VIKEK
ENVIRONMENTAL
ENGINEERS, LLC

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METHANE GAS GENERATION & RISK MITIGATION ASSESSMENT REPORT

GO EAST LANDFILL

SNOHOMISH COUNTY, WASHINGTON

GO EAST LANDFILL

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LIST OF ACRONYMS

Acronym	Definition
CH4	Methane
CO2	Carbon Dioxide
DOC	Degradable Organic Carbon
DOE	Department of Ecology, Washington State
DPH	Department of Public Health
EH	Environmental Hazard
EPA or USEPA	U.S. Environmental Protection Agency
ESA	Environmental Site Assessment
Ft^3/Mg	Cubic Feet per Megagram
Half-life	Time for half the decomposable component to completely decompose
IPCC	Intergovernmental Panel on Climate Change
k	Rate constant used in landfill gas modeling (1/year)
Lo	Methane generation potential used in landfill gas modeling, m3 methane/Mg of waste
LandGEM	Landfill Gas Emission Model
LEL	Lower Explosive Limit for Methane Gas
LFG	Landfill Gas
M^3/Mg	Cubic Meters per Megagram
MGRA	Methane Gas Generation and Risk Mitigation Assessment
MSW	Municipal Solid Waste
MSWLFs	Municipal Solid Waste Landfills
NMOC	Non Methane Organic Compounds
QA/QC	Quality Assurance /Quality Control
RCRA	Resource Conservation and Recovery Act
RMAE	Risk Mitigation Alternatives Evaluation
USACE	United State Army Corps of Engineers
WE	Work Element

EXECUTIVE SUMMARY

ES 1.0 PURPOSE AND SCOPE

Vikek Environmental Engineers, LLC (Vikek) is pleased to present this *Methane Gas Generation and Risk Mitigation Assessment (MGRA)* Report to support the proposed residential development around the GO EAST landfill. The report documents current and future methane gas generation rates, methane gas risk classification, alternative risk mitigation assessment and recommendations regarding any further actions needed to validate projected methane gas generation rates, and risks mitigation alternatives related to the proposed land use.

This MGRA is completed in accordance with Tasks 5.4*: Complete Methane Gas Generation Modeling; Task 5.5: Complete Qualitative Methane Gas Risk Assessment, and Task 5.7 :Prepare Methane Gas Generation, Risk Assessment and Alternative Analysis Report,* of the related Subconsultant Agreement between PACE Engineers Inc., and Vikek Environmental LLC.

ES 2.0 SUMMARY AND RECOMMENDATIONS

This report documents the findings associated with the MGRA completed for the GO EAST landfill. It has been completed in accordance with best practice for Landfill Gas (LFG) generation modeling and risk assessment.

There are no existing methods for measuring actual methane gas generation, so estimates must be obtained through varied methods. Because there are various variables that influence methane gas generation rates in waste dumps, estimates can vary significantly regardless of method. In the absence of model calibration data, an attempt to define a range of reasonable results, using different scenarios were simulated. To qualitatively evaluate accuracy of the modeling results, a comparison with selected and normalized literature methane gas generation rates for similar wastes, landfills and conditions was made. The outcome of this comparison was used to indicate the most likely methane gas generation rates profile.

The absence of recorded annual site operations data or scale records for material received, entails the inclusion of uncertainties and approximations in the estimation of the methane gas generation potential. The application of the methane gas generation modeling allowed the generation of a range of methane generation potential curves to account for the variability of the methane gas generation.

A calibration of the models would have been needed, for a more accurate application of the model, but the absence of a spatially well-represented methane generation monitoring system or pump test information made this impossible. However, the described approach represents a useful tool and a conservative approach to estimate the lowest, average and highest methane gas generation rates into the future in order to inform the proposed residential development near the landfill site.

ES 2.1 ESTIMATED METHANE GAS GENERATION RATES

On the basis of the four scenarios considered, the estimated methane gas generation rates showed expected variability for simulations based on calculated potential methane gas generation capacity and the USEPA model default values for municipal solid waste landfills (MSWLS) as follows:

- **Results for Calculated Potential Methane Gas Generation Capacity**
    - Annual peak methane generation rates range from 5.*10 ft^3/minute to 9.20 ft^3/minute*
    - Average methane generation rates range from 1.*88 ft^3/minute to 2.01 ft^3/minute*
    - Peak generation rates occurred in 1983, the year of cessation of waste deposition.

- **Results for USEPA Default Potential Methane Gas Generation Capacity**
    - Annual peak methane gas generation rates range from 7.85 *ft^3/minute to 14.16 ft^3/minute*
    - Average annual methane gas generation rates range from 2*.89 ft^3/minute to 3.09 ft^3/minute*
    - Peak generation rates also occurred in 1983, the year of cessation of waste deposition.
- **Results for Methane gas generation since after closure in 1983 to 2112**
    - Average annual methane gas generation ranged from 1.80 *ft3/minute to 1.83 ft3/minute for calculated generation parameters*
    - Average annual methane gas generation ranged from 2.76 *ft3/minute to 2.82 ft3/minute for USEPA default generation parameters*
- **Results for Methane gas generation from 2019 to 2112 (current year to the future)**
    - Average annual methane gas generation ranged from 0.58 *ft3/minute to 1.13 ft3/minute for calculated generation parameters*
    - Average annual methane gas generation ranged from 0.89 *ft3/minute to 1.74 ft3/minute for USEPA default generation parameters.*
- *Decline of average methane gas generation rate* from the peak year in 1983 to 2019 ranged from *44% to 69%* for model results using calculated site - specific parameters.
- Based on the half - life of woodwaste, *100% of the landfilled wood waste should completely decompose between 2007 and 2017f (at 17 years of half- life) and between 2043 and 2053 (at 35 – year half – life).*
- The site *has reached and passed its peak methane gas production period under current conditions.*
- Although there is a potential for some temporary increase in methane generation after the planned capping, this increase is projected to be within the range forecasted by the current study. *Therefore, such potential temporary increase in methane gas generation will not change the continuing decline of any methane gas generation within the site as predicted by this study.*

ES 2.2 COMPARISON OF RESULTS TO PUBLISHED DATA

The model results were compared with literature values for wood waste landfills to evaluate whether modifications to the model assumptions were required. The analysis showed that;

- Methane potential generation capacity for landfilled wood waste materials from published literature varied from averages of *0.30 m^3/Mg to 0.40 m^3/Mg*
- Methane potential generation capacity simulated for the GO EAST landfill biodegradable waste varied from *0.26 m^3/Mg to 0.43 m^3/Mg.*
- Average potential methane generation capacity simulated was 0.342 m^3/Mg and within the range expected for sites with similar waste materials.
- Compared to Municipal Solid Waste Landfills (MSWLFS), wood wastes decompose very slowly even in wet climate. Available, but limited studies indicate that on a per ton basis, wood wastes generate 2 - 30% *less* methane gas.
- Due to the landfill hydrogeologic setting and composition of the waste, there is a likelihood that some portions of the site will remain aerobic, thus keeping methane generation in the predicted post – closure range.

ES 2.3 SPATIAL METHANE GAS DISTRIBUTION AND TREND

According to site exploration and monitoring results recorded during 2009, methane gas was detected at a single location, in the middle of the site, at above regulatory Lower Explosive Limit (LEL). This result, albeit from 2019, combined with the current assessment, and the absence of detections near the property boundary or offsite, provides a clear trend regarding current and future methane gas generation potential at the site. This assessment indicate as follows :

- Significantly declined methane gas generation towards baseline conditions.
- Methane gas generation rate, on average is not expected to increase above current baseline conditions near the property boundaries.

ES 2.4 QUALITATIVE METHANE GAS RISK ASSESSMENT

Based on the conceptual site model and the review of the key risk factors associated with methane gas, Vikek considers that the risk of lateral methane gas migration occurring and causing an unacceptable human health or environmental impact to the surrounding homes is **Low**, while risk to human health and the environment due to vertical methane gas migration is **Unlikely** resulting in an overall risk classification of **Very Low Risk**.

No further methane gas investigation or assessment is warranted, *but appropriate measures should be taken to mitigate the projected low methane gas generation rates.*

This MGRA was completed exclusively for the use of PACE Engineers Inc. to support the planned development of the GO EAST landfill site for residential use. No other party, known or unknown to Vikek is intended as a beneficiary of this report or the information it contains. Third parties use this report at their own risk. Vikek assumes no responsibility for the accuracy of information obtained from, or provided by, third-party sources.

