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Improved methodology to assess modification and completion of landfill gas management in the aftercare period

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ABSTRACT

Municipal solid waste landfills represent the dominant option for waste disposal in many parts of the world. While some countries have greatly reduced their reliance on landfills, there remain thousands of landfills that require aftercare. The development of cost-effective strategies for landfill aftercare is in society's interest to protect human health and the environment and to prevent the emergence of landfills with exhausted aftercare funding. The Evaluation of Post-Closure Care (EPCC) methodology is a performance-based approach in which landfill performance is assessed in four modules including leachate, gas, groundwater, and final cover. In the methodology, the objective is to evaluate landfill performance to determine when aftercare monitoring and maintenance can be reduced or possibly eliminated. This study presents an improved gas module for the methodology. While the original version of the module focused narrowly on regulatory requirements for control of methane migration, the improved gas module also considers best available control technology for landfill gas in terms of greenhouse gas emissions, air quality, and emissions of odoriferous compounds. The improved module emphasizes the reduction or elimination of fugitive methane by considering the methane oxidation capacity of the cover system. The module also allows for the installation of biologically active covers or other features designed to enhance methane oxidation. A methane emissions model, CALMIM, was used to assist with an assessment of the methane oxidation capacity of landfill covers.

1. Introduction

Landfills represent the dominant option for non-hazardous solid waste or municipal solid waste (MSW) disposal in many parts of the world. Laner et al. (2012) reported that 54% of MSW generated in the US was landfilled in 2008 and the corresponding figures were 70% in Australia, 77% in Greece, 55% in the UK, and 51% in Finland. In contrast, landfilling accounted for less than 5% of MSW management in 2008 in Germany, the Netherlands, Sweden, Denmark, and Austria (Eurostat, 2010). While the use of landfills is decreasing in many parts of the world, there are nonetheless thousands of closed landfills and many more that will close over the next 10–30 years. For example, there were about 1800 MSW landfills reported to be operating in the US in 2008, down from 6300 in 1990 (USEPA, 2009). Similarly, the number of operating MSW landfills in Germany decreased from 560 in 1993 to 330 in 2000 (BMU, 2006). In the UK, more than 2000 MSW landfills were operating in April 2004, but by December 2009 only 465 remained in operation (Environment Agency, 2010). Thus, even in countries that have greatly reduced their reliance on landfills, there are thousands of landfills that require aftercare (post-closure care). This leads to the question of appropriate levels of aftercare and when aftercare can be reduced or terminated.

The development of cost-effective strategies for landfill aftercare is in society's interest for several reasons. First, funding accrual mechanisms currently in place do not typically consider the potential for aftercare periods in excess of a specific time (e.g., 30 years). If necessary, reform of the current time-based systems would be most effective if changes were made while landfills are still in operation and accruing funds. Second, appropriate management of existing aftercare funds is critical to provide proper protection of human health and the environment (HHE), the financial health of landfill owners, and to prevent the emergence of landfills with exhausted aftercare funding.

Recently, Laner et al. (2012) reviewed three approaches that can be applied to the long-term management of closed municipal solid

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waste landfills. The approaches were described as: (1) target value; (2) impact/risk assessment; and (3) performance based. In a performance-based approach to long-term management of closed MSW landfills, information on landfill performance is used to determine when the landfill poses an acceptable risk to the surrounding environment. The evaluation is site-specific and provides guidance on a sequential reduction of aftercare activities that may, if warranted by performance data, ultimately lead to aftercare completion. There have been several descriptions of performance-based approaches including work by Morris and Barlaz (2011), Sizirici et al. (2011), and van Vossen (2010). The focus of this manuscript is on an improvement to the Evaluation of Post-Closure Care (EPCC) Methodology described by Morris and Barlaz (2011).

The EPCC methodology considers landfill performance in four modules including leachate, gas, groundwater, and final cover. The methodology seeks to provide long-term stewardship of landfills by assessing current and future impacts/risks to the environment based on the evaluation of "functional stability." Functional stability defines a closed landfill that does not present an unacceptable threat to HHE in the absence of aftercare, though some remaining level of control to protect the cover may be required (Morris and Barlaz, 2011). Site-specific landfill performance is the basis for making decisions on maintaining, extending, reducing, or modifying aftercare activities consistent with a predefined end-use condition. Once a change in aftercare is implemented, the owner is expected to verify no adverse effect by "confirmation" monitoring followed by "surveillance" monitoring at a decreasing frequency. Monitoring procedures also identify high and low level trigger conditions requiring an immediate response to resolve a condition. While the concept of a performance-based approach to aftercare has been considered in several countries (Laner et al., 2012), to the authors' knowledge no country has adopted a formal regulation or policy of the nature proposed here. However, hypothetical but realistic case studies have documented the benefits of a performance-based approach (Morris and Barlaz, 2011).

When initially developed, the gas module focused on a quantitative evaluation of potential threats posed by the migration of explosive gas (methane) as a result of modification or elimination of gas controls or monitoring. The objective of this paper is to describe an improvement to the gas module to include quantitative evaluation of control of methane emissions and qualitative screening for the potential for non-compliance issues or impacts due to GHG emissions, air quality concerns, and odors. Particular focus is given to evaluation of methane oxidation in a landfill cover as a strategy for gas control. Examples are provided to illustrate how a new model to estimate methane emissions can be incorporated into the gas module to consider the methane oxidation capacity of a landfill cover as function of climate.

