbed. It is these areas of high and low CH_4/CO_2 ratio being extracted that lead to the non-homogeneity in the borehole well headspace and inconsistency in repeat sampling each day.

2. Dilution of the landfill gas sample at the top of the borehole well headspace also leads to

inconsistent results when repeat sampling is employed, as the gas sample is often mixed with varying amounts of atmospheric air (Kjeldsen and Fischer, 1995; Boltze and de Freitas, 1997). Ingress of atmospheric air common occurs to stabilise the pressure, leading to a dilution of the landfill gas present. It has been recorded that the ingress of atmospheric air can affect the gas concentration up to 2 m from ground level, to varying degrees (Ward et al., 1996).

3. During sampling, especially prolonged sampling at the perimeter, the composition of the landfill gas can change (Boltze and de Freitas, 1997). Extraction of gas can lead to the ingress of migrated landfill gas and/or atmospheric air, leading to changes in component concentration and/or ratio in the same sampling cycle. Prolonged sampling creates a localised area of low gas pressure, promoting gas migration and the filling of the borehole well with gas from different areas within the perimeter, leading to different concentrations and ratios of CH_4/CO_2 being seen (Kim et al., 2009).

These three points are summarised visually in Fig. 2.1.

To further understand the variability of the major gas components (CH_4 and CO_2) in the borehole well and to provide the most effective sampling cycle for the landfill gas sampling prototype units, five additional studies were carried out:

1. An investigation into the appropriate sampling time needed for the prototype device to provide a representative sample of landfill gas;
2. A study of the influence of sampling landfill gas at varying depths in the borehole well headspace on the time needed for the gas sensors to report a consistent concentration of the gas components, CO_2 and CH_4;
3. An examination of the impact of a relatively small perturbation (i.e. insertion of a borehole well depth probe) on the changes in the gas composition;
4. Exploration of the changes in gas composition that occur when a sample is extracted from the borehole well headspace; and
5. A study of the impact of the reintroduction of the extracted and measured landfill gas sample into the borehole well headspace on the internal gas composition.

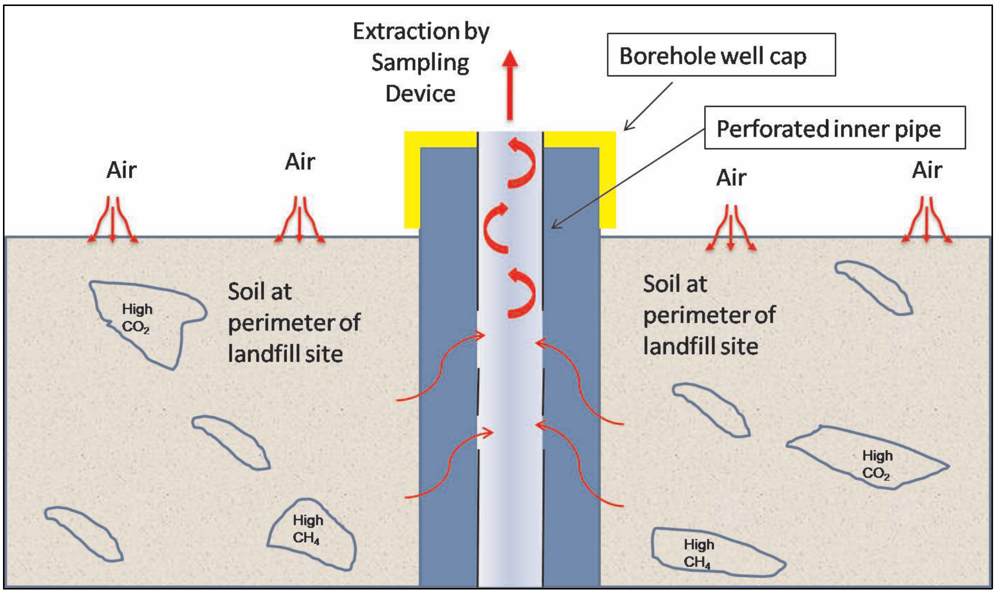


Figure 2.1. The dynamics of the gas migration and extraction system at perimeter borehole wells. CH_4, methane; CO_2, carbon dioxide.

2.1 Investigation of Extraction of Multiple Samples from One Headspace

The headspace of borehole well A1 was measured repeatedly at 0.0 m and at 1.0 m from the top of the borehole well using a prototype device (Prototype III) and a reference instrument, the GA2000.

The following procedure was used for each experiment. The measuring units were baselined for 3 min with ambient air. Then a gas sample was extracted from the borehole well headspace for 3 min before the sample chamber of the measuring units was purged for 3 min with ambient air. The set-up used is shown in Fig. 2.2.

Figure 2.2. Set-up of experiment.

The following results were noted for the study run in the borehole well A1 which has a headspace of 4.46 m. The measurements given in Figs 2.3 and 2.4 show only the CO_2 component of landfill gas. This is because the concentration of CH_4 present in the extracted samples was negligible and showed no change throughout the study. The results given by the GA2000 system and the Prototype III unit for the CO_2 component are compared in Fig. 2.3, when the gas samples were extracted from the borehole well headspace at 0.0 m depth.

The most evident result from Fig. 2.3 is that the two systems do not adequately correlate or show the same concentration of CO_2 gas. They do, however, show similar trends. The analyser devices both use IR sensors to detect the CO_2 gas. However, the GA2000 system has sensors with the range calibrated over 0–100% v/v CO_2 whereas the Prototype III system has sensors calibrated only in the gas range 0–5% v/v CO_2. Therefore, at higher concentrations, (>5% v/v) the Prototype III unit is out of calibration. Because of this discrepancy, the discussion will centre on the trends in gas concentration present, and not the actual gas concentrations.

Figure 2.3 shows that the gas concentration for the CO_2 component is prone to change over time for repeated sampling. As in previous studies, a number of extractions are required before the highest gas concentrations are measured. Because of the depth of the gas headspace, the gas volume is vast, as more migrated gas will diffuse into the borehole well pipe as the gas is extracted from the headspace. In all, 11 gas samples were taken from the well headspace, ranging from 11.2 to 16.8% v/v when measured with the GA2000 device. There is a significant difference in concentration between the lowest value and the highest value, showing that taking a representative sample of the landfill gas from a borehole well of deep headspace can be a complicated procedure. However, it also shows that, at the top of the borehole well headspace, air ingress can affect the sample concentration, causing variance in the measurements.