ES 2.5 METHANE GAS MITIGATION ALTERNATIVES EVALUATION

Assessment of nine potential methane gas risk mitigation alternatives indicate as follows:

1. *Dilution/Dispersion with methane gas Monitoring*: In - ground methane gas dispersion coupled with a monitoring program in perimeter probes are the most effective risk mitigation approaches.
2. Installation of *a vertical perimeter barrier with venting trench system or a horizontal barrier (cap) with perimeter venting trench system are the highest ranked methane risk mitigation alternatives* for the site.
3. Based on the projected future methane gas generation rates, *the proposed landfill cap, perimeter dispersion trench , monitoring probes, and home methane gas monitoring system for the Landfill Closure Plan, is a conservative plan, and consistent with the recommendations provided in this MGRA*
4. Vikek recommends, that in addition to the proposed gas monitoring probes around future homes, that *one to* three *additional perimeter monitoring probes be installed directly downstream of the two locations where methane gas was measured in 2009. One probe should be directly downstream while one or two others may be between 200 feet to 500 feet away from it, and installed in accordance with regulatory guidelines and the hydrogeologic conditions at those locations.*

1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE

Vikek Environmental Engineers, LLC (Vikek) is pleased to present this *Methane Gas Generation and Risk Mitigation Assessment (MGRA)* Report to support the proposed residential development around the GO EAST landfill. The report documents current and future methane gas generation rates, methane gas risk classification, alternative risk mitigation assessment and recommendations regarding any necessary further actions.

This MGRA is completed in accordance with Tasks 5.4*: Complete Methane Gas Generation Modeling; Task 5.5: Complete Qualitative Methane Gas Risk Assessment, and Task 5.7:Prepare Methane Gas Generation, Risk Assessment & Alternative Analysis Report,* of the related Subconsultant Agreement between PACE Engineers Inc., and Vikek Environmental LLC.

1.2 SITE LOCATION AND BACKGROUND

1.2.1 Site Location - The GO EAST Landfill site is located at 4330 108th Street SE, Everett, Washington.

1.2.2 Background - The site was operated as an excavation and sand reclamation site from 1969 through 1971. Between 1972 and 1977 the landfill operator (Rekoway) accepted wood waste debris that included partially burned trees and stumps, and concrete solid material that were compacted and placed in sealed cells before the site was closed in 1978. After reopening in 1979 with GO EAST as the Owner/Operator, the site accepted wood waste placed in enclosed cells from 1979 to 1983, after which the landfill ceased all operations.

1.3 METHANE GAS GENERATION ASSESSMENT OBJECTIVE(S) & APPROACH

The key objectives of this assessment are as follows:

- Estimate generation rate(s) of methane gas currently and through a minimum of 3*0 years* from the inception of waste deposition.
- Define existing quantity and extent of methane gas at the site.

The approach taken for this study is as follows:

- Reviewing site conditions and available background information, including waste quantities and composition, landfill type and configuration, and meteorological data for the area.
- Reviewing and analyzing historical and current methane concentration data.
- Estimating methane gas generation rates and potential from the waste site using computer modeling based on available information and related engineering experience.

1.4 METHANE GAS RISK MITIGATION ALTERNATIVES EVALUATION & APPROACH

The key objectives of this evaluation are as follows:

- Performing qualitative risk assessment to identify methane gas risk classification for the site.
- Assess how well the methane gas mitigation alternatives align with project/owner site development objectives.
- Narrow the focus on viable alternatives to be considered for further cost estimating and pre-design.

The approach taken for this study is as follows:

- Summarizing and reviewing mitigation alternatives previously discussed with the Client.
- Reviewing and agreeing on selected evaluation criteria and approach.
- A Strategy Grid method is used for evaluation and ranking the alternatives.

1.5 STUDY LIMITIATIONS

- Vikek relied upon information provided and various assumptions in completing the MGRA. Judgments and analysis are based upon this information and Vikek's experience with landfill systems and Landfill Gas (LFG) generation modeling. **Specific limitations include**:
- The methane gas generation projections have been prepared in accordance with the care and skill generally exercised by reputable LFG professionals, under similar circumstances, in this or similar localities. No other warranty, expressed or implied, is made as to the professional opinions presented herein. Changes in the site property use and conditions (for example, variations in rainfall, waste processing operations, gas extraction or redevelopment) may affect future gas generation at the site.
- Assumptions were made in this MGRA regarding historical waste inflow, in-place waste volume, in-place waste density, waste composition, and organic contents embedded in inert materials (interstitial organic material), based on information available at the time this study was conducted. These assumptions were made in the absence of specific information regarding the dates that various portions of the waste were placed or waste composition records. Because the assumptions were used to estimate the in-place waste mass, waste characteristics and modeling parameters, they have significant impacts on projected future methane gas generation and resulting estimates of alternative mitigation measures.
- Although a pump test helps reduce the uncertainties of predicting methane gas generation rates, it also has limitations. First, the pump test is conducted on only a limited area of the site and the results are assumed to apply to the entire site. Secondly, pump tests can only indicate the quantity of methane during the period of the field test and don't provide any indication of future methane gas potential. There were no pump tests conducted or results available for calibrating the model.
- This MGRA has been conducted exclusively for the use of PACE Engineers Inc. to support the proposed residential site development around the site. No other party, known or unknown is intended as a beneficiary of this report. Third parties use this report at their own risk. Vikek assumes no responsibility for the accuracy of information obtained from, or provided by third-party sources.

1.6 REPORT ORGANIZATION

The remaining sections of this report are organized as follows:

- Section 2.0 presents information collection and data synthesis.
- Section 3.0 identifies key methane gas data and selection used in the models.
- Section 4.0 presents the key methane gas assessment parameters.
- Section 5.0 presents spatial distribution of methane gas
- Section 6.0 presents a methane gas generation estimates
- Section 7.0 presents methane gas qualitative risk assessment & mitigation alternatives
- Section 8.0 presents description of the risk mitigation alternatives evaluation.
- Section 9.0 presents the summary findings and recommendations.
- Section 10.0 lists references for literature cited/ reviewed, and
- Section 11.0 lists and presents the appendices.

2.0 INFORMATION COLLECTION AND DATA SYNTHESIS

This section details the sources and basis for data collection and analysis of, the historical waste quantities, estimated waste characteristics, meteorological data and moisture content.

2.1 HISTORICAL FILL (WASTE) TONNAGE

Exact historical records of waste disposal rates, waste in-place and waste composition is unknown between 1972 and 1979 when the landfill was operated by Rekoway. Historical and in-place waste quantity estimates are developed using the following information provided by PACE Engineers Inc. and Gary East, owners/operators of the landfill from 1979 to 1983 when landfill operations was conducted by GO EAST as owner/operator:

- Since 1972, the site has been operated as a sand and gravel excavation dump, accepting wood, concrete solid materials, wood waste debris, soil/sand, asphalt, and other construction demolition waste.
- The site has a volumetric fill capacity of 255,531 cubic yards.

Based on these assumptions, Vikek estimates that the site contains in-place fill and waste totaling approximately 97,287 tons assuming an average waste in-place density of 761 pounds per cubic yard. Annual waste disposal estimates are illustrated in Figure 2.1 and Appendix Table A-2.1.