2. Revised EPCC methodology gas module

The objective of the gas module is to provide a procedure by which to evaluate modification or elimination of an existing gas collection system (GCS). When initially developed in 2006, the gas module focused on quantifying potential threats to HHE posed by methane migration as a result of modification or elimination of the GCS and/or migration monitoring system. To this end, the module provided qualitative screening criteria to evaluate whether the existing GCS could be modified or shut down without causing methane migration impacts. In cases where it remained unclear whether or not a proposed modification was suitable, the module provided guidance on whether a more detailed engineering and/or environmental risk evaluation was required (Morris and Barlaz, 2011). In recent years, it has become clear that it is necessary to broaden the gas module's range of application (Morris et al., 2009). The module has been expanded to include quantitative evaluation of gas management and monitoring requirements for control of methane emissions and qualitative screening for potential non-compliance concerns due to emissions of non-methane organic compounds (NMOC), hazardous air pollutants (HAPs), hydrogen sulfide (H_2S), and other odoriferous compounds. Evaluation of revisions to an existing GCS would include a number of interrelated factors: (1) the end-use strategy for the landfill property; (2) the age and size of the landfill; (3) the current gas collection rate; (4) the design of the existing GCS; (5) the proposed GCS modification; (6) cover system properties; (7) climatic conditions; (8) geologic and other site-specific conditions; (9) the nature and proximity of receptors to potential gas impacts; and (10) governing regulations. If modification of a hitherto effective GCS is to be successful, the extent to which future (post-modification) conditions at the landfill are likely to differ from current conditions needs to be well defined. Once GCS changes are implemented, the effect of the changes must be monitored to confirm the continued absence of threat to HHE until quasi steady-state conditions are established.

Evaluations in the revised module are performed in three sub-modules. In initiating an evaluation using the revised gas module, it is assumed that an active GCS with forced gas flow under applied vacuum to a combustion control device (CCD) such as a flare or engine is in place. Potential GCS modifications therefore consist of scaling back from fully active gas control to a semi-passive or passive system that may feature non-combustion control devices for methane oxidation such as biovents, biowindows, or, in the absence of a geomembrane layer in the cover structure, a biocover (Scheutz et al., 2009). Future reevaluations, or initial evaluations at sites where the GCS already comprises semi-passive or passive systems, may use the module to evaluate further modifications to gas controls or monitoring systems. In these cases, the evaluation would start further down the process or skip certain steps as described below.

2.1. Sub-module 1 – prerequisites and planning

The purpose of this sub-module is to ensure that data are available and prerequisites can be met before embarking on more detailed analyses (Fig. 1). It is important from the outset to consider the end use of the landfill, as this will assist in orienting the evaluation in terms of the long-term plans for the property and the performance requirements for the landfill unit from other EPCC methodology modules. For example, leachate management is generally predicated on an assumed level of cap integrity and infiltration control; therefore, modification of the cover system for long-term passive gas control cannot be considered independently of this need for cover performance (Morris and Barlaz, 2011). Consideration of factors outside the gas module may also help govern the choice of an intermediate GCS where complete shut down and elimination of all gas control (passive venting) is not appropriate.

Sub-module 1 specifies the data required to complete an evaluation. A minimum of 3 years of monthly methane flow data is recommended, calculated as average total monthly gas flow to the CCD multiplied by the methane concentration. As discussed later in relation to sub-module 2, this quantity of data is necessary to infer some statistical certainty regarding whether methane flow is stable or trending downward. The requirement to provide monthly data, and awareness that the site will be in a better position if there is minimal fluctuation between monthly readings, should incentivize optimal operation of the GCS in this regard, although it is recognized that seasonal climatic factors may lead to variability in measured gas flow. For planning purposes, the methane flow rate should be estimated from models such as LandGEM (USEPA, 2005) or similar models, taking account of site-specific factors where possible (De la Cruz and Barlaz, 2010). This should help

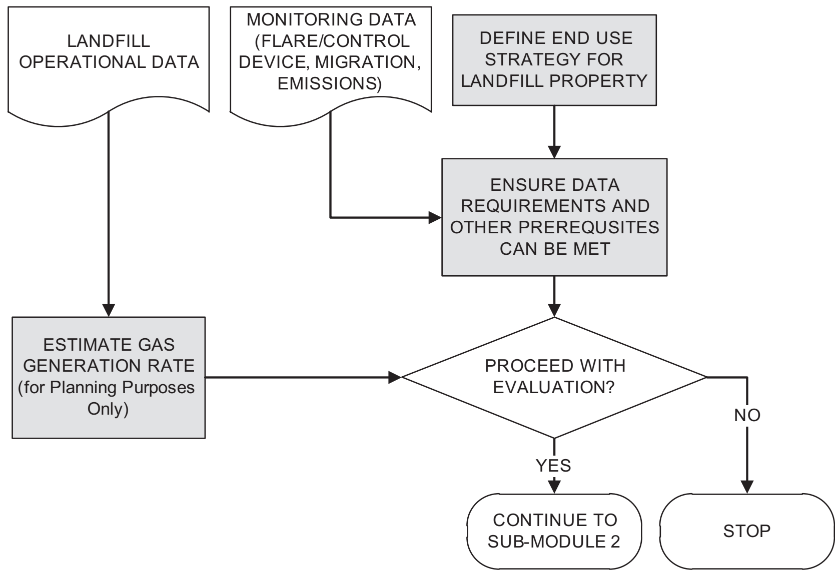

Fig. 1. Flow logic for sub-module 1 of EPCC gas module.

assess the future time at which the measured methane flow rate may be below certain threshold values as discussed under sub-module 2. Sub-module 1 also provides guidance on the assembly of national or site-specific standards and specifications which will be needed for comparisons during subsequent evaluations to modify or eliminate the existing GCS. Standards may be related to: (1) methane migration control (e.g., maximum concentrations of methane allowed in the vadose zone at the landfill point of compliance); and/or (2) allowable emissions of methane, other GHGs, NMOC, HAPs, H_2S, and/or other odoriferous compounds. If methane migration or emission control standards do not exist (i.e., it can be documented that compliance with any such standards is not required under site permit conditions), then all subsequent steps related to demonstrating compliance with standards under modified gas controls may be skipped. Specifications for best available control technology (BACT) for gas control at the subject landfill should also be assembled if applicable. Again, if it can be documented that control of gas to a minimal BACT specification is not required under site permit conditions, then all subsequent steps related to demonstrating compliance with BACT specifications under modified gas controls may be skipped. In some cases, a *de minimus* gas flow rate representing the limitation for specific BACT gas controls may be specified, such as a practical lower-bound cutoff gas flow rate for effective flare operation. Often, however, BACT as a limiting factor for gas control is implied in national standards or permit conditions, but no guidance on what actually constitutes BACT is provided. In this case, it is recommended that the USEPA's long-standing five-step BACT determination process be used (Cit. in USEPA, 2011a): (1) identify available control technologies; (2) eliminate those technically infeasible on a site-specific basis; (3) evaluate and rank remaining controls based on environmental effectiveness; (4) evaluate cost effectiveness of controls; and (5) select BACT. A state of the practice review of BACT for GHG control at landfills is provided in USEPA (2011b). In addition, the Irish EPA provides guidance on selecting BACT for gas control at landfills with low residual gas levels, including the use of non-combustion technologies such as methane oxidation covers and biofilters (EPA, 2011).