The data collected by the Prototype III unit and the GA2000 unit at 1.0 m headspace depth in borehole well A1 are displayed in Fig. 2.4. Again, the trend in both data sets is the same but the concentration values were different, because the sensors in the Prototype III unit were only calibrated in the range 0–5% v/v. Unlike the data shown in Fig. 2.3, where extraction of gas samples took place at the top of the borehole well headspace, the concentration of the CO_2 component is more consistent at 1.0 m headspace depth, with the concentration ranging from 12.3 to 15.2% v/v over the course of the gas sample extractions. Therefore, as predicted, a strong case can be made for extracting gas from the borehole well at a lower headspace depth than at 0.0 m to get a more consistent measurement

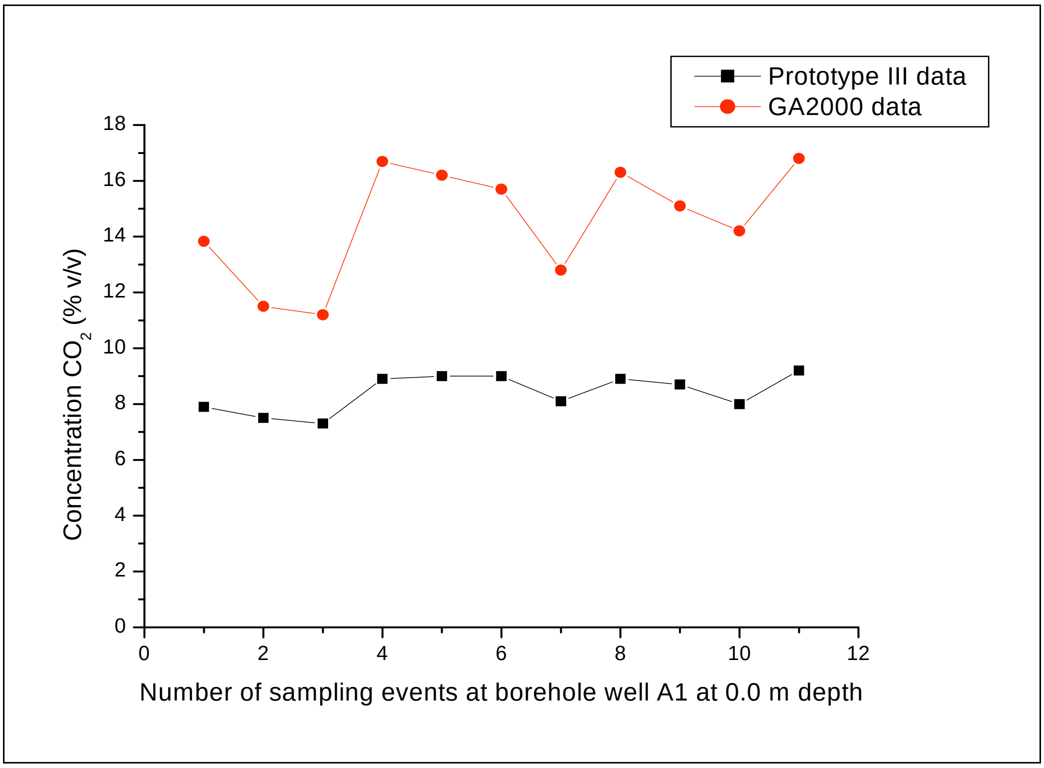


Figure 2.3. Borehole well A1 carbon dioxide (CO_2) data at 0.0 m headspace depth.

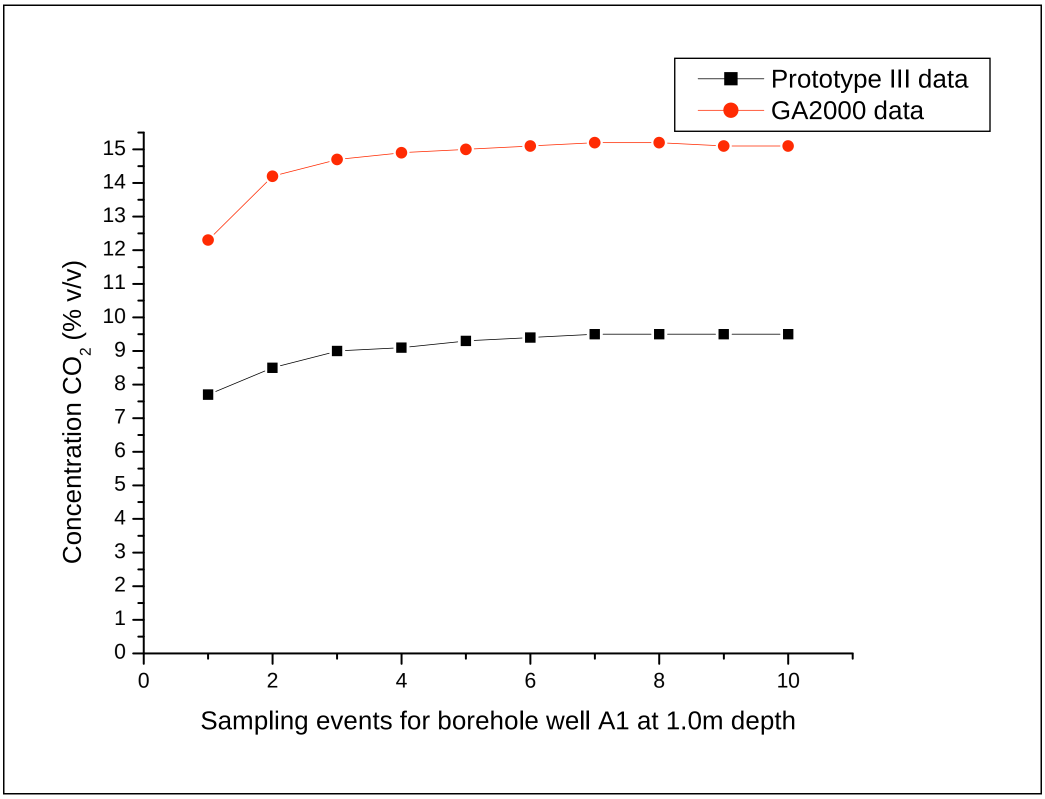


Figure 2.4. Average carbon dioxide (CO_2) data for borehole well A1 at a headspace depth of 1.0 m.

and a more accurate picture of the true concentration of the gas components present in the borehole well.

In conclusion, it has been shown through this study that repeat gas extractions from the top of a borehole well headspace will return differing values. However, if the headspace of the borehole well is deep enough so that a large gas volume exists, then a steady state can be found and multiple gas samples showing similar values can be obtained.

2.2 Real-Time Multiple Depth Study of Gas Homogeneity

Taking multiple samples from a borehole well of deep headspace can lead to a representative sample of the landfill gas concentration being found after a number of extractions. For the prototype being constructed, one of the aims is to be able to take from a borehole well headspace one measurement that is representative of the gas migrating from the waste body in the landfill to the perimeter of the site. Therefore, a study was undertaken extracting gas samples at different headspace depths from a number of borehole wells of different headspace depths. This was carried out to ascertain if extractions taken from deeper in the well gave more consistent results and whether there is an optimum depth of extraction which is deep enough to give consistent results but not so deep that it is near the water table.

2.2.1 Experimental design

The first study using multiple depth extractions was at a single borehole well, A1, which had a headspace of 4.46 m. The well was fitted with a new custom-designed ‘cap’ which had taps capable of sampling at three different headspace depths (0.0 m, 0.5 m and 1.0 m).

To facilitate the extraction of gas at multiple depths the borehole well ‘cap’ was fashioned in Dublin City University (DCU), as shown in Fig. 2.5. The ‘cap’ was fabricated in acrylonitrile butadiene styrene (ABS) plastic using a rapid-prototyping 3-D printer to fit the dimensions of the well. Three stainless steel taps capable of accepting 6-mm tubing were screwed into the cap and 4-mm tubing was attached to two of the taps – at 1.0 m and 0.5 m length – for extracting gas samples at these headspace depths. The third tap had no tubing attached, as it was used to extract gas at the top of the borehole well. The Prototype III unit was used to carry out this study in conjunction with the GA2000 unit which was used to correlate the measurements taken.

