Autonomous Greenhouse Gas Measurement System for Analysis of Gas Migration on Landfill Sites

Stephen Beirne, Breda M. Kiernan, Cormac Fay, Colum Foley, Brian Corcoran, Alan F. Smeaton and Dermot Diamond
CLARITY: Centre for Sensor Web Technologies
National Centre for Sensor Research
Dublin City University
Glasnevin, Dublin 9, Ireland
dermot.diamond@dcu.ie

Abstract - **This paper describes the design, development and validation of an autonomous gas sensing platform prototype for monitoring of the greenhouse gases, methane (CH_4) and carbon dioxide (CO_2). The deployment undertaken for validation of the developed prototype monitored landfill gas migration to perimeter borehole wells on a landfill site. Target gas concentrations were captured via infrared gas sensors tuned for each target gas and data reported to an offsite data collection point at 12 hour intervals. This bespoke platform and the accompanying data recording and interface software provide a flexible alternative to the presently employed labor intensive, manual monitoring routines. This successful trial brought about a change in the management of the trial sites gas extraction system.**

Keywords - field deployable, autonomous gas sensor, landfill gases, greenhouse gases, carbon dioxide, methane

I. INTRODUCTION

Landfill gas is produced by the decomposition of biodegradeable waste in an anaerobic environment. The main components of landfill gas are the greenhouse gases, methane (CH_4) and carbon dioxide (CO_2) [1]. Regulated landfill sites are constructed with gas management systems using extraction pipes which are laid under the waste cells prior to the commencement of landfilling activity [2]. As the landfill gases are generated, they are extracted by pumps so that the combustible CH_4 component can be flared off or used as a fuel if its composition is above 50 % [2]. Landfill sites are required to have borehole wells located at their perimeter to permit monitoring of any gas migration through the soil and away from the site [2]. The outlined threshold limit for CH_4 migration is 1.0 % v/v, while the threshold limit for CO_2 is 1.5 % v/v [2]. The amount of gas produced in a closed landfill is difficult to predict and is dependent on a number of factors, including the type of waste degrading in each cell, the temperature, the atmospheric pressure, and the amount of rainfall [3,4].

The current monitoring practice outlined in each site's waste license permit (approved by EPA, Ireland) dictates that monitoring of the perimeter borehole wells must take place once per month and that these measurements must be reported to the appropriate EPA department [2]. If the recorded levels exceed defined thresholds, *i.e.,* 1.0 % v/v for CH_4 and 1.5 % v/v for CO_2, an incident report must be submitted to the Office of Environmental Enforcement (OEE) [2]. At present, the required measurement procedure at the trial landfill site uses a handheld infrared device such as the GA2000 Plus unit, manufactured by Geotechnical Instruments Ltd. The time taken for each borehole well measurement is a period of one minute with gas extracted from the top of the borehole well and vented to atmosphere. This method is labor intensive, requiring an operator to physically travel to every active borehole well on the site, perform the sampling procedure and physically record the average gas concentration reading. Consequently, measurements are taken at extended intervals, typically once per month, and with limited spatial coverage.

We have previously reported the integration of infrared gas sensors into a bespoke platform and demonstrated that the system could be used to manually monitor emissions of the landfill gas components CH_4 and CO_2 from perimeter borehole wells [5]. The unit described herein is a progression upon the previously described system. In contrast to the presently employed manual monitoring, the field validated prototype described here is fully automated, whilst also robust and reliable. It is deployed at the borehole well of interest and automatically takes twice daily measurements from a headspace depth of 1 m from the top of the borehole well prior to relaying the measurement value back to the stakeholder using wireless communications after each sampling cycle.