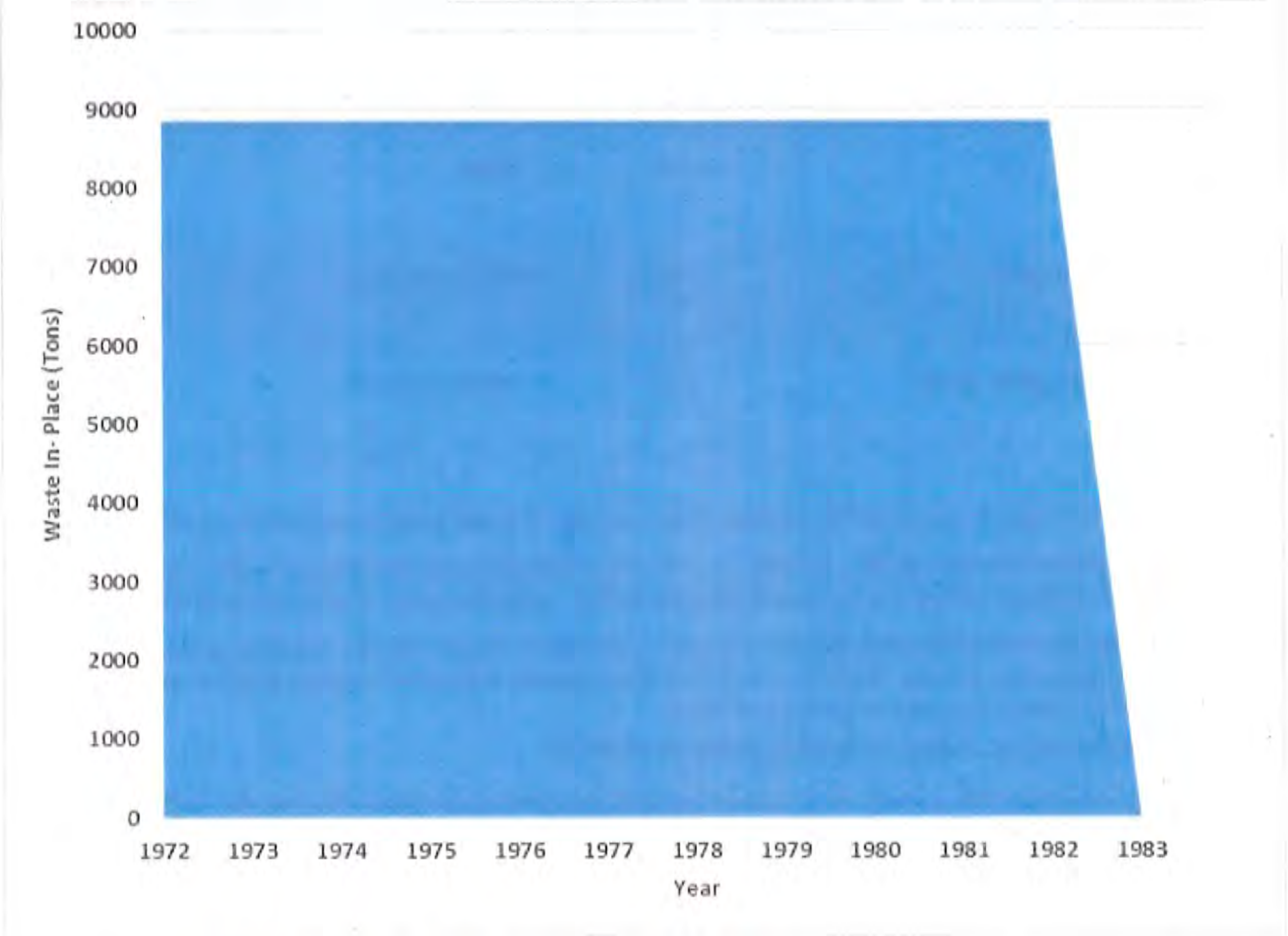

Figure 2.1: Historical Annual Waste Quantity

2.2 WASTE CHARACTERISTICS

An accurate estimate of waste composition is required to predict the methane gas generation potential of a site. The total quantity of methane gas that can be generated from a unit mass of waste is dependent on the fraction of the organic content, because the decomposing organic wastes are the source for all waste gases produced.

Information describing the characteristics of waste in-place was provided by PACE Engineers Inc. for the period, 1979 to 1983. The same waste composition is assumed, based on similarity of permitted operations for the 1972 to 1979 period when the site was operated by Rekoway. The waste composition estimated are therefore based on the following assumptions:

- **1972 - 1979** : 60% wood/demolition debris, 25% native soil/sand, 15% concrete, rock, glass, and asphalt
- **1979 - 1983** : 60%, wood/demolition debris, 25% native soil/sand, 15% concrete, rock, glass, and asphalt
- **Native soil & sand**: Used to cover refuse daily is assumed to contain about 5% of decomposable organics.
- **Asphalt, concrete, rock, glass, metal**: These are assumed to contain very little to zero decomposable organic materials. For the purposes of the MGRA, they are assumed to produce no methane gas.

Table 2.1: Waste Components and Degradability Classification

Waste Component	GO EAST (%)	Degradability Classification
Wood waste	60.0	Slow
Native soil and sand	25.0	Relatively Inert
Concrete, rock, glass, metal	15.0	Relatively Inert

Waste composition and the degradability classes shown in Table 2.1, and result in the following two fractions:

- **Relatively inert fraction (RIF)** – Relatively inert waste include waste materials with little or no degradable organic carbon, such as metal, cement, asphalt, concrete, glass, plastic, soil and dirt, and soils.
- **Slowly decomposable fraction (SDF)** - Slowly decomposable waste includes materials with slower rate such as wood, trees, stumps, organics in soil matrices, organics mixed with asphalt fraction and organics mixed with construction and demolition material.

2.3 METERIOLOGICAL DATA AND MOISTURE CONTENT

The moisture content within a waste site is one of the most important parameters affecting the methane gas generation rate. Moisture provides an aqueous environment necessary for anaerobic processes responsible for methane production, and serves as a medium for transporting nutrients and bacteria drive the decomposition process.

Existing hydrogeological explorations did not provide information on in-waste moisture content, therefore average literature values (wood 30%; inerts 6%; soil 10%) was used to estimate an overall average of 21%. This value was used to estimate dry weights of the in-place waste and modeling parameters.

3.0 METHANE GAS GENERATION PROJECTION APPROACH

There are no existing methods for measuring actual methane gas generation rates, so estimates must be obtained through varied methods. Because there are various variables that influence methane gas generation rates in waste dumps, estimates can vary significantly regardless of method. In the absence of model calibration data, an attempt to define a range of reasonable results, using different scenarios were simulated. To evaluate qualitatively accuracy of the modeling results, a comparison with selected and normalized literature potential methane gas generation potential for similar waste types and conditions is made. The outcome of this comparison is used to suggest the most likely methane gas generation rates.

3.1 METHANE GAS MATHEMATICAL MODELING

After a review of several approaches, *two models* for estimating of methane gas generation quantities selected for this study are; LandGEM version 3.02 developed by the USEPA, and the Intergovernmental Panel on Climate Change (IPCC)s waste model. The use of the IPCC model is limited to application of the recommended equations to estimate the quantity of degradable organic fractions, and the methane generation potential (Lo).

❖ ***USEPA LandGEM***

LandGEM uses the following first-order decomposition rate equation to estimate annual methane gas generation over a time period that is specified by the user.

$$QCH4 = \sum n \sum j \; kL_0 \{Mi/10\} \; e - ^{ktij \; i=1}$$

Where:

- QCH4 = annual methane generation in the year of the calculation (m^3/year)
- i = 1 year time increment
- n = (year of the calculation) - (initial year of waste acceptance)
- j = 0.1 year time increment
- k = methane generation rate (year-1)
- Lo = potential methane generation capacity (m3/Mg)
- Mi = mass of waste accepted in the ith year (Mg)
- tij = age of the jth section of waste mass Mi accepted in the ith year (decimal years, e.g., 3.2 years)

❖ ***IPCC Waste Model***

The IPCC methodology is based on the First Order Decay (FOD) approach. The following modified IPCC equations are used to estimate DOC, Lo and select k values that are then applied to the LandGEM models:

$$K = \sum i, n \; (\%ri * vp)$$

$$Lo = F * DOC * DOCf * MCF * 16/12 * 1000 * 1/0.714$$

Where:

- %ri is the percentage of waste in each category ; vp is the selected decay constant
- MCF is the correction factor for methane
- DOC is the degradable organic carbon (fraction)
- DOCf is the fraction of degradable organic carbon that actually degrades (assimilated)
- F is the fraction of CH4 in the waste gas ; the ratio 16:12 is the stoichiometric constant
- 0.714 is the density of methane in kg/m3
- 1000 converts methane kg to Mg

4.0 METHANE GAS ASSESSMENT PARAMTER SELECTION

The following section describes the selection of MGRA model input parameters and assumptions:

- ***Waste Disposal Rates*** - The historical filling rates used in the model are shown in Figure 2.1.
- ***Waste Characteristics*** - Based on visual site inspections and existing site material characterizations, the soil/sand material is assumed to contain low quantity of degradable waste components – lower organic content (LC) of 5% entrained in the soil/sand (interstitial organics) is used for the methane gas generation simulations. These input values are presented Appendix Figures A- 4.1 through A- 4.3.
- ***Methane Gas Content of the LFG gas*** – Methane content (% v/v) varies in measured gas concentrations from 0% to 8%. Because the methane content of LFG fluctuates over time, it is standard industry practice to normalize the methane content to 50 percent for the purposes of LFG modeling. However, because of the extremely low levels of methane gas measured, and lack of subsequent detections elsewhere, and because methane gas concentrations tend to double after the application of impermeable cover, an average concentration of 20% is used in this study.
- ***Methane Gas Generation Rate Constant [k]*** - The decay rate constant is a function of refuse moisture content, nutrient availability, pH, and temperature. Research has shown that the half - life of landfilled woodwaste ranges from 17 to 35 years, and that the generation rate is an exponential function of the half-life. Therefore, two corresponding values of methane gas generation rate is calculated and used for the MGRA as outlined in Table 4.1.
- ***Methane Gas Generation Potential [Lo]*** - The methane gas generation potential or capacity is the total amount of methane gas that a unit mass of refuse will produce given enough time. The Lo is a function of the organic content of the waste. Two values of Lo - 78 m^3/Mg and 120 m^3/Mg for the Low organic content waste – 78 m^3/Mg is the estimated value, and 120 m^3/Mg is the default USEPA LandGEM value approved for use at landfills without data, and for regulatory permitting.
- ***Degradable Organic Carbon (DOC)*** – Are derived from estimated degradable waste components.
- ***Methane Correction Factor [MCF]*** – At unmanaged disposal sites, aerobic conditions will exist in a significant portion of the waste mass. To account for the portion of disposed waste which does not attain anaerobic conditions and produce LFG, the IPCC recommends that for uncategorized sites, to apply a methane correction factor (MCF) of 0.6. An MCF of 0.6 is used to estimate the Lo values.
- ***Methane Gas Generation Period*** – The simulation was conducted for the LandGEM 130- year period.