2.2.2 Results and discussion

The results from the study are shown in Fig. 2.6. It is evident that the deeper headspace extractions return higher concentration values and in this study there is a linear relationship between headspace depth and gas concentration. Additionally, there is evidence that the deeper extractions show increased consistency in the concentration of the gas. The gas extracted at 0.0 m did not reach a steady state during the 3-min sampling cycle, but increased in concentration throughout. The gas samples extracted at 0.5 m and at 1.0 m showed that a definite steady state had been reached after

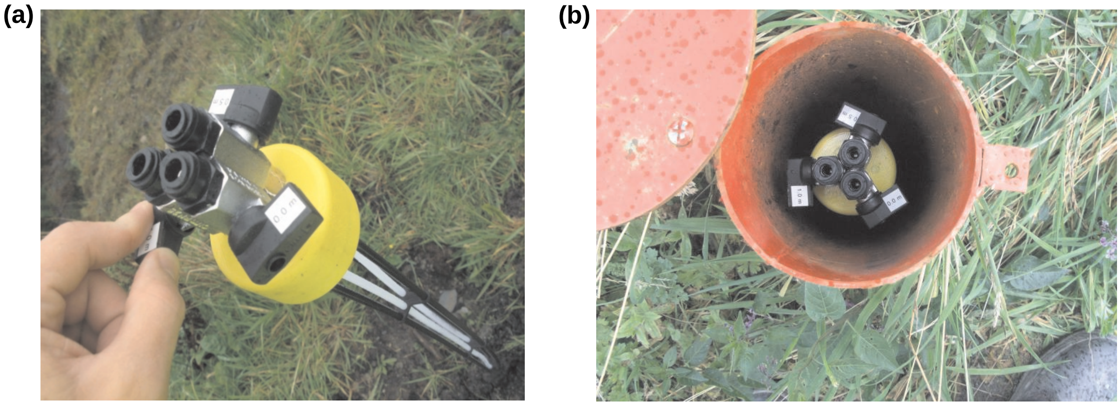


Figure 2.5. Borehole well ‘cap’ (a) before and (b) after insertion into the well.

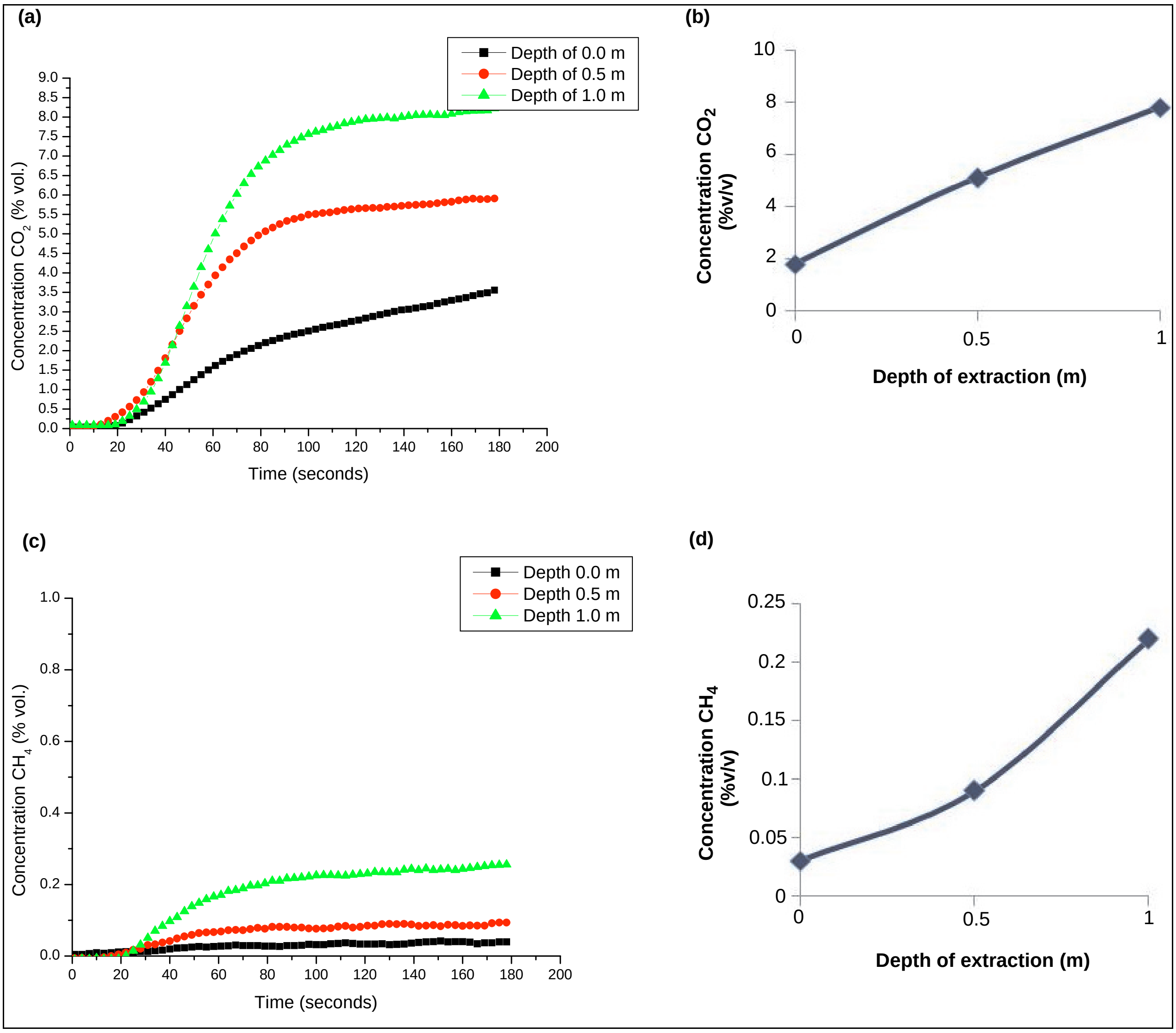


Figure 2.6. Multiple depth extractions from A1: (a) and (b) carbon dixide (CO_2) concentrations; (c) and (d) methane (CH_4) concentrations.

approximately 90 s of measuring. Therefore, it can be postulated that sampling the headspace at a depth in the borehole well instead of from the top of the well leads to samples of non-diluted gas being measured. Also, there is evidence that, as the gas concentrations reach a steady state quicker, the sampling time could be decreased, thereby reducing the energy consumption of the unit and increasing the efficiency of the system.

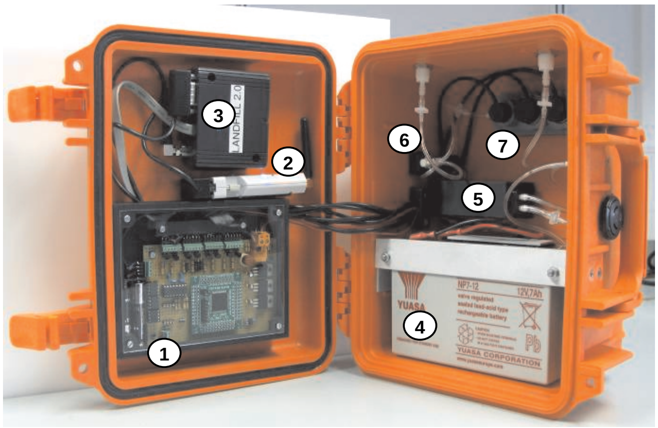
2.2.3 Conclusions

This study gives evidence that the concentration of the landfill gas components increases with depth in the borehole well, at least where there is a deep headspace. This is partly because the air at the top of the borehole well is not present as a diluent for the gas at lower levels (Boltze and de Freitas, 1997). In addition, extracting samples from lower in the borehole well gives measurements with a longer steady state, meaning that it is easier for the operator to achieve a representative sample measurement. This could also have implications for adaptive sampling with the prototypes, i.e. once a steady state is measured, the unit would stop sampling, leading to decreased power consumption, enhanced efficiency and decreased gas extraction from the borehole well headspace.