The prototype unit described here has been deployed and operational for a period in excess of 4 months at an active landfill site. The field validation data show that the gas concentration limits for migrated gas can be significantly exceeded within the described monthly monitoring interval, and that this can go unnoticed between the current monthly monitoring regimes leading to unwanted and undocumented fugitive emissions of landfill gases. Moreover, by making small changes to the gas extraction routine on-site, using this much more regular information, landfill personnel can more effectively control the build-up of perimeter gas, leading to much more efficient flaring of the gas and better control of the entire site operation. From these results, it is clear that in order

The authors would like to thank the funding bodies for their support of this work –Environmental Protection Agency, Ireland under grant 2005-AIC-MS-43-M4 and SFI under grant 07/CE/I1147.

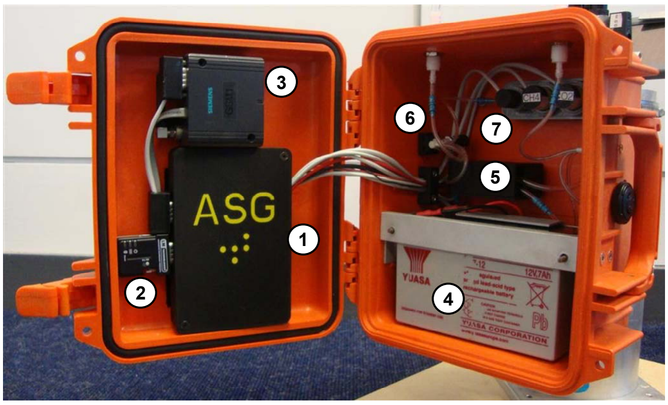

Figure 1. Annotated representation of an assembled autonomous landfill gas monitoring platform. (1) Control board, (2) Bluetooth module, (3) GSM module, (4) Battery, (5) Extraction pump, (6) Inlet/Outlet selection valves, (7) Sample chamber.

to more accurately control and manage gas emissions, it is essential to dramatically increase the rate at which perimeter borehole well headspaces are sampled from the currently employed once per month to twice per day (a 60-fold increase). This is only practical through the adoption of an autonomous wireless sensor network based on devices like the developed platform described in this paper.

II. Gas Sensing Platform

A. *General System Setup*

System components were packaged within a robust protective housing suitable for deployment in outdoor environments (Peli Case Model 1300) as shown in Fig. 1. The system components are outlined below and discussed in more detail throughout subsequent sections.

The sampling operation was controlled by a custom built microcontroller board (1). The power source (4), gas flow management (5,6), gas sampling (7) and communication (1,2) components were all connected to the controller board to achieve a successful autonomous sampling procedure. The power supply for the unit was a 12V 7Ah lead acid battery. At present, this power source has sustained the system for 7 weeks at a sampling frequency of two sample cycles per day (approximately 100 separate sample cycles). The application requires that gas be introduced into the system from two separate sources (ambient air and gas headspace) and removed from the system via two independent exhaust points. To achieve this, 3/2 way latching solenoid valves (Lee Products Ltd. LHLA0531211H) were included to select the required port to draw sample gas from or exhaust sampled gas to. An SKC Grabair pump (SKC Inc. 222-2301) was used to draw sample gas through a custom sampling chamber at a flow rate of 0.6 L/min. A total of four sensors were housed within the sample chamber. These were; an IR gas sensor for CO_2 (Dynament Ltd. IRCEL-CO2), an IR gas sensor for CH_4 (Dynament Ltd. IRCEL-CH4), a humidity sensor (Honeywell HIH-4000-001), and a temperature sensor (Thermometrics DKF103N5).