Table 4.1: Waste Characterization, Methane Generation Potential and Rate

Waste Characterization	Methane Generation Potential Lo (m^3 methane/Mg)	Methane Generation Rate, K (1/yr.)
Relatively Inert	0	0.00
Slowly Decomposable	78 (site –specific)	0.02, 0.04
Slowly Decomposable	120 (LandGEM default value)	0.02, 0.04

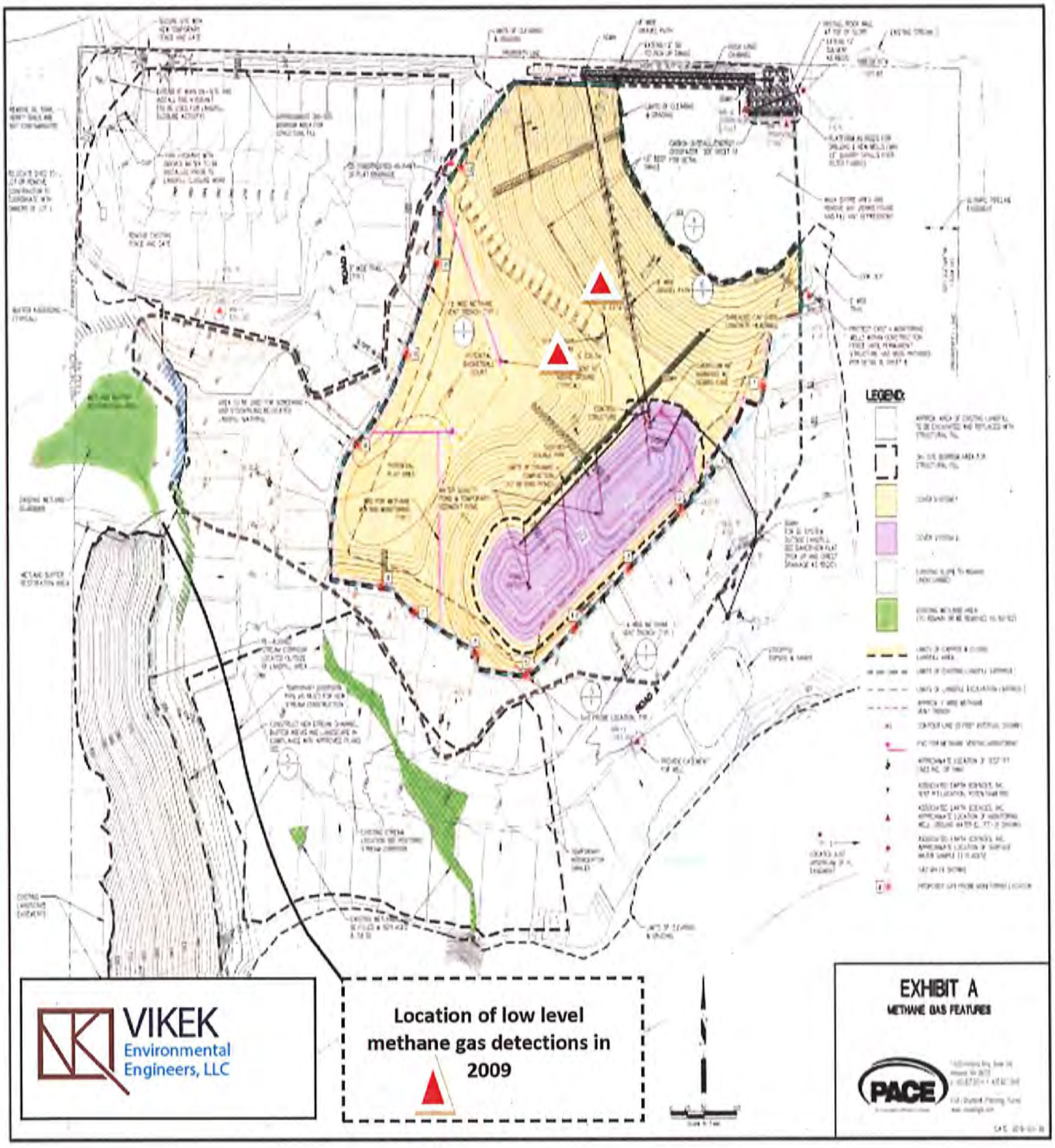

Figure 5.2: Locations of Methane Gas Detections in 2009

5.0 SPATIAL METHANE GAS DISTRIBUTION

The approximate locations of methane gas levels measured in 2009 by AESI, Inc. (2011, 2013) are shown in Figure 5.2. These monitoring results indicate that, methane gas is present in only two locations, GS - 3 and GS – 5. The measured levels varied from 0% to 8.4 % at GS- 3, and from 0% to 2.7% at GS – 5. Only two measurements…6.4% and 8.4% at GS- 3 exceeded the regulatory thresholds in 2009. These results are presented in Figures 5.1 and indicate very low levels of methane gas.

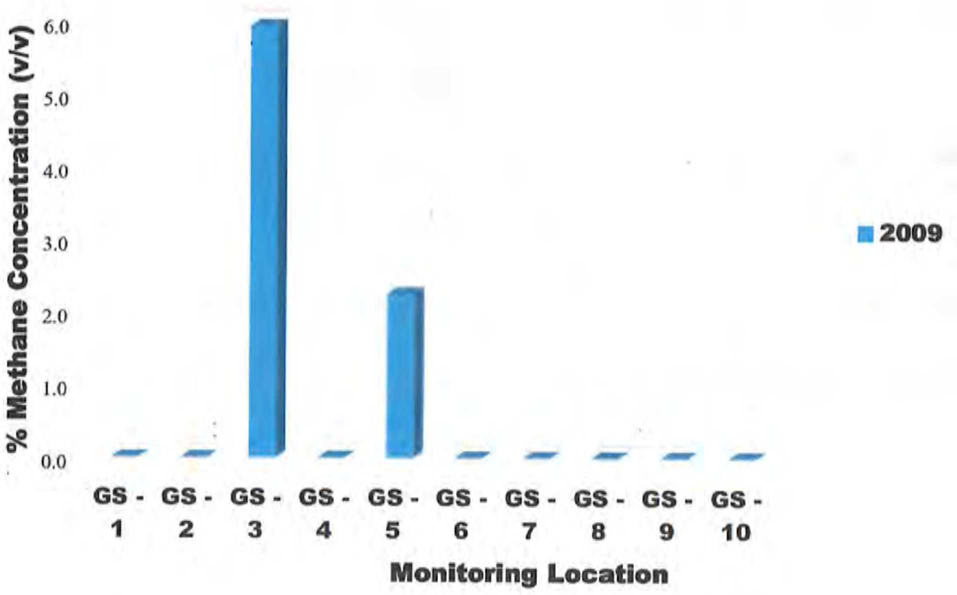

Figure 5.1: Methane Gas Occurrence (% v/v) - All Monitored Locations

6.0 METHANE GAS GENERATION ESTIMATES

The absence of reliable pump test data or continuous methane extraction /monitoring system for the site, conventional model calibration was not conducted. To account for the wide variability in the values of variables that influence methane gas generation rates in waste dumps, and the related methane gas generation estimates, four scenarios were simulated using estimated and USEPA default values of Lo and two values of Ki estimated using published half- life values for woodwaste landfills. This information is presented in Table 6.1.

Table 6.1: Methane Gas Generation Modeling Scenarios and Selected Lo and K Values

Scenario	Model	Organic Content	Lo (m3/Mg)	K (1/yr.)	
				Average	Comment
1	LandGEM: Low Lo	LC	78	0.02	K = 0.02 is calculated value based on a half-life of 35 years. K = 0.04 is calculated value based on a half-life of 17 years.
2	LandGEM: High Lo	LC	120	0.02	
3	LandGEM: Low Lo	LC	78	0.04	
4	LandGEM: High Lo	LC	120	0.04	

6.1 METHANE GAS GENERATION POTENTIAL

Tables 6.2, and Figures 6.1 and 6.2 provide detailed results of the methane gas modeling effort.

Table 6.2: Summary Peak and Average Annual Methane Gas Generation Rates (Average ft3- min).