3 The Final Prototype Design

The final system is illustrated in Fig. 3.1. The unit is smaller in size than Prototype III. In part, by changing the sensors used, the overall power consumption of the system has been significantly reduced. Now one lead acid battery is sufficient to power the entire system for over 3 months, giving 100 sampling cycles without recharging. Table 3.1 details the main components of this prototype.

The GSM unit, the Bluetooth unit and the air pump all remain the same as in previous prototypes. The Bluetooth module is now used on-site to download the stored data from the flash memory or to change the sampling time or reset the automated sampling cycle. Data are saved using a 2-MBit onboard flash memory chip in case of connection interruption and a representative measurement is sent via GSM text



1. Control Circuitry
2. Bluetooth Communications
3. GSM Communications
4. 12 V 7 Ah Battery
5. Extraction Pump
6. Extraction Control Valve ×2
7. Gas Sample Chamber

Figure 3.1. System design layout.

Table 3.1. List of main components for Prototype IV.

Component	Supplier	Description	Catalogue number	Price (€)
Carbon dixide infrared sensor	Dynament	Range 0–20%	P/HCO2/5/V/P	120
Methane infrared sensor	Dynament	Range 0–20%	P/HC/5/V/P	120
Air pump	SKC Inc.	Grabair Pump	Model 222-2301	150
Lead acid battery	Radionics	12 V, 7 Ah	511-3460	30
Thermistor	Farnell	10 kΩ	DKF103N5	5
Humidity sensor	Radionics	0–100% RH	528-3171	30
Peli case	Kelly Fire & Rescue	Orange	Model 1300	85
Bluetooth	Expansys	LM Technologies Serial Adaptor	141437	50
GSM[1]	John Andrew Electrical Services	Siemens MC35i		150
Flash memory chip	Farnell	2 MBit NUMONYX M25P20	9882863	5

[1] GSM, global system for mobile communications; RH, relative humidity.

message to a base station in DCU where the data are analysed and converted from analog/digital converter (ADC) values to actual concentration. The data were saved to the flash memory chip where the memory was arranged to allow storage of 3 × 213 data values, facilitating logging of data on the device and on-site retrieval in the event of transmission difficulties.

3.1 Sampling Procedure

Prototype IV units were deployed at two borehole wells on Site A. Well A1 had a gas headspace >5 m, and so landfill gas was extracted at 1.0 m. The second borehole well, A2, had a headspace of between 2.5 and 1.8 m, depending on the water table. Therefore, landfill gas was extracted at a headspace depth of 0.5 m in this borehole well.

The entire sampling procedure took 9 min, consisting of:

- 3-min baseline with ambient air;
- 3-min measurement of the extracted landfill gas (and recycling back into the borehole well); and
- 3-min purge of the cell with ambient air.

All data points for each 9-min sampling cycle were saved onto flash memory onboard the unit. Representative data were sent to a base station in DCU via GSM. Measurements were taken twice daily at 11 am and 11 pm, representing a 60-fold increase in sampling rate at the site compared with existing monthly sampling using the hand-held units, such as the GA2000.

The data sent via GSM text message had the following content:

- ADC value for the system battery;
- Baseline sample: average ADC value for the last 10 points for each IR sensor;
- Sample value: maximum ADC value for each of the four sensors – CO_2 IR, CH_4 IR, temperature and humidity; and
- Purge value: minimum ADC value for each IR sensor.

From this, the battery power was known and it could be confirmed that all sensors were measuring accurately. Finally, a representative measurement of the maximum concentration of CO_2 and CH_4 at the extraction depth in the borehole well could be compared with previous readings from that well.

The data were saved to the DCU base station and a conversion to percentage v/v carried out for the IR sensor data for each target gas. The battery ADC values were converted to voltage values so that the performance of the battery could be monitored. These ADC value data were then placed on a ‘live’ website internally at DCU for easier comparison between data points. The website had a private password-protected area in which the converted data could be accessed by site personnel and the project team. The ADC values showing the general trends of the data were publicly available.

3.2 Long-Term Field Validation Trials

The data for the entire 4-month field validation trial at Site A, borehole well A1, are shown in Fig. 3.2. The trial started on 28 May and ended on 8 October 2009. There are four series of data presented here, two for CO_2 gas concentration and two for CH_4 gas concentration. The first CO_2 series shows the maximum data values sent via GSM text message to the base station. The second data series shows the averaged steady-state data used when the entire sampling series was downloaded from the flash memory chip and averaged. The same two series are shown for the CH_4 data, that of the maximum data point value as communicated via GSM text and the average of the steady-state value generated from the analysed flash drive data. It can be seen, from the data presented in Fig. 3.2, that the data correlations between the maximum data sent via GSM text and the averaged data from the flash drive are excellent.

Examining the graph in more detail, a number of events can be seen each month through the deployment, particularly in June and September. To look in detail at each group of events, the trial data have been broken down into subsets for each month of the trial. These monthly data sets will be discussed in detail in the following paragraphs.

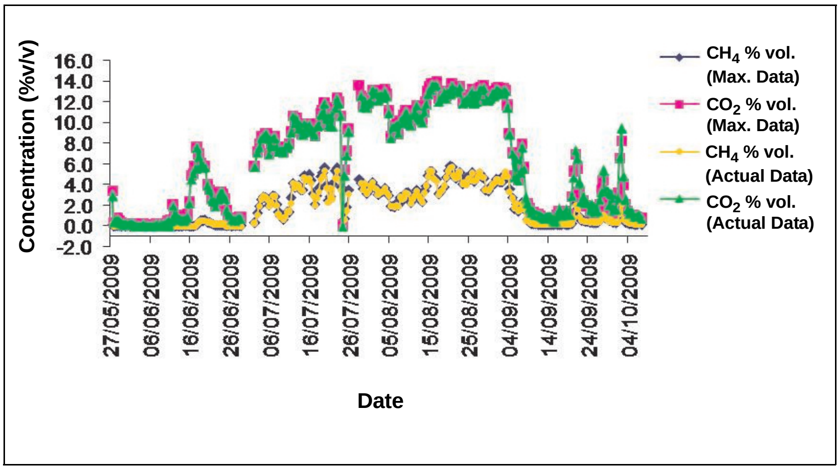


Figure 3.2. Correlation study over the 4-month deployment at well A1 on Site A.

Data from borehole well A2 are shown in Fig. 3.3. One of the Prototype IV units was deployed here over a 3-month period, from July to October 2009. Again, a number of events are evident, whereby the gas component CO_2 exceeded its threshold limit of 1.5% v/v.

The deployment at borehole well A1 over the first 5 weeks is shown in Fig. 3.4. Three distinct events can be seen over that period. For the first 2 weeks of the deployment, both the CH_4 and the CO_2 measurements are at almost baseline levels, considerably lower than their threshold limits. However, in early June, additional soil cover was added to a closed cell adjacent to borehole well A1 and this led to complications for the site gas management system, which will be further outlined below.