As a condition for proceeding with an evaluation in the gas module, no current compliance issues related to surface emissions or methane migration should be evident at the landfill. Previous compliance issues that have been satisfactorily mitigated do not necessarily disqualify a site from proceeding, but the fact that compliance has been an issue in the past should be considered. It is recommended that an assessment of current compliance be based on methane migration and/or surface emission monitoring data reported for the most recent 12-month period in full compliance with conditions for monitoring under the site permit. If either monitoring program is not required under the site permit, then the absence of this data does not represent failure of this criterion. However, the absence of such data should potentially temper the extent of GCS modifications considered. Further, it should be recognized that the absence of a monitoring probe network will restrict the ability to perform confirmation monitoring for gas migration following GCS modification. In some cases, installation of a targeted migration monitoring network might be required if the long-term end use of the property or the surroundings are sensitive to this aspect of reduced gas control.

The intent of requiring a high level of GCS performance data and highly compliant monitoring programs as a prerequisite is to give the operator the opportunity to remedy any issues (e.g., cracks in the cover surface) before proceeding to an evaluation of GCS modification. The data requirements also serve to emphasize to the operator the importance of long-term data collection and how such data can be useful as part of reduced gas management requirements after closure. It is recognized that setting comprehensive compliance and performance standards for data collection as a prerequisite for use of the gas module may mean operators will instead prefer to continue operation of the existing CCD for as long as possible, particularly if this represents a low level of cost and maintenance, and migration or emissions monitoring are not required. The cost of installing passive flares, biofilters, biowindows, or enhanced oxidative biocovers as intermediate steps to complete elimination of gas management may also limit enthusiasm for proactive use of the gas module. Nevertheless, this consideration is consistent with the conservative intent of the module. If continuation of current levels of gas management is considered preferable to modifying gas management based on demonstrable levels of performance, then the operator may simply elect to continue operating the current GCS.

2.2. Sub-module 2 – evaluate gas flow and emissions

The purpose of this sub-module is to evaluate gas generation and emissions relative to allowable emission standards and/or

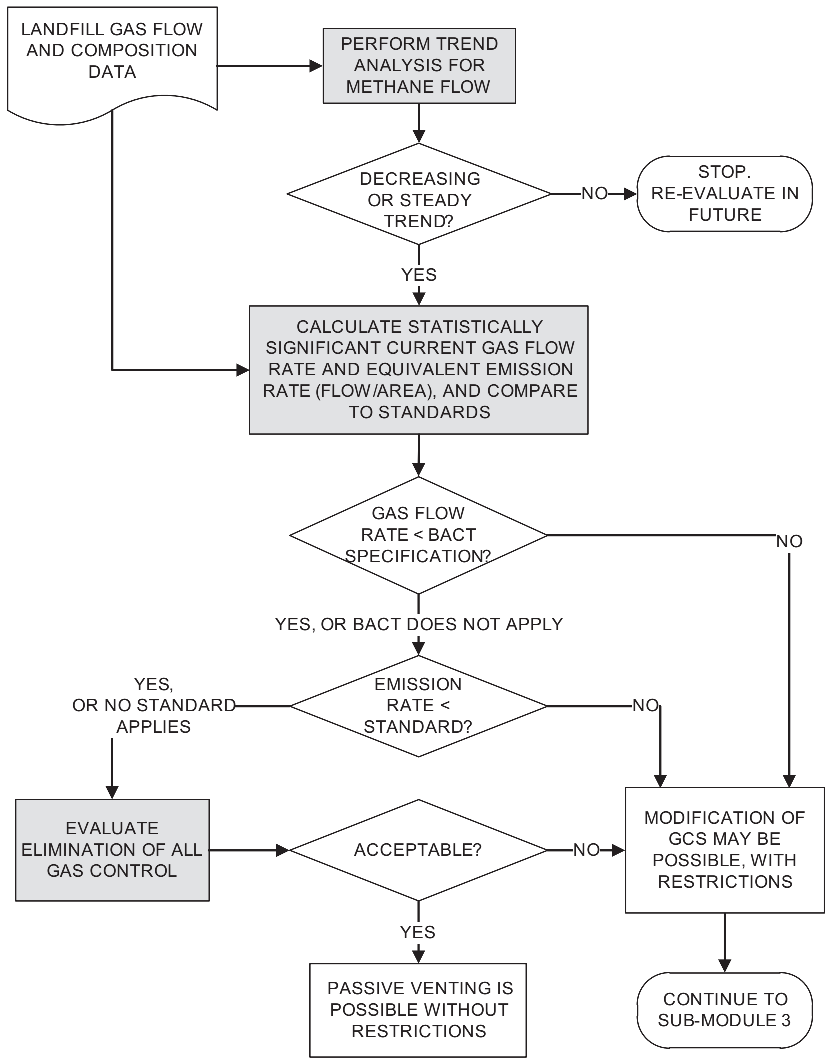

Fig. 2. Flow logic for sub-module 2 of EPCC gas module.

BACT specifications for gas control (Fig. 2). The sub-module provides a path that may lead to elimination of active gas control and transition to passive venting or, more commonly, to alternative gas controls. In the first evaluative step, a decreasing or steady trend in methane flow data should be demonstrated. It is recommended that Sen's test be used, which is a nonparametric estimator of trend which is robust to outliers, missing data, and non-detects, and provides both an estimate of the rate of change and a test of the null hypothesis of no trend (Sen, 1968). Given the minimum 3-year data requirement and the conservative nature of the test, this statistical demonstration provides a high level of confidence that methane generation at the landfill is on a stable or downward trend. If such a trend can be demonstrated, further evaluations can proceed. If not, the landfill is not in a position to evaluate modifying the existing GCS and the operator should maintain the GCS, continue all gas-related aftercare activities, and focus on data collection until reevaluation at some future time is warranted.