Scenario	Peak	Peak Generation Year	Annual Average
1. (LandGEM Low Lo –Low Ki) (LLLC)	5.10	1983	1.88
2.(LandGEM High Lo – Low Ki) (LHLC)	7.85	1983	2.89
3.(LandGEM Low Lo – High Ki) (HLLC)	9.20	1983	2.00
4.(LandGEM High Lo- High Ki) (HHLC)	14.16	1983	3.09

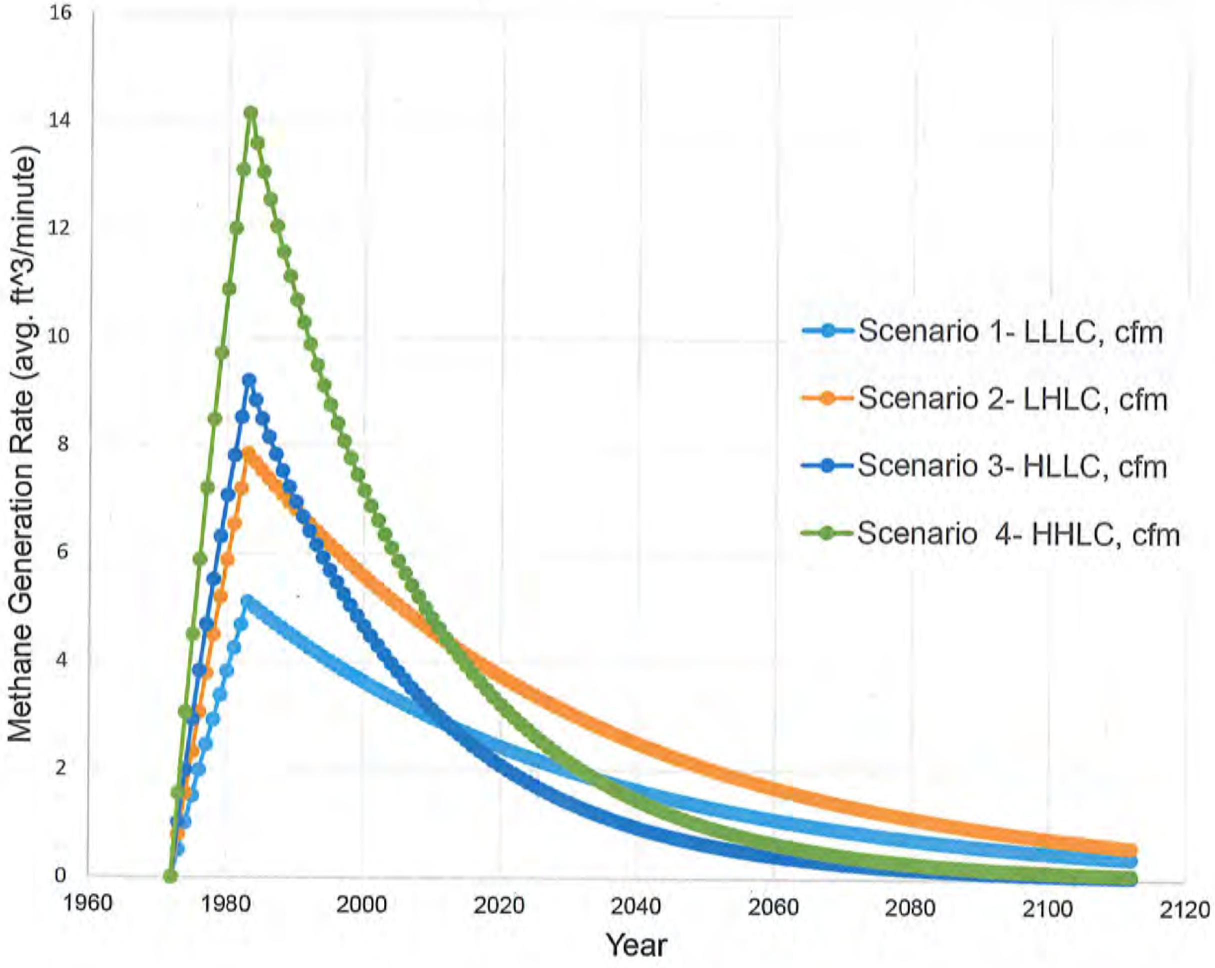

Figure 6.1: Average Annual Methane Gas Generation Rates for the four Scenarios Modelled

On the basis of the four scenarios, the projected methane gas generation rates show variability between the low and high Lo, and Ki values as follows:

Results for Calculated Potential Methane Gas Generation Capacity

- Annual peak methane generation rates range from *5.10 ft^3/minute to 9.20 ft^3/minute*
- Average methane generation rates range from *1.88 ft^3/minute to 2.01 ft^3/minute*
- Peak generation rates occurred in 1983, the year of cessation of waste deposition.

- **Results for USEPA Default Calculated Potential Methane Gas Generation Capacity**
  - Annual peak methane gas generation rates range from *7.85 ft^3/minute to 14.16 ft^3/minute*

  - Average annual methane gas generation rates range from 2*.89 ft^3/minute to 3.09 ft^3/minute*
  - Peak generation rates also occurred in 1983, the year of cessation of waste deposition.
- **Results for Methane gas generation since after closure in 1983 to 2112**
  - Average annual methane gas generation ranged from 1.80 *ft3/minute to 1.83 ft3/minute for calculated generation parameters*
  - Average annual methane gas generation ranged from 2.76 *ft3/minute to 2.82 ft3/minute for USEPA default generation parameters*
- **Results for Methane gas generation from 2019 to 2112 (current year to the future)**
  - Average annual methane gas generation ranged from 0.58 *ft3/minute to 1.13 ft3/minute for calculated generation parameters*
  - Average annual methane gas generation ranged from 0.89 *ft3/minute to 1.74 ft3/minute for USEPA default generation parameters.*
- *Decline of average methane gas generation rate* from the peak year in 1983 to 2019 ranged from *44% to 69%* for model results using calculated site – specific parameters.
- Based on the literature values for wood waste, the half- life varies from 17 to 35 years. *Therefore, and under ideal conditions, 100% of the landfilled wood waste should completely decompose between 2007 and 2017, assuming a 17 – year half-life, and between 2043 and 2053 for a 35 – year half - life.*
- The site has reached and passed its peak methane gas production period under current conditions, which, includes aerobic and anaerobic conditions.
- However, and because potential future closure of the landfill will increase the percent impervious surface areas, and therefore in - situ anoxic conditions, the likelihood of some increased methane generation within the range forecasted by the model under the related assumptions, therefore exists.

6.2 COMPARISON OF METHANE GAS GENERATION RESULTS TO LITERATURE VALUES

As shown in Figure 6.2, the model results were compared with literature values for wood waste landfills to evaluate whether modifications to the model assumptions were required. The analysis showed that;

- Methane generation potential or capacity for landfilled wood waste materials from published literature varied from averages of *0.30* m^3*/Mg to 0.40* m^3*/Mg*
- Methane generation potential or capacity simulated for the GO EAST landfill biodegradable waste varied from *0.26* m^3*/Mg to 0.43* m^3*/Mg.*
- Average methane generation potential or capacity simulated was 0.342 m^3/Mg and within the range expected for the literature average value of 0.333 m^3*/Mg* indicated or woodwaste sites.
- Compared to Municipal Solid Waste Landfills (MSWLFS), wood wastes decompose very slowly even in wet climate. Available, but limited studies indicate that on a per ton basis, wood wastes generate 2 - 30% less methane gas.
- Due to the landfill hydrogeologic setting and composition of the waste, there is a likelihood that some portions of the site will remain aerobic, thus keeping methane generation in the predicted post – closure range.

Figure 6.2: Comparison of Simulated Methane Gas Generation Potential Results to Published Values

7.0 METHANE GAS QUALITATIVE RISK ASSESSMENT & MITIGATION STRATEGIES

A qualitative risk assessment is completed to facilitate the decision-making process for devising a best - fit strategy to manage any potential risks in support of development of residential buildings around the site. Field investigations and modelling results indicate a methane gas risk. The following assessment determines the level of this risk and informs the decision on the extent of measures that are required to manage the risk. The following framework adopted from various literature sources is employed in the assessment:

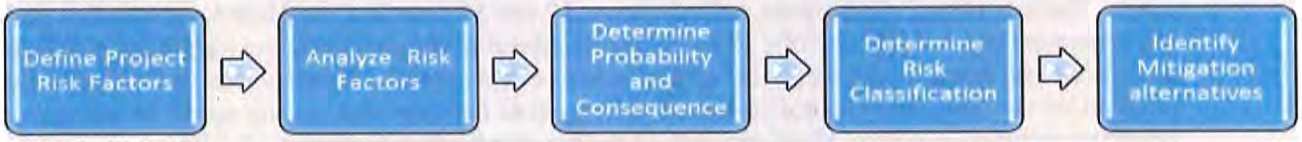

Figure 7.1: Methane Gas Risk Assessment Framework Processes

7.1 PROJECT RISK FACTORS

Based on the analysis completed in the preceding MGRA sections, the conceptual site model is developed and shown in Table 7.1 for methane gas risks with the related key risk factors, in consideration of the source-pathway-receptor (SPR) conceptual site.