On 12 June, Event 1 took place whereby the CO_2 concentration exceeded the threshold limit. This event was short-lived, with the highest concentration occurring late on a Friday night, when work on the site had stopped and the active cell was covered. Through consultation with the site operators it was identified that additional extraction had not been set up because significant gas build-up had not been expected overnight. Once personnel returned to the site the next day, extraction was increased and the CO_2 component fell immediately below its threshold limit. The component concentration did not fall back to negligible

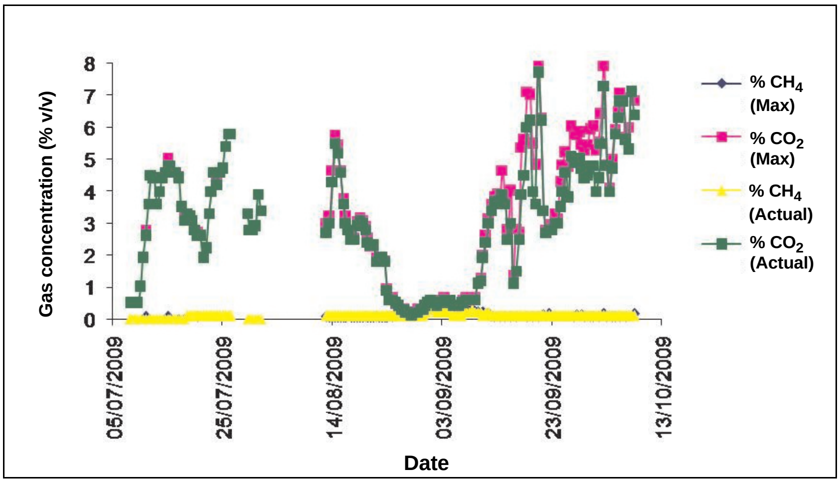


Figure 3.3. Full 3-month deployment at borehole well A2.

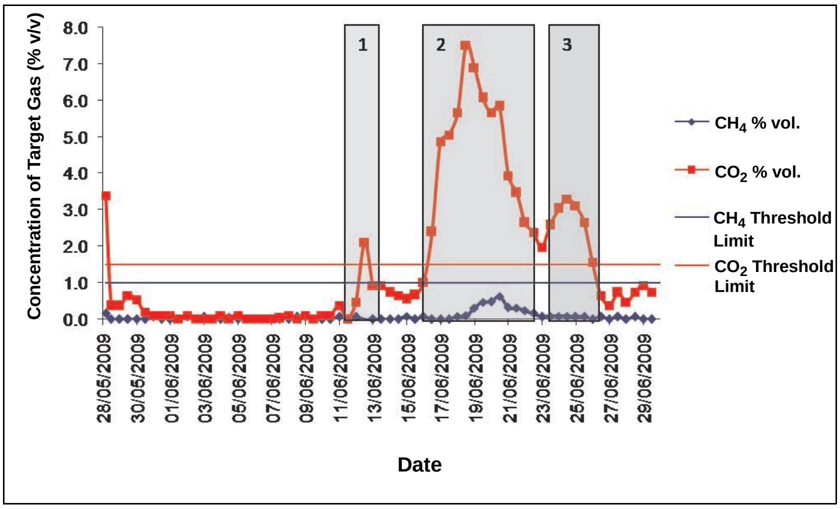


Figure 3.4. Deployment for June 2009 at borehole well A1.

levels as had previously been recorded, but did stay below the threshold limit until 16 June.

Event 2, starting 16 June, recorded that the concentration of CO_2 migrating to the perimeter of the landfill site increased significantly and exceeded the threshold limit of 1.5% v/v. The gas build-up occurred because the gas management system was not extracting enough gas from the site, leading the excess to migrate to the adjacent borehole well. Before the additional cover was added to the cell, some of the gas build-up escaped through the top of the cell, reducing the gas migrating to the perimeter. However, after additional cover was added, this could no longer happen. After 3 days, the remedial measures taken resulted in a decrease in the migration of gas to the perimeter borehole well.

However, Event 3 occurred on 23 June when one of the underground pipes used to extract gas from the main site became partially blocked. This decreased the flow rate of gas extracted, resulting in gas migration increasing once more. After the blockage had been identified and removed, the CO_2 gas component fell below the threshold limit once again, where it remained for some time.

In this time, only the CO_2 component had breached the threshold limit. The CH_4 concentration remained below its threshold limit of 1.0% v/v at all times. However, this did not last, as both gas components breached their threshold limits in July 2009.

The measurements taken from borehole wells A1 and A2 during July 2009 and the main events identified during this period are displayed in Fig. 3.5. As can be seen, for most of this month both the CH_4 and CO_2 concentrations exceeded the threshold limits in borehole well A1. There are a number of reasons for this. As discussed for June, additional cover on an adjacent closed cell led to an increase in gas migration as the new cover stopped the fugitive emissions from escaping through the top of the cell. This build-up of gas was dealt with by increasing the gas extraction from this part of the site. The additional gas extraction led to all burners at the flare working at maximum. Unfortunately, once additional extraction was carried out for this borehole well, the gas balance on the entire site was no longer maintained and gas concentrations in other borehole wells began to exceed the threshold limits. This can be seen in borehole well A2. When the gas concentration in borehole well A1 decreased, 8–11 July (Event 1), the concentration at borehole well A2 increased above threshold limits. Once informed, site personnel began the task of restoring the balance on the site, while still keeping the gas concentration below the threshold limits of the perimeter borehole wells and without increasing the gas flow rate. One main event (Event 2) occurred through most of July for borehole A1 and this was up to 25 July, when the concentration levels dropped to 0% v/v (Event 3). This is because the staff on-site took action, greatly increasing the amount of gas extracted to flare from this part of the site. As a counter-effect to this, the concentration at borehole

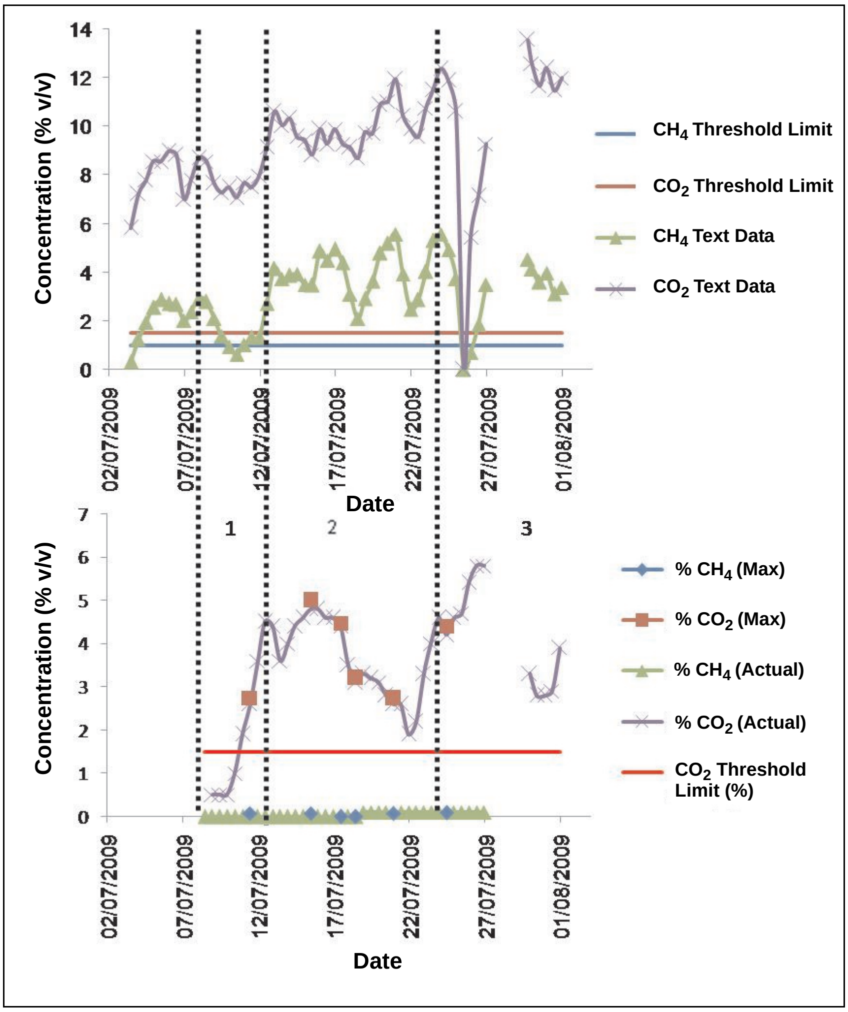


Figure 3.5. Deployment for July 2009 at borehole A1 (top) and at borehole A2 (bottom).