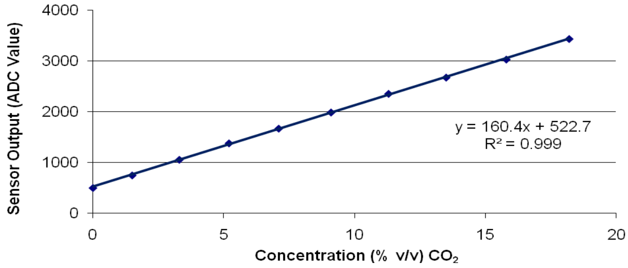

Figure 2. Calibration of CO_2 infrared sensor

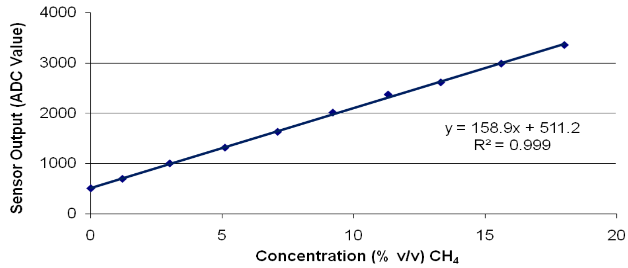

Figure 3. Calibration of CH_4 infrared sensor

Two communication methods were available for data transfer and system control. Short range communication between the system and a laptop computer (for the purpose of laboratory testing and in-field system management) was performed via Bluetooth serial communication. Autonomous communication of harvested data to a remote base-station was achieved via a GSM communication module. These data are statistically represented and sent in SMS format to a central base-station.

B. *Infra-Red Gas Sensors*

Infra-red gas sensors with a Ø 20 mm form factor were sourced from Dynament Ltd. (www.dynament.com). The measurement range of both sensors was 0 - 20 % v/v of their respective target gases, CO_2 and CH_4. The analog output of the sensors over their measurement range was 0 – 2.5 V. The sensor output was connected to individual 12-bit ADC inputs of the MSP430 microcontroller. Calibration of the sensors was conducted to determine the relationship between recorded ADC values and specific gas concentrations.

The CO_2 and CH_4 infra-red gas sensors were calibrated in triplicate against a calibration gas, sourced from Scott Specialty Gases, containing concentrations of the target gases in the range 0 - 50 % v/v with a nitrogen balance. The percentage gas concentration was managed via mass flow controllers for both the target gas and a diluent gas (compressed air). The GA2000 unit (an industry standard infrared handheld device manufactured by Geotechnical Instruments) was used to verify the accuracy of the gas dilutions.

The chosen sensor was placed in a calibration chamber. The target gas at the chosen concentration moved through this chamber at a flow rate of 0.6 L/min past the sensors and then

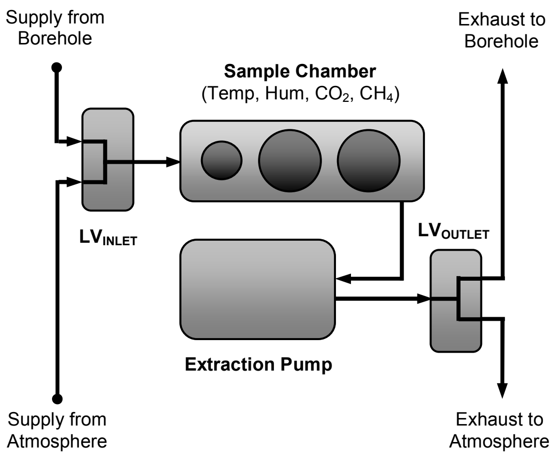

Figure 4. Block diagram of gas management system elements, indicating gas supply and exhaust ports, latching 3/2 way control valves (LV), custom sample chamber housing sensors, and gas extraction pump.

through the GA2000 Plus unit for gas concentration verification. The ADC values from the sensors were captured via Hyperterminal on a laptop computer. Calibration graphs for the CO_2 and CH_4 IR gas sensors are presented in Fig. 2 and Fig. 3 respectively. As expected, the 10 point calibration graphs of both commercial sensors show a linear relationship between ADC value and gas concentration with a standard deviation of less than 2 %. These data were used to directly convert the output value of the sensor to a percentage gas concentration.

Another aspect of these sensors which needed to be evaluated was their reliability over time. After the prototype had completed the 4 month validation trial, the sensors were reassessed and it was found that the CO_2 sensor had a 1.3 % drift from the original calibration, while the drift for the CH_4 sensor from the original calibration was 1.6 %. This proved the reliability of the sensors after an extended period in the field, making them an excellent choice for the monitoring units.