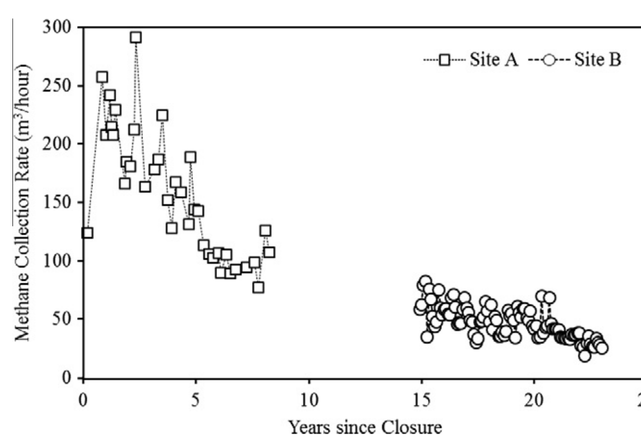

Fig. 3. Methane collection data in the aftercare period at two landfills.

By way of example, methane collection data available for the aftercare period at two sites are presented in Fig. 3. Site A, located in northern France, was operated from 1980 through 2002 and contains about 875,000 Mg of MSW in two units with a combined area of 13.5 ha. The cover system at Site A comprises a low permeability geosynthetic clay liner (GCL) overlying a 1 m compacted clay barrier layer. Site B is located in Delaware, USA, was operated from 1980 through 1988 and contains about 645,000 Mg of MSW in a single 10.9 ha unit (Morris et al., 2003). The cover system at Site B comprises 60 cm of relatively permeable sandy silt. Although neither site collected methane data prior to 2003, the dataset is much more complete at Site B (98 datum) than at Site A (38 datum). The methane flow rate at Site B is also more consistent, suggesting that review of GCS operating procedures might be warranted at Site A. Analysis of the two datasets indicates that the methane collection rate is decreasing at both sites. In accordance with the above conditions, an evaluation could therefore proceed at both sites.

Next, a statistically significant current methane flow rate based on a 95% upper confidence limit of the mean (UCL) should be calculated. In brief, the UCL is used to compare a variable dataset (in this case, methane flow) to an absolute standard; if the UCL is below the standard there is 95% confidence that the true flow is below the standard. Use of this and similar statistical procedures to help make environmental impact decisions is common (e.g., USEPA, 1988). Again by way of example, a UCL was calculated from the methane data for Sites A and B. Using the entire dataset, the UCL calculated for Site A was 106.8 m^3 CH_4/h while that for Site B was 35.6 m^3 CH_4/h. Once calculated, the UCL should be compared to the allowable emission rate under BACT specifications for a gas control device. If the calculated flow rate is less than the allowable rate, or if there are no BACT specifications, then the evaluation can proceed (i.e., elimination of gas control has not been ruled out). If the calculated flow rate is not less than the allowable rate, then gas control cannot be eliminated; however, the operator should decide based on operational experience and performance data for the current CCD if the current methane flow rate can consistently support the current CCD, or whether a modified or alternative GCS would be better suited for gas control at the site.

As examples of BACT specifications, guidance issued in France (Bour et al., 2005) and Ireland (EPA, 2011) suggests a methane flow of 25 m^3/h as the practical threshold for operating a standard flare. According to Bour et al. (2005), there is unlikely to be an unacceptable risk associated with eliminating a flare below this flow rate and passive treatment methods should be investigated. Of course, such general statements must be evaluated in the context of site-specific conditions. Similarly, the Irish EPA (2011) advises that low-calorific flares, other specialized thermal technologies, or non-combustion treatment methods are needed below this threshold. Interestingly, the Irish guidance also suggests that biofiltration technologies can constitute BACT at methane flows up to 100 m^3/h, which is higher than the rate at which flow to the flare becomes a limiting factor. Based on these examples, the flare is likely to remain the BACT for some time at Site A which is only 8 years post-closure. In contrast, Site B, which is nearly 23 years post-closure, would be close to needing an alternative control technology as the methane flow rate will no longer support a standard flare.

As a final calculation in sub-module 2, a surface emission rate should be estimated for the landfill by dividing the previously calculated UCL methane flow rate by the total area of the landfill cover, and converting from volume to mass to obtain a value in terms of g/(m^2-day), the most common unit for expressing surface fluxes. It is recognized that surface emissions are generally not uniformly distributed (especially at sites with geomembrane covers) and that gas collection rates do not represent 100% of generated gas, although relatively high gas collection efficiencies can be expected for a landfill with a well-maintained final cover in place (Barlaz et al., 2009). To attempt to account for preferential flow and the presence of some uncollected gas, it is proposed that the calculated surface emission rate be doubled to yield a final equivalent emission rate (EER) for the landfill. This doubling is arbitrary, but is intended to steer the operator toward making a conservative decision on whether to modify the GCS. Ultimately, confirmation monitoring performed after making a change to a GCS will be critical in demonstrating that surface emissions and gas migration control remains in compliance with standards. Using the previous two example sites, the EER for Sites A and B is 27.0 and 11.2 g/(m^2-day), respectively. If the EER is less than the allowable emissions as defined under country-specific regulations, or if there are no emission standards, then the evaluation has shown that the current combustion control device (CCD) can be deactivated. For example, Austrian regulations (BMLFUW, 2008) establish methane emission limit values for temporary soil-capped landfills at 13.7 g/(m^2-day) as a mean value and 27.4 g/(m^2-day) as a "hotspot" maximum. Guidance in France (Bour et al., 2005) suggests methane emission values suitable for uncontrolled passive treatment in cover soils of 8.6–17.2 g/(m^2-day). Thus, Site A would not meet emission standards in the absence of gas control but Site B would. It should be noted that the thickness of waste in both sites is rather low (<10 m on average). The likelihood of the calculated EER meeting emission standards may be higher at shallower landfills because the emission flux is lower as the volume of waste per unit surface area is lower. In all cases, it is also important to ascertain the precise definition of terms used in emission standards (e.g., "hotspot" in the Austrian guidance or "uncontrolled passive treatment" in the French guidance).