Table 7.1: Summary Risk Factors

Risk Factor	GO EAST Landfill Risk Assessment
Sources :	
Waste Composition	Slowly decomposing urban wood wastes
	Very small potential for future methane gas generation
Methane gas concentration	Methane gas concentration is very low at locations measured in 2009
Age of in-place waste	Approximately 32 - 46 years
Nature or Scale of waste placement	Compacted, placed in cells and covered with soil /sandy cover materials. Refuse depth is variable ,deepest areas up to 68 feet
Potential Fluid Leakage from proposed pond on top of landfill	Although proposed to be lined, any leakage from the proposed pond could add moisture to the waste and drive increased methane gas generation
Methane Gas Mitigation	Some intermittent passive venting systems
Pathways	
Distance to Buildings	Future residences to be built around the site, *but not on top of it.*
Groundwater depth	Groundwater depth is between 31 to 51 feet below ground
Site Geology	Vashon Advance Outwash underlain by Pre Vashon Glacial Lacustrine
Receptors	Proposed future on-site residences and existing adjacent homes

7.2 ANALYSIS OF RISK FACTORS

Based on a systemic review of the project risk factors, the following existing aspects will likely mitigate the potential for the creation of unacceptable risk:

- **Source** - The source of methane gas is mainly wood waste that is around 32 to 46 years old. Any significant leakage from the proposed lined ponds over the landfill, could trigger increased, temporary methane gas generation also. Modeling analysis indicate that methane gas generation has significantly declined, and will continue to, although the site might experience some intermittent increase after final cover. The half-life of wood wastes varies between 17 and 35 years and the MGRA indicate that peak gas generation was reached in 1983. As such, the likelihood of the site producing significant quantities of methane gas that may migrate to the adjacent homes or enter proposed new homes is diminished and likely to be very low. The planned residential development indicates that the site would be acting as a potential methane gas source, albeit very low. Therefore, some risk mitigation is advised.
- **Pathway** - Site geology indicates a potential for methane gas to migrate from the shallow zones via the advanced outwash soils overlaying the clayey materials. This condition, coupled with the fine nature of the fill material and coarse wood wastes, provide opportunity for lateral migration of methane gas rather than vertical migration. The underlying clayey materials potentially mitigate the amount of gas that could migrate laterally, as demonstrated by the lack of historical detections near the property boundaries or in any of the existing surrounding homes. The perched groundwater level is unlikely to be a significant driver for methane gas migration.
- **Receptors** - There are a several existing homes around the site. It would be expected that if there were a significant receptor risk, that the existing adjacent houses would have experienced an issue already. Methane gas monitoring completed in 2009 by AESI, showed very limited methane gas detections in the middle of the site but none near the site boundaries. However, and although this assessment indicates that the site is approaching methane gas generation stability (and reached stability is some areas), the potential for ongoing methane gas production at low levels remains due to increased anoxic conditions driven by the planned final cover system and remaining organics. Therefore, the current consideration of the site for future residential development, are indicators that the site would be acting as a potential low level methane gas source, while the new homes and occupants are potential receptors. Therefore, risk mitigation proportional to the risk is appropriate.

7.3 EVALUATION OF PROBABILITY, CONSEQUENCE AND RISK CLASSIFICATON

Based on the preceding evaluation, the following *risk assessment results* are indicated:

- **Probability**
  - ***Low Likelihood*** -There is credible linkage and conditions under which **an event** (1) - methane gas entry into buildings; and (2) - Methane gas migration horizontally (adversely affecting occupants health or causing explosions). *However, it is by no means certain that even over a longer period such an event would take place, and is less likely in the short term.*
- **Consequence**
  - ***Minor*** - Harm, although not necessarily significant harm, which may result in a financial loss or expenditure to resolve. Non – permanent health effects to human health (easily repairable effects of damage to buildings, structures and services or easily prevented by alternative means) if event occurs. The potential presence of methane gas points to use of protective equipment during site works.
- **Risk Classification**

  Very Low Risk –There is a low possibility that harm could arise to a receptor. In the event of such harm being realized, it is not likely to be severe.

7.4 SUMMARY OF METHANE GAS RISK ASSESSMENT

Based on the conceptual site model and the review of the key risk factors presented above, we consider that the probability of lateral methane gas migration occurring and causing an unacceptable human health or environmental impact on surrounding homes is **Low**, while the probability to health and the environment due to vertical methane migration is **Unlikely,** resulting in an overall risk classification of **Very Low Risk**. No further methane gas investigation or assessment is warranted. This conclusion is supported by the following factors:

- The age of the placed waste (between 32 to 46 years),
- The projected decreasing methane gas concentrations at the site and lack of historical detections at the perimeter or offsite,
- Slow decomposition rates for the wood wastes and its associated predicated low methane generation potential,
- Appropriate measures will be taken in order to control potential, but small and unsustainable increase in generation rates after construction of a final cover system.

7.5 METHANE GAS RISK MITIGATION ALTERNATIVES EVALUATION & APPROACH

Alternative methane gas risk mitigation actions evaluated to support the proposed development of the site for residential purposes are summarized in Appendix Table A - 7.2

7.5.1 EVALUATION CRITERIA

This section summarizes the evaluation criteria applied.

7.5.1.1 EFFECTIVENESS CRITERIA

These criteria helps identify indicators that together, show how effective each mitigation alternative will be in enabling successful and acceptable risk mitigation and project goal attainment. The selected effectiveness attributes are summarize in Table 7.2.

Table 7.2 – Description of Effectiveness Attributes and Scoring Guide

Effectiveness Attribute or Indicator	Description	Scoring Guide
Goal Alignment	To what extent the alternative aligns with; (1). Planned development of the site for residential purposes. (2) Mitigating methane gas impact to human health and the environment.	0: aligns with none 5: aligns with some 10: aligns with all

Ease of Implementation and Maintenance	Degree of difficulty for successfully implementing the alternative and maintaining it after installation.	0: low 5: moderate 10: high
Safety, Health and Environmental Sustainability	The extent to which home owners will be exposed to methane risk after implementation of the alternative	0: high risk 5: some risk 10: little/no risk
Impact on Project Schedule	The extent to which implementation of the alternative will impact project schedule.	0: high 5: moderate 10: none
Acceptance by Community /Home Owners	The extent to which implementation of the alternative influences the adjourning home owners, the community or future potential home owners on the property to accept the mitigation and the project.	0: negative influence 5: moderate positive influence 10: high positive influence
Regulatory Approval	The extent to which the alternative will facilitate project acceptance and approval by regulators.	0: very difficult 5: difficult 10: not difficult

7.5.1.2 PROJECT COST BURDEN AND SCORING GUIDE

The extent to which implementation of the alternative affects project implementation cost:

- **Scoring Guide** - **0**: nonet ; **3**: low cost burden; **7** : moderate cost burden; **10:** high cost burden

8.0 METHANE RISK MITIGATION ALTERNATIVES EVALUATION RESULTS

The results of the evaluation are presented in Table 8.1 and Figure 8.1:

Table 8.1: Result of Evaluation of Alternative Methane Gas Mitigation Strategies

Strategies				Effectiveness Indicators Score	Project Cost Burden
Methane Monitoring and Alarms In- Building or Probes		Gas Monitoring		40	7
		Gas Alarms		40	7
Barriers	In-Building	Ground slabs/foundations GCS		31	10
		Foundation membranes + GCS		38	6
Barriers	In-Building	Vertical Barriers + Passive Venting		36	3
Dilution and Dispersion	In-Building	Passive or Natural Venting		22	7
	In - Building	Active venting	Mechanical extraction / natural supply	19	10
	In- Building	Active Venting	Mechanical supply / Natural Air Flow	15	10
	In - Building	Active Venting	Combined mechanical supply and extraction	15	7
Dilution and Dispersion + Monitoring	In-ground	Vertical Perimeter Barrier +Passive venting		54	5
	In- ground	Passive Venting		52	3
	In- ground	Impermeable Cover + GCS		52	5
	In- ground	Impermeable Cover + venting		53	3
Miscellaneous techniques	Chemical or biological			15	10

Source: *Alternatives adapted from NHBC (2007). Guidance on Evaluation of Development Proposals on sites Where Methane and Carbon Dioxide are present*