C. *System Operation*

The system operated on a fixed sampling routine, automatically initiated at twelve hour intervals. It should be noted that for this initial long-term field deployment trial the sampling routine had not been optimized for energy efficiency. The sampling routine was configured to ensure that a representative gas sample was extracted from the borehole well and that the sample chamber was completely purged, with ambient air, before and after the introduction of the target sample gas into the system.

The 9 minute sampling routine, with reference to Fig. 4, was carried out in the following manner. Ambient air, taken from the "Atmosphere Supply" port, was drawn through the sample chamber for a period of 3 minutes and exhausted through the "Atmosphere Exhaust" port. This portion of the routine provided a baseline gas concentration measurement. The system inlet source was then switched to the "Borehole Supply" port and the outlet switched to the "Borehole Exhaust" port and landfill gas extracted for a further period of 3 minutes. During this portion of the routine concentration data for the two target gases within the borehole well were captured. To conclude the sampling routine, the valve states were switched so that ambient air was used for a final fixed period of 3 minutes to purge any remaining greenhouse gases from the sampling chamber.

D. *Control Circuitry*

The system's operation was managed by a custom design controller board and code using an ultra low power (MSP430F449) microcontroller (Texas Instruments). The circuitry (in collaboration with code) was designed to switch power to components, harvest sensor values, store data and communicate these data back to a relevant stakeholder with appropriate timing.

Each component was supplied with correct voltage levels using fixed LDO voltage regulators (LP2985A-33DBVTE4, LP2992IM5-5.0/NOPB), supplying 3.3 V or 5 V where appropriate. Power was switched to these components using transistors (NXP - BSR14, FDV304P – PMOSFET, IRLML2502PBF – NMOSFET) and IO ports of the MSP430. Signal lines from all four sensors and battery level were first conditioned and sampled using the 12-bit ADC functionality on the MSP430. The ADC core was powered down when not in use to conserve power. As a backup, all harvested sensor values were stored on a 2 Mbit flash memory chip (M25P20-VMN6P). During the sampling routine, the sensors were sampled every 3 seconds and stored on chip allowing over 200 sample cycles to be saved. The microcontroller allowed for two communication ports; the first (UART1) was used for bench testing and local user communication via Bluetooth, while the second (UART2) allowed the system to send SMS texts using the GSM module.

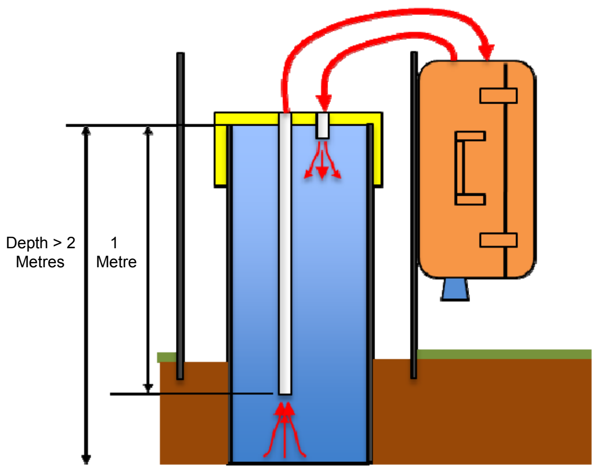

Figure 5. Cross sectional representation of system deployment detailing target gas extraction and return points within borehole well.

E. Gas Extraction Strategy

Previous studies have found that the ingress of ambient air at the top of the borehole well cap during a sampling procedure acts to dilute the sample composition, due to incomplete sealing of the borehole well cap, leading to inconsistent and misleading readings [6,7]. To address the issue of dilution of the sample by ambient air ingress, a modified borehole well cap was fabricated with two connection points. This allowed for gas to be extracted from a headspace depth of 1m by means of a Ø 8 mm pipe and, once analyzed, returned to the top of the borehole well, minimizing emission of greenhouse gases from the unit to atmosphere and dilution of the borehole headspace contents by ingress of air. This arrangement, Fig. 5, was a direct replacement for the standard Ø 62 mm borehole well cap, and, therefore, once a validation trial had been completed, allowed for the original borehole well cap to be replaced.