well A2 started to greatly increase. Unfortunately, the concentration of gases at borehole well A1 also began to increase once the extraction was decreased at that part of the site. One can see from just this 1 month of data how ineffective once-monthly sampling of a landfill site is as numerous events can take place in this time. Small changes in gas extraction or ineffective capping can have a huge effect over the entire site and taking only one measurement per month results in these effects being missed, or a delay in remedying the problem on-site. One can also see how effective multiple systems on one site can be in modelling a site and monitoring what is happening as extraction flow rates are varied on the site. Personnel become better informed and can make more effective choices about flaring/gas collection to make the gas management system more efficient. By having more information, personnel are also in more control and can make proactive instead of reactive decisions when a potential issue on-site, such as an increase in gas migration, is identified early.

The data taken for borehole wells A1 and A2 over August 2009 are shown in Fig. 3.6. For the entire month, both the CH_4 and CO_2 measurements in borehole well A1 exceeded their threshold limits of 1.0% v/v and 1.5% v/v, respectively. This is because a gas balance was being sought by staff on-site to deal with the extra gas in the landfill caused by the additional cover on the closed cells. During this period, the rate of extraction was clearly insufficient to deal with this extra gas generated. Therefore, ideas were put forward to increase the number of borehole wells in the cells so that gas could be piped more efficiently from specific cells with higher volumes of gas. The component concentrations at borehole well A1

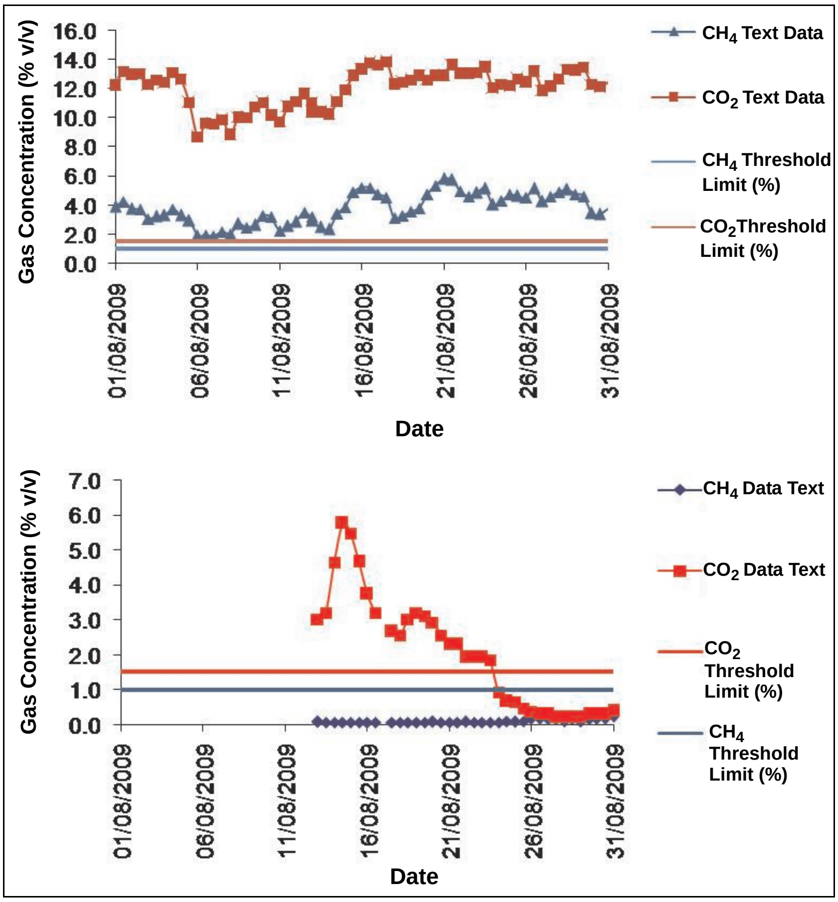


Figure 3.6. Deployment for August 2009 at borehole wells A1 (top) and A2 (bottom).

remained quite stable throughout the whole of August, though greatly exceeding their threshold limits.

The decrease in gas concentration for most of August at borehole well A2 can be seen in Fig. 3.6, with the CO_2 component levels falling below the threshold limit by 24 August 2009. Therefore, the gas migrating to this part of the landfill is now under control due to the modified procedures implemented by the site management team.

For September 2009 there was a limited balance achieved in borehole well A1 but, also, there were some events identified. The measurements for the final 5 weeks of the deployment at borehole wells A1 and A2 are shown in Fig. 3.7. Again, this appears to be a counter-effect to the balance seen at borehole well A2.

Event 1 shows that greater extraction at borehole well A1 led to a decrease in gas migration and the concentration of CO_2 and CH_4 fell below their threshold limits. Correspondingly, the concentration of gas in borehole well A2 increased above the threshold limits of CO_2 and CH_4. Event 2 shows that an increase in landfill gas exceeding the threshold limits in borehole well A1 led to a decrease in gas at borehole well A2. Event 3 shows that once the gas in borehole well A1 was decreasing, there was a corresponding increase in the concentration of the gas in borehole well A2. Event 4 shows a surge in landfill gas in borehole well A1 corresponding, again, with a decrease in the gas in borehole well A2. This is strong evidence that the gas migration on a site is linked to the balance of the gas extraction to flare on the site. Over-extraction in one area will lead to an increase in lateral migration to another area in the site. Therefore, it is only when the entire site is in balance that rapid increases in landfill gas migration can be reduced. This issue is complex and requires sophisticated control measures to be implemented if the CO_2/CH_4