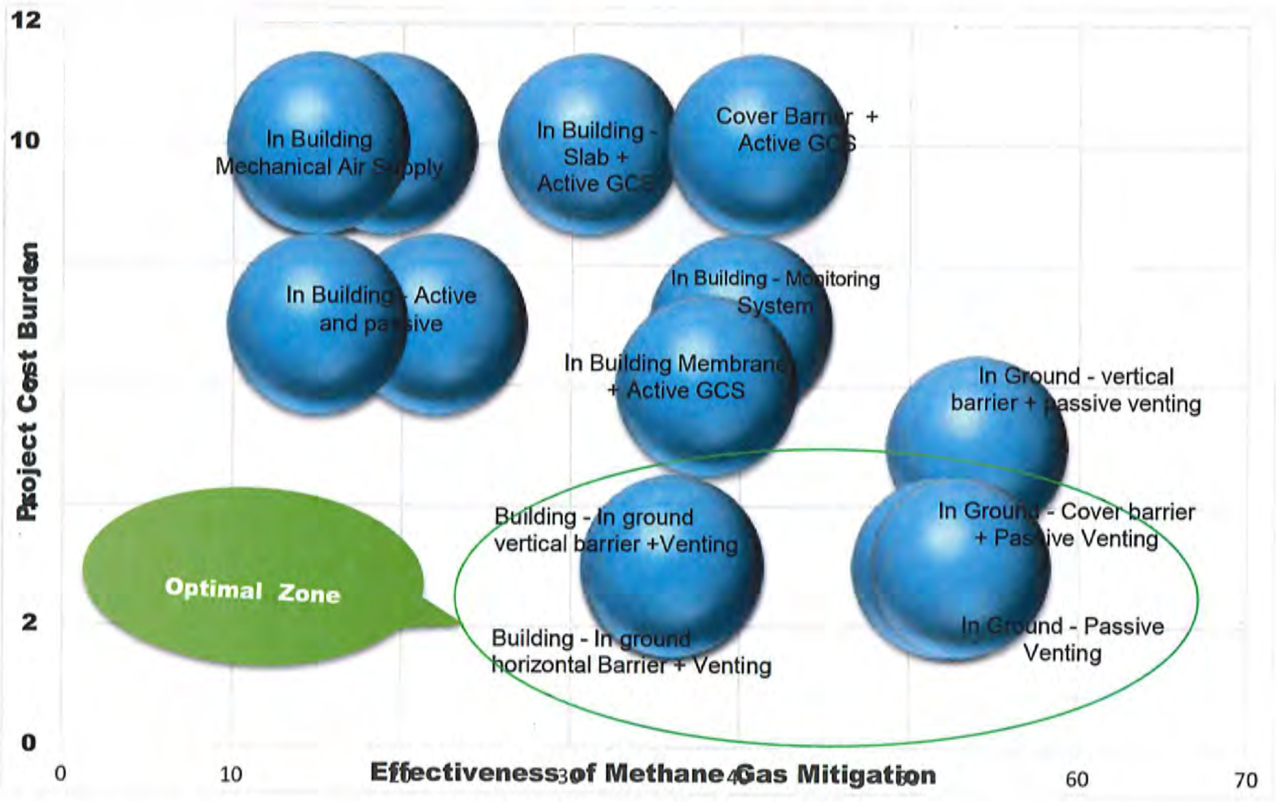

Figure 8.1: Project Cost Burden Vs Methane Gas Risk Mitigation Alternatives Effectiveness

8.1 METHANE GAS MITIGATION ALTERNATIVES EVALUATION RANKING

The RMAE documents the findings associated with the Methane Gas Risk Alternative Evaluation completed as part of the MGRA for the GO EAST Landfill. The RMAE has been completed in accordance with best practice for Mitigation Alternatives Assessment. The Optimal Alternatives are ranked in the Table 7.4.

Table 8.2: Ranking of Methane Gas Risk Mitigation Alternatives

Strategies			Effectiveness Indicators Score	Project Cost Burden	Rank
Methane Monitoring and Alarms In- Building or Probes		Gas Monitoring	40	7	5
		Gas Alarms	40	7	5
Barriers	In-Building	Ground slabs/foundations GCS	31	10	7
		Foundation membranes + GCS	38	6	6
Barriers	In-Building	Vertical Barriers + Passive Venting	36	3	8

Strategies				Effectiveness Indicators Score	Project Cost Burden	Rank
Dilution and Dispersion	In-Building	Passive or Natural Venting		22	7	9
	In - Building	Active venting	Mechanical extraction / natural supply	19	10	9
	In- Building	Active Venting	Mechanical supply / Natural Air Flow	15	10	10
	In - Building	Active Venting	Combined mechanical supply and extraction	15	7	11
Dilution and Dispersion + Monitoring	In-ground	Vertical Perimeter Barrier +Passive venting		54	5	1
	In- ground	Passive Venting		52	3	4
	In- ground	Impermeable Cover + GCS		52	5	2
	In- ground	Impermeable Cover + venting		53	3	3
Miscellaneous techniques	Chemical or biological			15	10	10

Source: *Alternatives adapted from NHBC (2007). Guidance on Evaluation of Development Proposals on sites Where Methane and Carbon Dioxide are present*

9.0 SUMMARY AND RECOMMENDATIONS

This MGRA documents the findings associated with the Methane Gas Generation and Risk Mitigation Assessment completed to support the planned development of the GO EAST landfill site for residential use. The MGRA has been completed in accordance with best practice for LFG generation modeling and risk assessment.

There are no existing methods for measuring actual methane gas generation, so estimates must be obtained through varied methods. Because there are various variables that influence methane gas generation rates in waste dumps, estimates can vary significantly regardless of method. In the absence of conventional model calibration data, an attempt to define a range of reasonable results, using different scenarios were simulated. To qualitatively evaluate accuracy of the modeling results, a comparison with the normalized literature methane gas generation rates for similar waste types and conditions was made. The outcome of this comparison was used to postulate the most likely methane gas generation rates.

The absence of recorded annual site operations data or scale records for material received, entails the inclusion of uncertainties and approximations in the estimation of the methane gas generation potential. The application of the methane gas generation modeling allowed the generation of a range of methane gas generation potential curves to account for the variability of the methane gas generation.

A calibration on the model with measurement data would have been needed, for a more accurate application of the model, but the absence of a spatially well-represented methane generation monitoring system or pump test information did not allow for this action. However, the described approach represents a useful tool to estimate the lowest, average and highest possible methane gas generation rates into the future in order to inform the proportional risk mitigation actions.

ESTIMATED METHANE GAS GENERATION RATES

On the basis of the four scenarios considered, the estimated methane gas generation rates showed expected variability for simulations based on calculated potential methane gas generation capacity and the USEPA model default values for municipal solid waste landfills (MSWLS) as follows:

- **Results for Calculated Potential Methane Gas Generation Capacity between 1972 and 2112**
  - Annual peak methane generation rates range from 5.*10 ft^3/minute to 9.20 ft^3/minute*
  - Average methane generation rates range from 1.*88 ft^3/minute to 2.01 ft^3/minute*
  - Peak generation rates occurred in 1983, the year of cessation of waste deposition.
- **Results for USEPA Default Calculated Potential Methane Gas Generation Capacity**
  - Annual peak methane gas generation rates range from 7.85 *ft^3/minute to 14.16 ft^3/minute*
  - Average annual methane gas generation rates range from 2.*89 ft^3/minute to 3.09 ft^3/minute*
  - Peak generation rates also occurred in 1983, the year of cessation of waste deposition.
- **Results for Methane gas generation since closure from 1983 to 2112**
  - Average annual methane gas generation ranged from 1.80 *ft3/minute to 1.83 ft3/minute for calculated generation parameters*
  - Average annual methane gas generation ranged from 2.76 *ft3/minute to 2.82 ft3/minute for USEPA default generation parameters*
- **Results for Methane gas generation from 2019 to 2112 (current year to the future)**
  - Average annual methane gas generation ranged from 0.58 *ft3/minute to 1.13 ft3/minute for calculated generation parameters*

  - Average annual methane gas generation ranged from 0.89 *ft3/minute to 1.74 ft3/minute for USEPA default generation parameters.
- *Decline of average methane gas generation rate* from the peak year in 1983 to 2019 ranged from *44% to 69%* for model results using calculated site – specific parameters.
- Based on the half- life of woodwaste, *100% of the landfilled wood waste should completely decompose between 2007 and 2017f (at 17 years of half- life) and between 2043 and 2053 for a 35 – year half - life.*
- The site *has reached and passed its peak methane gas production period under current conditions.*
- Although there is a potential for some temporary increase in methane generation after the planned capping, or if there is a sustained leakage from the ponds, such increase is projected to be within the range forecasted by the current study. *Therefore, such potential temporary increase in methane gas generation will not significantly change the continuing decline of any methane gas generation rates within the site as predicted by this study.*

COMPARISON OF RESULTS TO PUBLISHED DATA

The model results were compared with literature values for wood waste landfills to evaluate whether modifications to the model assumptions were required. The analysis showed that;

- Methane generation rates for landfilled wood waste materials from published literature varied from averages of *0.30 m^3/Mg to 0.40 m^3/Mg*
- Methane generation rates simulated for the GO EAST landfill biodegradable waste varied from *0.26 m^3/Mg to 0.43 m^3/Mg.*
- Average methane generation rate simulated was 0.342 m^3/Mg and within the range expected for sites with similar waste materials.
- Compared to Municipal Solid Waste Landfills (MSWLFS), wood wastes decompose very slowly even in wet climate. Available, but limited studies indicate that on a per ton basis, wood wastes generate 2 - 30% less methane gas.
- Due to the landfill hydrogeologic setting and composition of the waste, there is a likelihood that some portions of the site will remain aerobic, thus keeping methane generation in the predicted post – closure range.