III. Data Communication and Visualisation

A. Bluetooth Communications

The Bluetooth module (LM Technologies LM048) allowed the device to wirelessly communicate data within a local area of up to 100 m. During bad weather conditions it was desirable to maintain the water proof seal of the system's housing. To facilitate connectivity to the system without having to expose the internals to external weather conditions, the Bluetooth device could be activated via an external toggle switch (IP67 rated). Users could communicate with the module to obtain complete sensor data sets from over 200 previous sample cycles, saved to flash memory. In addition, the module was interchangeable with other radios with an RS232 or UART connection, allowing the device to comply with other wireless networks in the future.

B. GSM Communications

A GSM module (Siemens MC35iT) allowed for communication of data over the GSM network. Statistical representation of the sample data were compiled and transmitted to a GSM receiver (MC35iT) connected to a database server PC. A custom designed Java program was compiled for communication to the GSM receiver module. Incoming SMS data were parsed upon arrival and forwarded to relevant gas and system data sections of a dedicated storage database.

C. Database

A MySQL database was setup to host continuing and past datasets from multiple active devices. The following steps took place upon arrival of a new text message. A Java program (using Javax.comm library) parsed every new text, identified the source from the contact phone number, extracted the sampled data along with the device's battery level and finally placed the data onto the database. Conversion of data from an ADC representation to relevant concentration units (% v/v) took place at this point based on calibration data (as discussed in Section II). Email alerts were sent to stakeholders and all

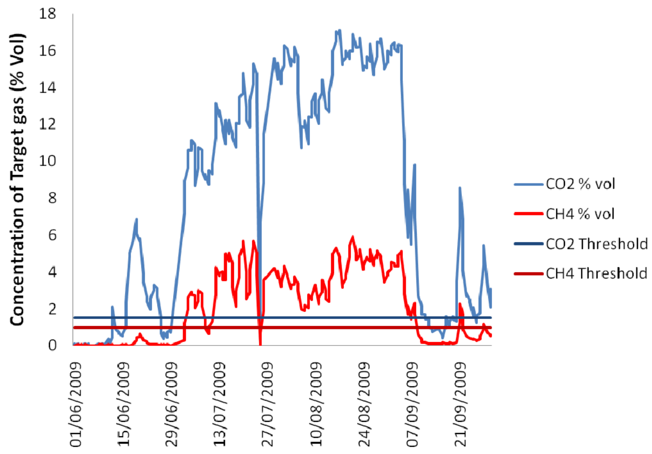

Figure 6. Recorded gas concentration data over the 4 month period of 1st Jun '09 to 30th Sep '09 with threshold limits of 1.5 % v/v for CO_2 and 1.0 % v/v for CH_4 also indicated.

incoming data were emailed to a dedicated email account for backup purposes.

D. Web interface

All present and historical sampled data were captured from the MySQL database and displayed online as a web application, powered by Timepedia Chronoscope. This feature enabled authorities and site personnel to view near real time gas concentration data remotely via their web browser. For security reasons actual gas concentration readings were not publicly accessible. However, non-converted data were accessible via,

http://kspace.cdvp.dcu.ie/public/colum/gasMonitor/.

IV. Deployment Site

The deployment site was in the north east of Ireland. The site had one closed cell and was actively receiving waste. Landfill gas was extracted to flare for the site, and there were 6 perimeter borehole wells to allow compliance monitoring on the site.