Sites that meet emission standards without gas control can immediately transition to passive venting if it can also be demonstrated that an unacceptable impact due to methane migration would not be expected under passive venting conditions. The recommended procedure for assessing methane migration impacts is discussed in Morris and Barlaz (2011). Similarly, if national standards or site-specific conditions for control of emissions of other gases or odorous compounds exist, these should also be evaluated prior to eliminating gas controls. If the EER is not less than the allowable emissions (such as at Site A), then active gas control cannot be eliminated; however, the operator should decide based on operational experience and CCD performance whether the current methane flow rate can consistently support the current CCD or if another, perhaps simpler, GCS would be better suited for gas control at the site. National guidance should be consulted if available. For example, a methane emission threshold of 120 g/(m^2-day) has been proposed in Ireland to assess when passive gas treatment/control by oxidation in soil covers may be feasible (EPA, 2011).

If deactivation of the current CCD and transition to passive venting is acceptable and desired by the operator, this may be done. In this context, passive venting means allowing direct flow of gas through conduits in the cover system (e.g., wells with disassembled wellheads) without any oxidation or flow retardation occurring. Each vent location would thereafter need to be considered an emission hotspot and a time-limited program of confirmation monitoring should be performed to demonstrate that both surficial and hotspot emissions are acceptable. If deactivation of the current CCD and transition to passive venting is not acceptable (e.g., because some level of gas control is required to mitigate potential migration or odor issues), or is acceptable but not desired (e.g., because the operator would like to avoid establishing long-term conditions for inspecting and maintaining passive vents), the operator should again decide if the current methane flow rate can consistently support the current CCD or if another GCS would be more suitable. Suitable alternatives that could be investigated include utilizing the oxidation capacity of an all-soil cover system (Chanton et al., 2011) or other means of non-combustive gas control (Gebert and Gröngröft, 2005).

2.3. Sub-module 3 – evaluate alternative gas controls

Entry to this sub-module means that: (1) the calculated methane flow rate or EER does not meet applicable standards; or (2) methane migration, odor, or other gas-related issues could be of concern if the current CCD were deactivated and gas control transitioned to passive venting only. However, entry to this sub-module also means there is a desire on the part of the operator to find an alternative mode of gas control that represents a reduction in cost, scope, fre-

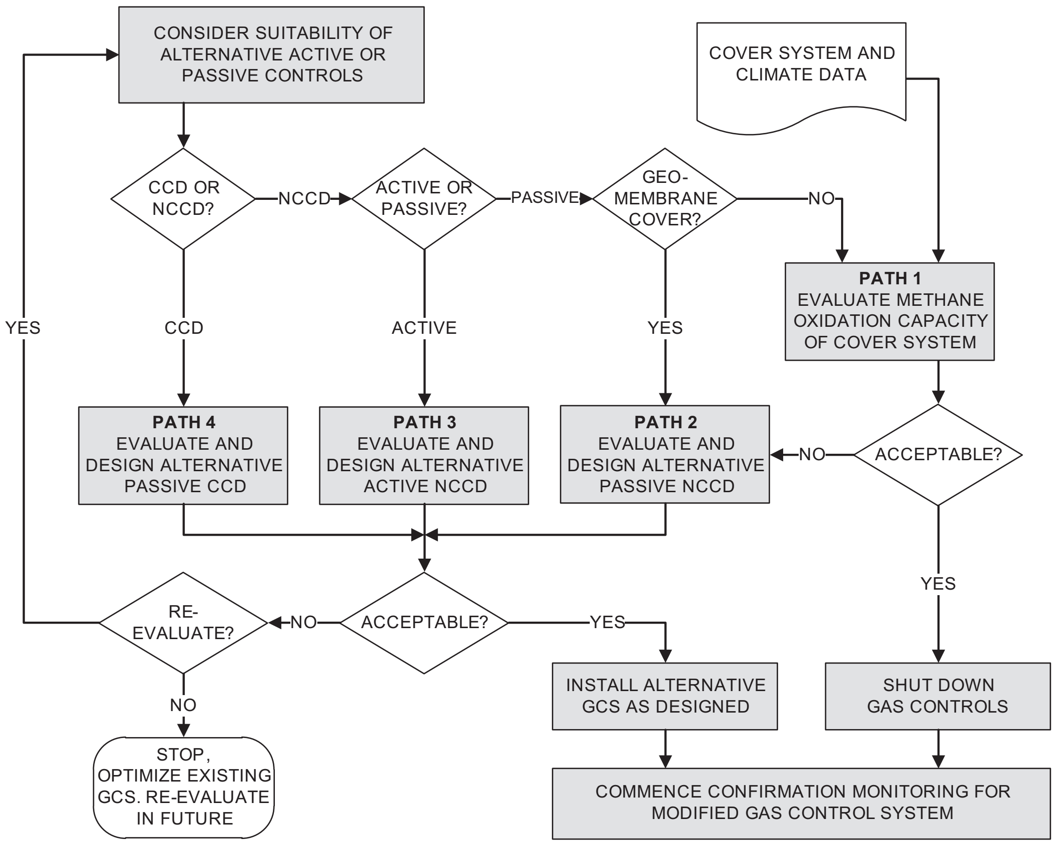

Fig. 4. Flow logic for sub-module 3 of EPCC gas module. Note: CCD = combustion control device, NCCD = non-combustion control device.