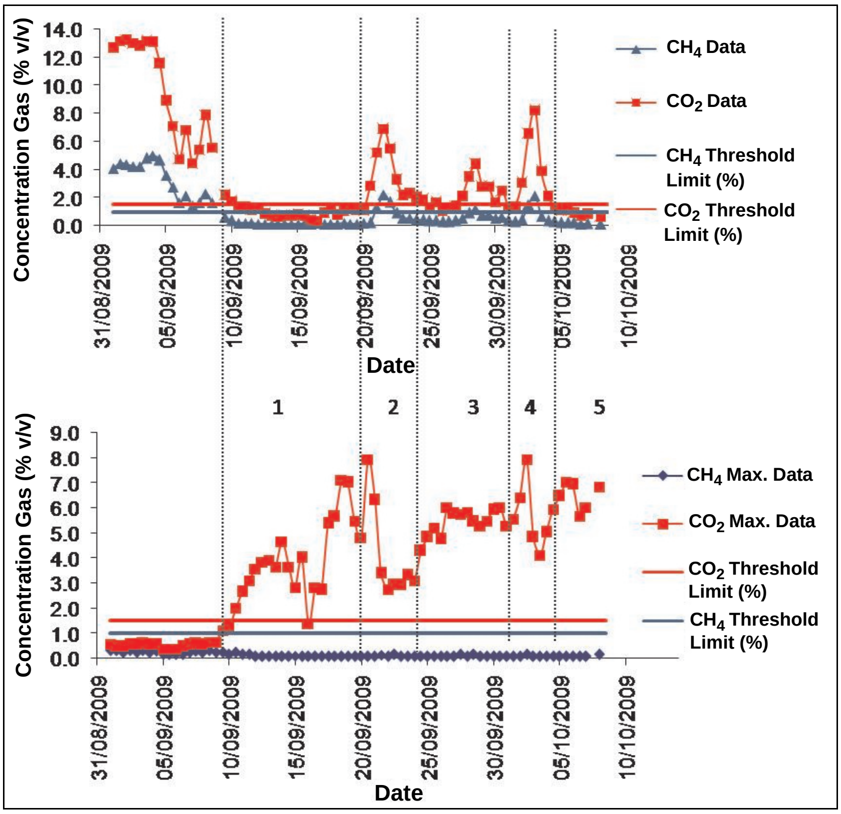


Figure 3.7. Deployment for September 2009 at borehole wells A1 (top) and A2 (bottom).

concentrations are to be maintained at acceptable levels.

This balance arises from changes in the management of the gas system on-site. In July 2009, the five on-site burners were set to their maximum rate, with the flare, therefore, working at its full capacity. The changes in the gas flow rate implemented by the site management can be seen in Fig. 3.8. Over the duration of the trial, the gas flow rate almost doubled, as a consequence of the attempts to deal with events identified from the site data generated by the autonomous sensing platform.

When the increased gas migration on-site was identified in June 2009 at borehole well A1, the gas flow rate was increased from c. 220 m^3/h to c. 300 m^3/h. For July and August, the flow rate stayed the same while staff adjusted where the gas was extracted

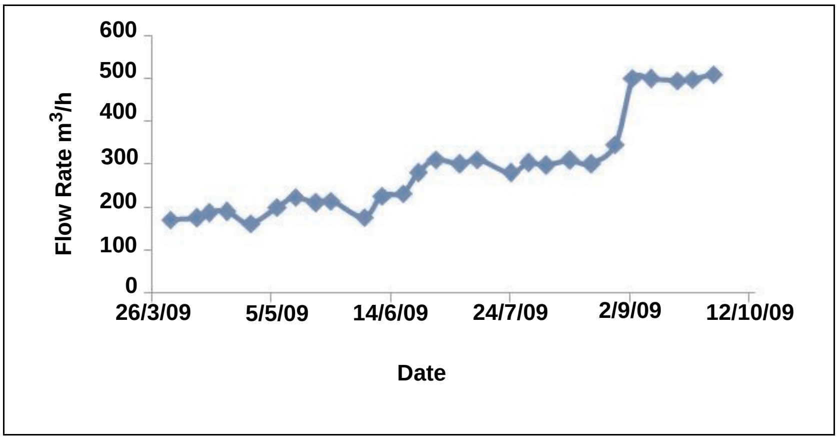


Figure 3.8. Flow rate of landfill gas to flare.

from on-site, trying to find a balance which would allow the gas flow to the flare to remain the same while managing to keep the gas migration to the perimeter borehole wells under control and under their threshold limits. When it became obvious that this task could not be successfully completed, the flow rate was once again increased in early September from c. 300 m^3/h to c. 500 m^3/h. This resulted in the gas migration at borehole well A1 greatly decreasing with only minor events taking place in September. However, gas migration at borehole well A2 is still not under control at the point of writing.

As can be seen in Fig. 3.9, there is much variation in the monthly measurements taken by site personnel to comply with the waste licence requirements. The measurements were taken using a GA2000 instrument at the top of the borehole well. In the June measurement, the gas component concentration for CO_2 exceeded the threshold limits when measurements were taken at both 0.0 m and 1.0 m and there is good correlation between the measurements at both the 0.0 m and the 1.0 m depth. This is due to mixing in the headspace, as there were a number of events recorded here, as seen in Fig. 3.4. In the July measurement, the gas concentrations for both the CO_2 and CH_4 components exceeded their threshold measurements, correlating well with the data from the prototype unit taken at 1.0 m depth. Again, this is due to mixing in the headspace as events were recorded in Fig. 3.5.

The same is not true for the August measurement where the measurements at the 0.0 m depth were well below the threshold limits for both components while at the 1.0 m depth the measurements greatly exceeded the threshold limits for both components. The reason for this is most likely due to the steady-state nature of the measurements in August. As seen in Fig. 3.6, the landfill gas measurements were relatively steady all month, though at a high concentration. Because there were no major events in this month, with rapid increases or decreases in concentration due to extra extraction for flaring, mixing in the borehole well would have been minimal, meaning that the higher concentration of gas would not have mixed to the top of the borehole well for measurement. When the component concentrations are changing from day to day or week to week, the changes are reflected in the measurements at 0.0 m depth due to mixing in the headspace. Therefore, when the component concentrations are steady, the reverse is true. This is of concern as on-site it can look as though the measurements are below the threshold limits if the monthly measurements are taken as representative of the overall migration on-site. This was not the case in August, where the CH_4 and CO_2 components were consistently and significantly above their threshold limits, as shown in Fig. 3.6.

The monthly measurements taken at the 0.0 m headspace depth for borehole well A2 are shown in Fig. 3.10. These measurements are compared with

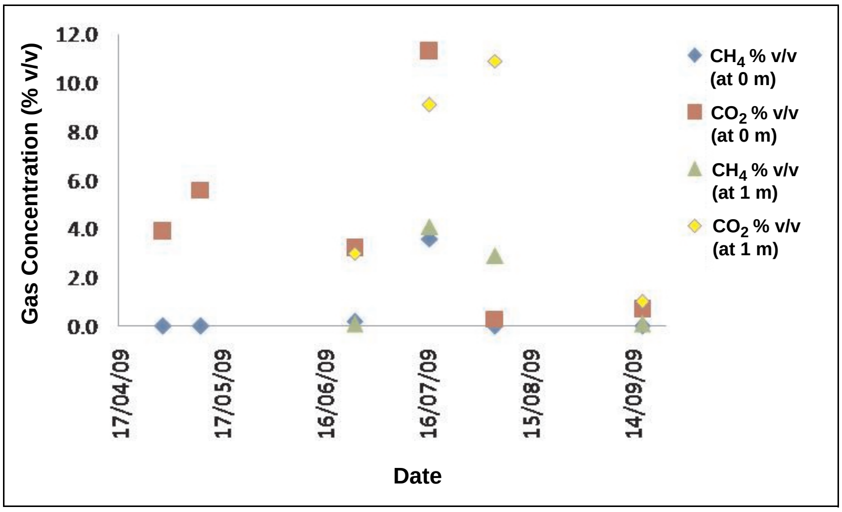


Figure 3.9. Monthly gas measurements taken at borehole well A1 (April–September) by site personnel.