V. Results

This prototype has been deployed at an active landfill site for a period of 4 months, during which time it has continued to successfully report gas concentration data from its assigned borehole well, Fig. 6. For the purpose of this results section and to emphasize the benefit of this system, a subset of these data corresponding to a one month period, June '09, Fig. 7, will be discussed. Over this deployment period, it can be seen that the measurements for CH_4 gas remain below the threshold limit of 1.0 % v/v at all times. However, the recorded CO_2 concentration level varies over the duration of the data presented and also exceeds the threshold limit (1.5 % v/v) for extensive periods. Data collected by the autonomous platform were periodically (on a once per week basis) verified by onsite personnel using their calibrated handheld measuring instrument (GA2000Plus).

A. *One Month Data Subset*

Three distinct events can be seen over this period, Fig. 7. For the first 2 weeks of the deployment both the CH_4 and the CO_2 measurements were almost at baseline levels; considerably lower than their threshold limits. However, in early June additional soil cover was added to a closed cell adjacent to the trial borehole well and this led to complications for the site which will be described in the following paragraphs.

On June 12th, Event 1 took place whereby the CO_2 concentration exceeded the threshold limit. Through consultation with the site operators it was identified that, there had been an unexpected gas build up that occurred due to the additional soil cover that had been put in place. Prior to this it had been possible for gas generated within the cell to escape to atmosphere through the top of the inadequately covered cell. The site operators addressed the gas build up by increasing the extraction flow rate on the morning of June 13th. This action is visible in the data as the concentration of the CO_2 component returned below the threshold limit. The component concentration did not fall to the negligible level that had previously been recorded, but did stay below the threshold limit until June 16th.

Event 2 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. This event was also attributed to insufficient gas extraction from the site, resulting from the increased soil cover that was applied to the landfill cell. This event was more prolonged than Event 1 and the maximum CO_2 concentration recorded by the autonomous gas monitor was 6.88 % v/v. After approximately 3 days, the CO_2 gas concentration began to return towards the threshold limit. The remedial work to achieve this reduction was to again increase the extraction rate from the monitored area of the landfill site.

The final event within this subset of data identified an increase in CO_2 concentration to a level of approximately 3.5 % v/v, which occurred on June 25th. This event was the result of a partial blockage of an underground gas extraction pipe. The blockage restricted the volume of gas extraction and caused an increase of gas migration towards the sampling point. 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 all 3 cases, data provided by the system assisted the site operators in first identifying that there was an issue on-site and subsequently allowed them to monitor the effectiveness of their remedial measures.

B. *Four Month Trial Data*

The deployment continued for an additional three months. Mean, minimum and maximum concentration data, for both gas components over the total four month trial period, extracted from the data presented in Fig. 6, are presented in Table I. The data clearly indicate that during the trial period there were significant problems with gas build up at the particular borehole well under investigation. As shown in Fig. 7, the CH_4 component concentration was consistently recorded as below the threshold limit of 1.0 % v/v. The mean CH_4 concentration

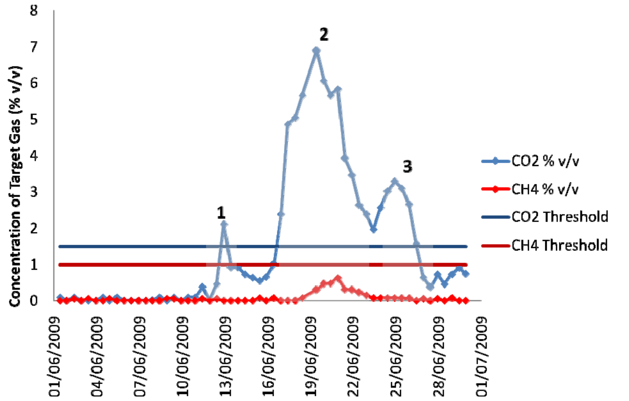

Figure 7. Recorded gas concentration data for Jun '09 with threshold limits of 1.5 % v/v for CO_2 and 1.0 % v/v for CH_4 also indicated.

was 0.08 % v/v, while the maximum was 0.63 % v/v, occurring during Event 2. However, as previously discussed, a number of recorded events occurred where the CO_2 concentration level exceeded the defined threshold limit. In fact, the mean CO_2 concentration for the month of June exceeded the limit, having a value of 1.52 % v/v.