quency, and/or intensity of monitoring, inspection, or maintenance activities relative to the current GCS. The purpose of this sub-module is therefore to evaluate whether an alternative GCS would be appropriate based on site-specific characteristics and performance data (Fig. 4). There are several factors that drive consideration of the suitability of an alternative GCS and ultimately dictate the path taken through this sub-module, including the type of gas control device that will be considered (i.e., combustion or non-combustion), whether the device will be operated actively or passively, and the type of cover in place (i.e., all-soil vs. geomembrane). These factors will be influenced by: (1) the magnitude of residual methane generation and emission rates; (2) climatic conditions; (3) buffers to potential receptors and other site-specific factors; and (4) the cost, level of effort, and permitting complexity likely to be associated with implementing an alternative GCS as an intermediate step towards the presumptive goal of eliminating all gas control at the landfill. The route of entry from the previous sub-module should be useful in providing full or partial indication of these factors. Finally, screening criteria developed to define and evaluate a future gas management strategy (Morris and Barlaz, 2011) can be used to facilitate the decision process, particularly with regard to less obvious issues such as whether to opt for a passive rather than active gas control device. These criteria include: (1) the extent of buffer zone between the landfill and the property boundary and/or offsite receptors; (2) the sensitivity of potential receptors; (3) the remaining gas generation potential (as percent of total) or current collection rate (as percent of peak); (4) the type of cover system in place; (5) the type of liner system in place; (6) subsurface geologic conditions; and (7) the proposed end use for the landfill.

The decision process in the sub-module will direct the operator down one of four paths shown in Fig. 4 to complete the evaluation. Following path 1, transition from active gas control to passive gas control can be provided solely by oxidation in the existing all-soil cover system or by installing an enhanced bioactive cover (i.e., a passive non-combustion control device). If path 1 is not an option (generally because a geomembrane cover system has been installed at the landfill), path 2 explores transition from an active CCD to passive gas control using other non-combustion devices such as biovents or biowindows. If path 2 is not an option, path 3 explores the transition from an active CCD to an active non-combustion device such as vacuum extraction of landfill gas to a gas biofilter. Finally, path 4 explores the transition from an active CCD to a passive CCD technology (i.e., passive flaring). As indicated in Fig. 4, although each path is quasi-independent, it is generally possible to move "up" a level of evaluation (path 1 being a special case that is incompatible with a geomembrane cover). In every case, failure to complete a path or change course to another path means that operation of the existing GCS must be continued, along with prescribed aftercare activities, until the Gas Module can be re-evaluated at a future date.

Following path 1, the cover oxidation capacity (COC) should be evaluated based on cover characteristics and climatic conditions and then compared to the EER calculated in sub-module 2. The idea is that when fugitive methane emissions (represented by EER), are less than the soil's capacity to attenuate methane emissions by biological oxidation (represented by COC), then it is permissible to eliminate an active GCS and assume that the cover will provide the sole means of gas control. The operator may assess the oxidation capacity of the existing cover or include proposed enhancements to develop a biocover. A biocover is designed by integrating compost and coarse material into the existing cover system to enhance methane oxidation. Based on long term trials using biocovers in Austria, a recommended design for a robust biocover consists of a 0.5 m gravel gas distribution layer overlain by up to

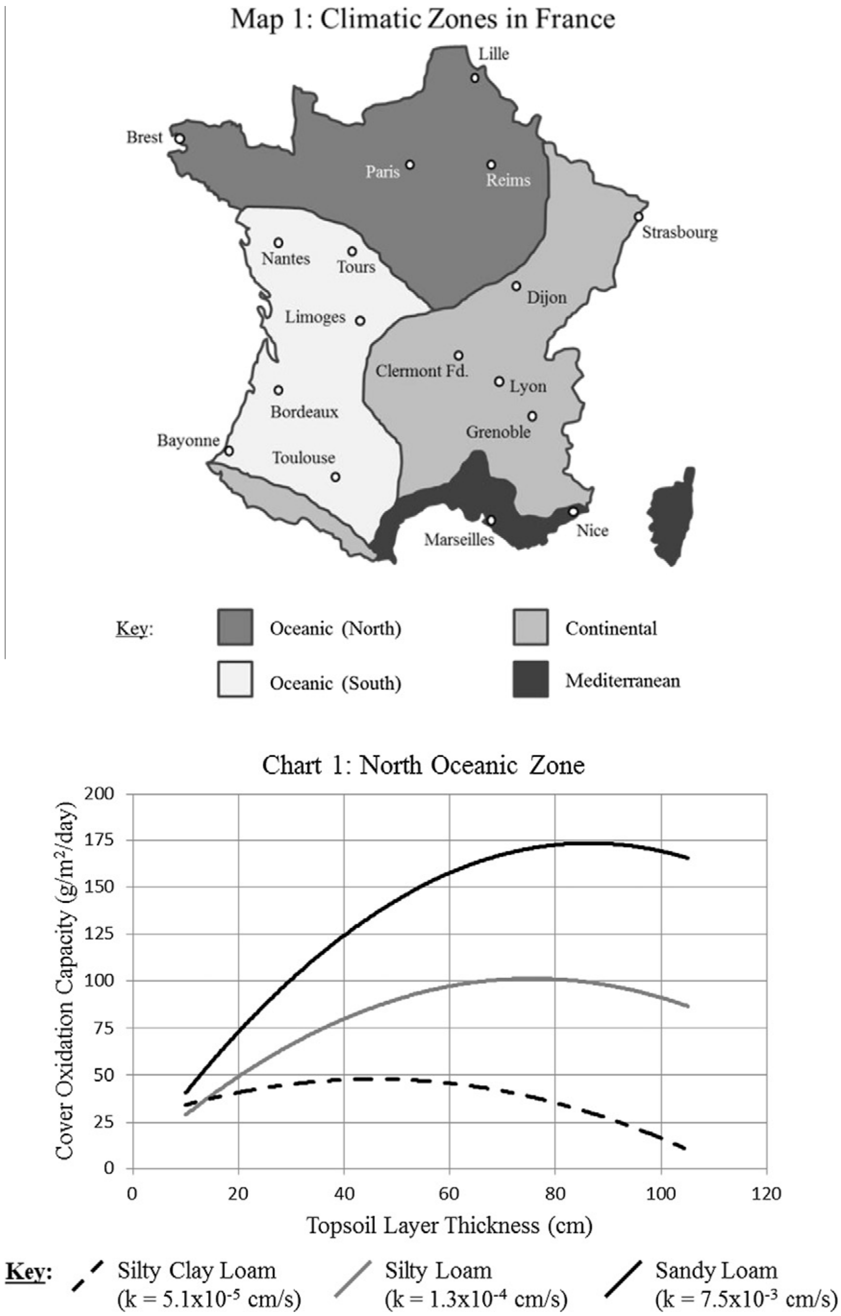

Fig. 5. Simplified illustration of cover oxidation capacity lookup chart application at a landfill in France.