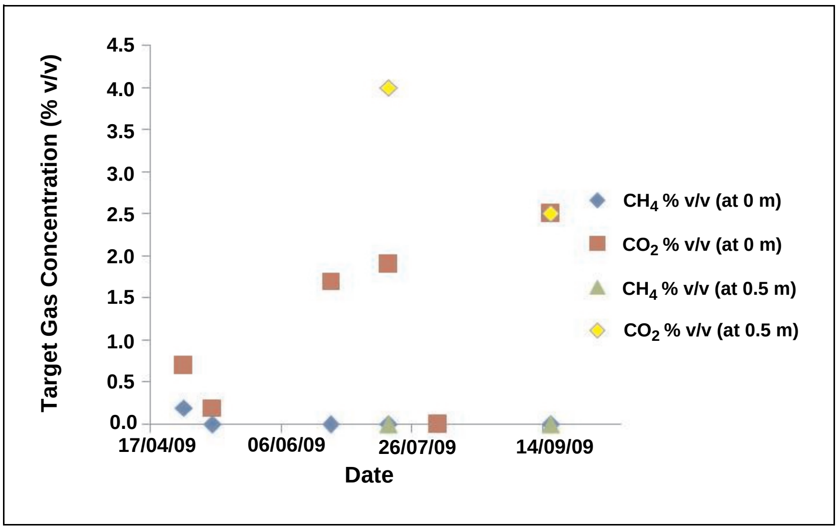


Figure 3.10. Monthly gas measurements taken at borehole well A2 (April–September).

those taken on the same day at the 0.5 m depth using the prototype unit. There is good correlation between the two measurements in September when there was mixing in the borehole well headspace, with the CO_2 component exceeding its threshold limit while, in July, the correlation is not as clear, even though events were identified (see Fig. 3.5). The CO_2 component at both depths exceeded the threshold limit but not by the same amount.

3.3 Conclusions

In conclusion, it can be seen that the Smart Landfill unit (Prototype IV) has had great practical impact on the management of greenhouse gas emissions from a landfill site. It can be a means to identify events on a site and/or to monitor the effects of gas migration when the extraction routine is changed to remedy the situation. It has been clearly seen that monitoring the landfill gas migration once per month is insufficient to accurately monitor the events on the site, and that the management is dramatically improved, and more accurate and informative information is generated by using the prototype autonomous sensing platform. Additionally, taking the measurements from the top of the borehole well does not give an accurate representation of the actual concentration of the migrated gas components. These results demonstrate clearly the value of using the prototype unit and the improved sampling protocol employed.

4 Overall Conclusions and Recommendations

From the work described in this report, the following conclusions have been drawn regarding lateral landfill gas migration on a landfill site and the management of this migration to the perimeter of the site.

1. The dynamics of CO_2/CH_4 (greenhouse) gas generation and migration within landfill sites, and their distribution into borehole wells are complex, and cannot be tracked or modelled adequately through a single monthly measurement. This study's on-site deployments have shown that significant events can build up and decline rapidly, and may be completely missed by a monthly sampling regime.

2. Sampling at the top of the borehole well (as is the current practice) will lead to significant underestimations of the true levels of these gases present. This means that the levels of greenhouse gases in landfill sites are very likely to be grossly underestimated, and management practices correspondingly cannot be efficient.

3. Sampling at lower depths in the headspace leads to much more reproducible data that are likely to be much more representative of the true levels of CO_2/CH_4 in the vicinity of the borehole well.

4. For active sampling (i.e. pumped) and continuous monitoring of the efficiency of the gas management system, recycling of the sample back into the borehole well appears to be a viable sampling method which does not appear to have an adverse effect on the headspace gas composition in the short term, compared with disturbance caused by non-return extraction from the headspace. However, for compliance monitoring, returning of the sample to the borehole well headspace should not be used without further investigation.

5. Accurate modelling and optimum management of CO_2/CH_4 generation and migration will require monitoring at multiple boreholes. It has been shown that remedial actions taken to reduce excessive levels of gases can lead to an upsurge of gas levels at other locations due to the unpredictable nature of gas dynamics across landfill sites.

The authors make the following recommendations for the sampling protocol:

1. For continuous monitoring of the efficiency of the gas management system, the extracted sample should be recycled back into the borehole well during measurements.

2. The sample should be extracted from a depth within the borehole well headspace and not from the top of the borehole well. The depth will be dependent on the water table and headspace depth within the borehole well, but 0.5–1.0 m would appear to be a reasonable compromise for most situations.

3. An extraction time of 3 min should be sufficient to get a steady-state measurement from the headspace and take a representative sample.

4. Sampling should take place more frequently. Sampling once per month means that a great number of events on the site can be missed. In the studies described in this report, twice-daily sampling was employed and this appeared to be sufficiently frequent to capture the dynamics of gas generation and migration within the chosen landfill site.

Through this project, a gas monitoring platform capable of extracting, measuring and communicating the concentrations of CO_2 and CH_4 present to a web database was successfully realised and validated. To provide frequent, reliable monitoring of landfill gas migration to perimeter borehole wells, the following criteria need to be attained. The unit needs to:

- Be fully autonomous and capable of functioning for several months unattended;

- Be capable of extracting a gas sample from a borehole well headspace independently of personnel;
- Be able to relay the data in near real time to a base station accessible via a web-based interface or mobile phone; and
- Have sensors with a range capable of adequately monitoring gas events accurately at all times.

The platform developed here meets these criteria, and it provides a powerful, customised tool for effective management of landfill site gases. The effectiveness of this unit has been recognised by the site management team at the trial site, and the data gathered have been used to improve the gas management system on-site.

Additionally, the authors strongly recommend that a pilot study should be carried out by the EPA using 10 of these autonomous devices over three to five sites to demonstrate the need and value for this type of sampling on Irish landfill sites. This would greatly assist improvement of site management procedures for controlling gas emissions, while also providing a means for the EPA to track compliance with legislation by site operators. Further, the authors believe that if this recommendation is acted upon, Ireland could rapidly become the leading country for developing such instrumentation and standards, and the resulting technology and improved management practices could be deployed and implemented globally. This represents a significant opportunity to enhance Ireland’s status as a leader in the development of emerging sensor systems for environmental monitoring.

It should be further noted that the autonomous sensor platform developed can be easily adapted for either monitoring the same gases in other applications, or fitted with gas sensors for other target species, such as sulfur oxides (SO_x), nitrogen oxides (NO_x), H_2S, CO, volatile organic compounds (VOCs), etc. The research team is in the process of completing several short demonstrator projects to illustrate the potential of the platform for some of these applications (see www.dcu.ie/chemistry/asg/kiernab/ for details).

At the time of writing, the sensors are still deployed at the landfill site and are actively recording data. The CO_2 levels can be accessed remotely via the web link: http://kspace.cdvp.dcu.ie/public/colum/gasMonitor/.

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Acronyms

ADC	Analog/Digital converter
CAFÉ	Clean Air for Europe Directive
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DCU	Dublin City University
EPA	Environmental Protection Agency
FID	Flame ionisation detection
GC-MS	Gas chromatography–mass spectrometry
GSM	Global system for mobile communications
H_2S	Hydrogen sulfide
IR	Infrared
NH_3	Ammonia
NO_x	Nitrogen oxides
SO_x	Sulfur oxides
VOC	Volatile organic compound

Appendix 1 Project Outputs

Published Papers

Hayes, J., Slater, C., Kiernan, B., Dunphy, C., Guo, W., Lau, K.-T. and Diamond, D., 2007. A wireless sensor network for methane monitoring. *Proceedings of SPIE* **6755:** 675504.

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