The results of the captured data during the subsequent three months show that the magnitude of gas build up, for both CO_2 and CH_4 within the borehole well headspace, was persistently above the respective threshold limits. The maximum concentration recorded for CO_2 was 17.13 % v/v, occurring in August '09. The maximum for CH_4 was recorded in the same month, at a level of 5.70 % v/v. It is clear from the presented data that the on-site gas management protocols were not effective at maintaining greenhouse gas emissions below their threshold limits.

TABLE I. MONTHLY GAS PERCENTAGE CONCENTRATION

Month	Recorded Gas Concentrations			
	Target Gas (% v/v)	*Mean*	*Min*	*Max*
June '09	CO_2	1.52	0.01	6.88
	CH_4	0.08	0.00	0.63
July '09	CO_2	11.39	0.01	15.60
	CH_4	3.11	0.00	5.70
August '09	CO_2	14.90	10.75	17.13
	CH_4	3.88	1.89	5.92
September '09	CO_2	4.94	0.43	16.46
	CH_4	1.24	0.12	5.11

These results give an indication of the frequency of events which can occur in any one month, but can only be identified and quantified through continuous monitoring. The results tabulated in Table I show the variability of data that can occur over each month. In the case of this particular landfill site, the variability is severe, and issues on the site arising for insufficient extraction capability are evident. This leads us to believe that taking measurements once per month is inadequate to provide a realistic description of landfill gas migration and that it is likely that events on this site and other sites are regularly going unrecorded.

By August, and due to the high temporal resolution data available to the site operators as a result of this trial, it was evident that employed practices were not successful in rectifying the inadequate gas extraction rate that was leading to gas build up on-site. It was identified that additional underground extraction points were necessary so that more effective extraction to the flare could be undertaken. When the field validation trial ended, the additional borehole wells and extraction points were added. Implementation of a modified site management protocol employing these improved capabilities led to a significant improvement in the control of site gas emissions.

VI. CONCLUSIONS

This four month validation trial has shown that a monitoring frequency of once per month is inadequate to give an accurate representation of the dynamics of gas production and extraction on a landfill site. There is conclusive evidence that significant events are being missed.

Accurate twice-daily measurements, available through the system presented in this paper and easily accessible to on-site personnel, allow informed decisions to be made without delay. This leads to a more optimized, efficient and better managed site with dramatically improved capability to monitor and control greenhouse gas emissions.

REFERENCES

[1] E. Aitchison, "Methane generation from UK landfill sites and its use as an energy resource", Energy Convers. Manage., vol. 37, issue 6-8, pp. 1111-1116, 1996

[2] “Landfill Manuals – Landfill Monitoring”, 2nd edition, 2003, Environmental Protection Agency, Ireland

[3] M. Christophersen, P. Kjeldsen, “Factors governing lateral gas migration and subsequent emissions in soil adajacent to an old landill”, in Proceedings of Intercontinental Landfill Research Symposium, 11-13 Dec. 2000, Lulea University of Technology, Lulea, Sweden

[4] “Guidance on monitoring landfill gas surface emissions”, 2004, Environment Agency, UK.

[5] B. M. Kiernan, C. Fay, S. Beirne and D. Diamond, "Development of an Autonomous Greenhouse Gas Monitoring System", in Proceedings of World Academy of Science, Engineering and Technology, vol. 34, pp. 153-157, Venice, Italy, October 29-31, 2008

[6] B. M. Kiernan, S. Beirne, C. Fay and D. Diamond, “Measurement of Representative Landfill Gas Migration Samples at Landfill Perimeters: A Case Study” in Proceedings Twenty-Fourth International Conference on Solid Waste Technology and Management, pp. 941-952, Philadelphia, PA, USA, March 15 - 18, 2009

[7] U. Boltze and M. H. de Freitas, “Monitoring Gas Emissions from Landfill Sites”, Waste Manage. Res., vol. 15, pp. 463-476, 1997