1.2 m of mature, well-structured compost or treated waste substrates (Huber-Humer et al., 2008).

If the COC exceeds the EER, or the EER minus the COC does not exceed the allowable emissions as defined under national or site-specific standards, the current CCD can be deactivated because adequate passive gas control can be provided by the cover soil alone. Fig. 5 illustrates COC estimates for different cover soils in one climate zone in France. As an example, an operator wishing to avoid site-specific modeling at a soil-capped site located in this zone can thus derive a representative COC value from Fig. 5 (note that Fig. 5 illustrates the COC for just one of the four climate zones; separate charts were developed for the other zones). Assuming that Site A (located near Lille) has the same cover construction as Site B (i.e., 60 cm of sandy silt with permeability on the order of 1×10^{-4} cm/s), the two-step procedure requires that a climatic zone for the landfill location is first identified (in this case, North Oceanic). Next, the thickness and soil type representing the top cover soil layer should be defined. For a cover soil thickness of 60 cm and reading off the silty loam curve, the COC is about 95 g/(m^2-day), significantly higher than the EER for Site A of 27.2 g/(m^2-day). Under these conditions, the cover could serve as the sole means of gas control. The public domain software *California Landfill Methane Inventory Model* (CALMIM) was used to develop the charts. Use of the model in this capacity is discussed in the next section.

In general, the purpose of paths 2 and 3 is for a passive/active non-combustion control device (non-CCD) to be designed such that the oxidation capacity of the non-CCD exceeds the EER, or the EER minus the oxidation capacity of the non-CCD does not exceed emission limits. For an active non-CCD design (path 3), the blower should be sized based on the total residual gas flow. If an adequate non-CCD design can be found, the current CCD can be deactivated. Gas cannot be allowed to vent, so any wellhead appurtenances and pipes not used for the NCCD network should be physically removed or blocked. If deactivation of the current CCD and transition to a non-CCD is not found to be acceptable, the operator may review alternative paths for evaluation. Guidance has been published on the design of passive non-CCD systems for landfills, such as biowindows (installed in the cover) or biofilters (installed above the cover), and active non-CCD systems utilizing the landfill's existing network of wells or collector trenches connected under vacuum to a biofilter (Streese and Stegmann, 2003; DECCW, 2010; Yazdani, 2010). In principle, all of these systems direct methane though a porous media (e.g., soil or compost) that offers a gas permeable pore space, adequate surface area, and environmental conditions to promote biological methane oxidation (Huber-Humer et al., 2008). In all cases, even distribution of gas flux into the base of the system, and hence increased methane oxidation efficiency, can be achieved by installing a high permeability gas distribution layer at the bottom (Einola et al., 2009; Jung et al., 2011).

Although quantification of overall methane emission mitigation efficiency is challenging using non-combustion control technologies, various long- and short-term trials at full scale have been reviewed by Scheutz et al. (2009). Reported methane oxidation efficiencies vary over a wide range and are dependent on several different site-specific factors, such as cover type, climatic conditions, and methane loading rate. Overall, experience shows that the most critical control factors concern maintaining a steady loading rate and even spatial distribution of methane across the system. Optimal flow control and process conditions are easier to maintain in active systems. With passive systems, where the gas loading rate is more difficult to control, it is important to conservatively assess the magnitude of methane emissions to be treated so as to limit the amount of methane delivered to the system under peak conditions. Finally, if there is no interest in a non-CCD, the site may transition to passive flaring following path 4 of sub-module 3 if it can be demonstrated that an unacceptable risk of emissions, methane migration, or odor issues is not expected. If national or site-specific standards for emission of methane, other gas constituents, and/or odorous compounds exist, the ability of a passive flare to achieve necessary destruction efficiencies for these compounds should be quantitatively evaluated.

Regardless of the path selected to modify the existing GCS, a time-limited program of confirmation monitoring should be implemented. Confirmation monitoring should include monitoring of surface emissions, methane migration, air quality, and/or odors. Monitoring requirements for the cover should also be defined. Generally, a certain level of cover maintenance is necessary to avoid development of cracks and fissures with associated uncontrolled gas emissions and infiltration, which could potentially lead to higher gas generation rates. Following completion of confirmation monitoring activities at sites with only passive gas controls, confirmation monitoring should transition to surveillance monitoring on a geometrically reducing schedule until the required frequency of a monitoring activity exceeds 4 years, at which point all monitoring for that activity is completed. Sites with active gas controls cannot enter surveillance monitoring. Aftercare activities related to gas control and monitoring can be ended following successful completion of all surveillance monitoring. Any remaining *de minimus* gas-related cover monitoring and maintenance activities can be provided via the cap module (Morris and Barlaz, 2011).

3. Use of CALMIM to estimate cover oxidation capacity

Historically, the assumed 10% allowance for methane oxidation in landfill cover soils is referenced back to the first study which estimated seasonal oxidation at a landfill in New Hampshire, USA (Czepiel et al., 1996). However, recent field scale estimates across a variety of climates have suggested potentially higher average rates of 30–40% oxidation (Chanton et al., 2011), with peak rates in excess of 100% reflecting uptake of atmospheric methane (Bogner et al., 2011). In estimating methane oxidation in cover systems, it is important to note that methane oxidation is controlled by a number of environmental factors, including soil texture, temperature, soil moisture content, methane and oxygen gas supply, vegetation, nutrients, and the potential presence of methanotrophic inhibitors. Thus, it can be assumed that the top soil layer of the cover system will be the layer where most, if not or all, of the methane oxidation takes place (Boeckx et al., 1996). Further, the major mechanisms for transport of methane from the waste through the cover soil to the atmosphere are diffusion and advection. Diffusive transport is caused by a concentration gradient through the soil while advective transport results from pressure gradients induced by wind, changing barometric pressure, or internal pressure build up from gas generation due to waste degradation (Abichou et al., 2006). The rate of gas movement is generally orders of magnitude faster for advection than for diffusion (Williams et al., 1999) and there are several circumstances in closed landfill settings where pressure gradients can develop such that the advection-controlled flux dominates the diffusion-controlled flux; for example, under saturated or low permeability layers (Scheutz et al., 2009).

As previously mentioned in reference to path 1 in sub-module 3, the model selected for estimating COC was the *California Landfill Methane Inventory Model* version 4.2 (CALMIM) as described and field validated by Spokas et al. (2009, 2011) and Spokas and Bogner (2011). CALMIM is a 1-dimensional transport and oxidation model that calculates annual site-specific landfill methane emissions based on the major processes that control emissions: (1) surface area and properties of the cover; (2) the proportion of surface area of each cover type subject to engineered gas recovery; and (3) climatic factors affecting seasonal methane oxidation in each cover type. The driving force for emissions assumed by the model is the methane concentration gradient through each cover type coupled with typical annual soil moisture and temperature variability which control methane transport and microbial methane oxidation over an annual cycle. Climate related factors such as meteorology and soil microclimate are automatically accessed based on the site location and physical properties of the cover materials. CALMIM calculates daily methane emissions for each cover type which are summed to provide an annual total. CALMIM does not rely on a first order model for methane generation based on the mass of waste in place.

CALMIM was considered the best model available at the time of writing as it can be manipulated to estimate cover oxidation capacities given different cover soil and climate conditions. However, the model has a number of limitations. First, the model assumes a static methane concentration gradient through time at the base of the cover and calculates a flux through the soil based on diffusion only, advection is not considered. Second, the model cannot be used to obtain COC directly as it was not developed for this purpose. Rather, to estimate the COC, methane oxidation in CALMIM was turned on and off such that two emission values are returned for a given cover system with the base concentration set to 55% methane: (1) "methane emissions without oxidation," which represents the rate of methane diffusion through the cover system; and (2) "methane emissions with oxidation," which considers net emissions after methane oxidation. Subtracting the latter from the former yields the COC estimate for a given cover.

To develop COC look up charts such as the example in Fig. 5, CALMIM was configured to consider a landfill with only a single soil layer for the final cover. This is necessary because the COC, as calculated here, cannot exceed the rate of methane diffusive flux through the top layer of the cover system. In landfills with a multilayer cover system, as would be typical for a final cap, the diffusive flux to the top layer would be limited by a low permeability layer. Such a low permeability layer would limit the rate of methane diffusion and hence the estimated COC. To overcome this, only the top (surface) layer of the cover system was modeled, such that methane oxidation in the top layer was not limited by slower diffusion through the lower barrier layers. This yields a more representative COC value for the cover system as a whole. Furthermore, the COC represents the maximum methane oxidation rate for the cover scenarios with the same soil "maximum oxidation capacity" (Spokas and Bogner, 2011), which is achieved solely when all conditions for methane oxidation are ideal. Methane oxidation is also controlled by the inward diffusion of oxygen into the cover materials, balanced by the outward diffusion of methane. Therefore, a thinner cover can theoretically possess a higher COC than a thicker cover (Fig. 5) as a function of climate, due to increased oxygen transport through the thinner cover.

Finally, in developing the look up charts, seasonality must be addressed (i.e., oxidation rates are lower in the winter than in the summer). CALMIM calculates hourly surface emission data over a simulated 12-month period. The most conservative approach would thus be to assign COC as the lowest oxidation rate (i.e., highest individual surface emission value) given for an annual cycle. However, this would mean the oxidation rate achieved over the majority of the year was significantly underrepresented. Therefore, in common with many approaches to dealing with environmentally-influenced data (e.g., Sara, 2003), it was decided to assign the COC based on a 10-percentile value obtained from the hourly surface emission data (i.e., the COC value assigned is lower than 90% of the values in the hourly data set). It should be recognized that, consistent with the approach throughout the gas module, the use of modeling is intended only to facilitate planning and steer the operator toward a conservative decision on eliminating the CCD. Ultimately, subsequent confirmation with field monitoring will be required to demonstrate that passive control of surface emissions remains in compliance with regulatory standards.

4. Summary and conclusions

The updated gas module described in this paper demonstrates an analytical framework by which a landfill owner could justify transition from active to passive levels of gas control. A high level of GCS performance data and highly compliant monitoring programs are required as prerequisite conditions to undertaking an analysis. This should give the operator the opportunity to fix any issues (e.g., cracks in the cover surface) before proceeding. While this may give the perception that the module is overly burdensome, such data availability will be to the operator's advantage in the longer-term given that monitoring to confirm the validity of changes made is likely to be required.

When initially developed, the gas module focused on quantitative evaluation of potential threats posed by migration of explosive gas (methane) as a result of modification or elimination of gas controls or monitoring. The module has been expanded to include quantitative evaluation of control of methane emissions and qualitative screening for the potential for non-compliance issues or impacts due to GHG emissions, air quality concerns, and emissions of H_2S or other potentially odoriferous compounds. Using the revised module, a proposed modification to the scale and/or intensity of gas control and/or monitoring can be evaluated based on a demonstration that there would be no increased threat to HHE as a result of the modification. Potential GCS modifications consist of scaling back from a fully active GCS to a semi-passive or passive system featuring non-combustion control devices for methane oxidation such as biovents, biowindows, or biofilters. Particular focus is given to evaluation of cover oxidation as an alternative means of passive gas control. A simplified two-step lookup procedure was developed in which the cover oxidation capacity for different soil cover designs can be read off a chart corresponding to the landfill's climatic conditions. In all cases, the models employed facilitate planning and ultimately confirmation monitoring must be conducted following any modification to existing gas controls to verify that the change does not result in unexpected impacts or emissions.

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