SPATIAL METHANE GAS DISTRIBUTION AND TREND

According to site exploration and monitoring results recorded during 2009, methane gas was detected at a single location, in the middle of the site, at above regulatory Lower Explosive Limit (LEL). This result, albeit from 2009, combined with the current assessment, and the absence of detections near the property boundary or offsite, provides a clear trend regarding current and future methane gas generation potential at the site. This assessment indicate as follows :

- Significantly declined methane gas generation towards baseline conditions.
- Methane gas generation rate, on average is not expected to increase above current baseline conditions near the property boundaries.

QUALITATIVE METHANE GAS RISK ASSESSMENT

Based on the conceptual site model and the review of the key risk factors associated with methane gas, Vikek considers that the risk of lateral methane gas migration occurring and causing an unacceptable human health or environmental impact to the surrounding homes is **Low**, while risk to human health and the environment due to vertical methane gas migration is **Unlikely** resulting in an overall risk classification of **Very Low Risk**.

No further methane gas investigation or assessment is warranted, *but appropriate measures should be taken in mitigate the projected low methane gas generation.*

This MGRA was completed exclusively for the use of PACE Engineers Inc. to support the planned development of the GO EAST landfill site for residential use. No other party, known or unknown to Vikek is intended as a beneficiary of this report or the information it contains. Third parties use this report at their own risk. Vikek assumes no responsibility for the accuracy of information obtained from, or provided by, third-party sources.

METHANE GAS MITIGATION ALTERNATIVES EVALUATION

Assessment of nine potential methane gas risk mitigation alternatives indicate as follows:

- *Dilution/Dispersion with methane gas Monitoring*: In- ground methane gas dispersion coupled with a monitoring program in perimeter probes are the most effective risk mitigation approaches.
- Installation of *a vertical perimeter barrier with venting trench system or a horizontal barrier (cap) with perimeter venting trench system are the highest ranked methane risk mitigation alternatives* for the site.
- Based on the projected future methane gas generation rates, the proposed landfill cap, perimeter dispersion trench , monitoring probes, and home methane gas monitoring system for the Landfill Closure Plan, is a conservative plan, and consistent with the recommendations provided in this MGRA
- Vikek recommends, that in addition to the proposed gas monitoring probes around future homes, *that one to three additional perimeter monitoring probes be installed directly downstream of the two locations where methane gas was measured in 2009.* One probe should be directly downstream while one or two others may be between 200 feet to 500 feet away from it, and installed in accordance with regulatory guidelines and the hydrogeologic conditions at those locations.

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11.0 APPENDICES

APPENDIX A - 2.1

Year	Estimated Waste- In- Place, tons
1972	8,844
1973	8,844
1974	8,844
1975	8,844
1976	8,844
1977	8,844
1978	8,844
1979	8,844
1980	8,844
1981	8,844
1982	8,844
1983	
TOTAL	97,287

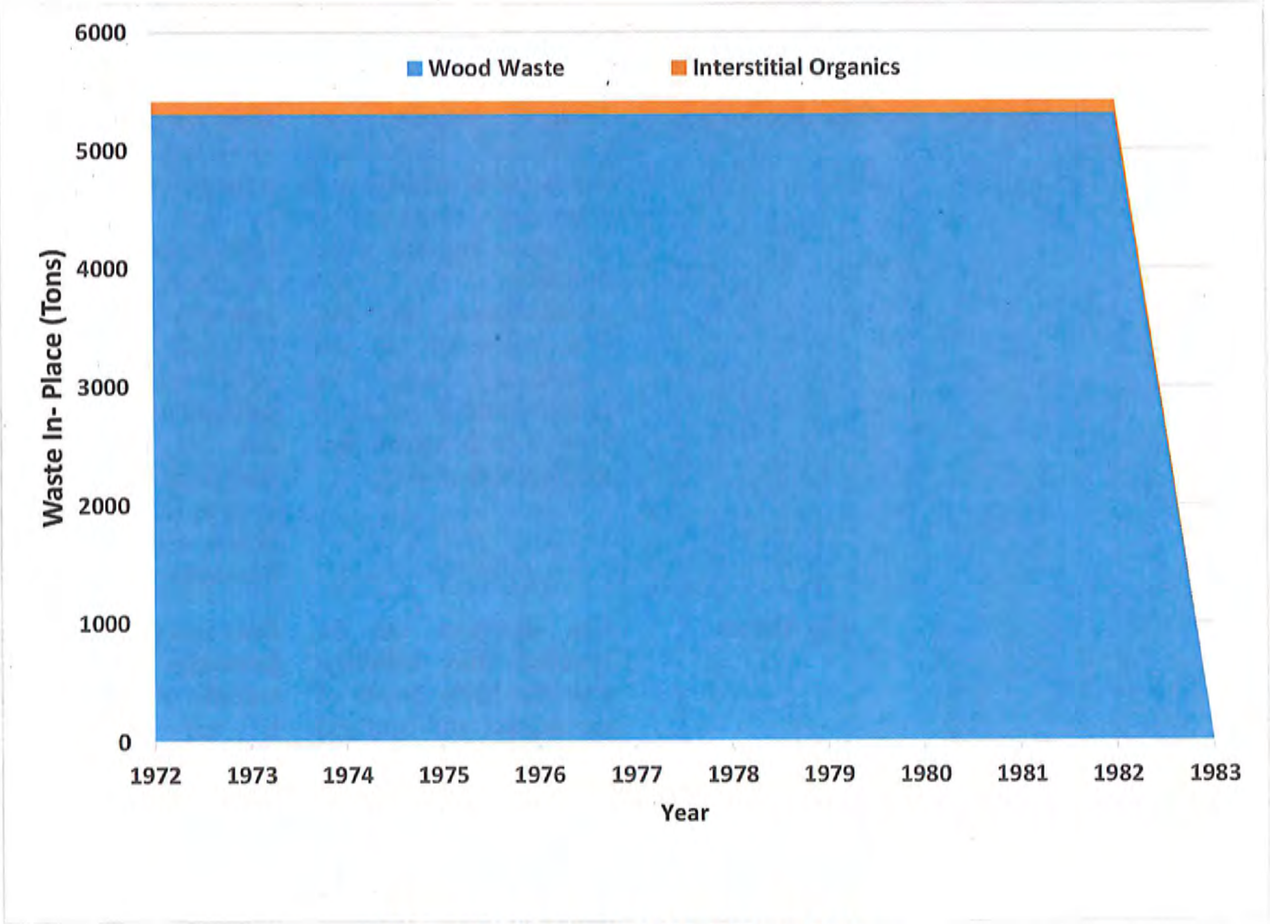

Figure A-4.1: LandGEM Model Input Data

Table A-7.2: Alternative Mitigation Strategies

Strategies		Description	Comments
Methane Monitoring and Alarms	Gas Monitoring	Either periodic or continuous monitoring can occur of methane and other gases, depending on the nature and use of the building and concentrations of gas. The frequency of gas monitoring may be reduced after a period of time if it is shown that methane risk is low.	Does not provide physical protection against the hazards of ground gases. Is not considered a replacement for permanent protection measures. It is generally agreed that this technique alone SHOULD NOT be installed in residential developments due to the extreme sensitivity of the receptor to even minor fluctuations in gas concentrations and flow rates
	Gas Alarms	Gas detectors can be installed into buildings near the likely points of gas ingress and confined spaces (e.g. sub-floor voids and cavities). If pre-set gas concentrations are exceeded, an automatic audible alarm sounds to prompt building evacuation.	Does not provide physical protection against the hazards of ground gases. Is not considered a replacement for permanent protection measures. It is generally agreed that alarms SHOULD NOT be installed in residential properties due to the general apathy of residents and maintenance issues.

Strategies			Description	Comments
Barriers	Building	Design and construction of ground slabs/foundations	Impermeable gas barriers are constructed on top of a high permeability layer, from which ground gas can be extracted in a controlled manner (e.g. concrete slab overlying gravel layer). No barrier is completely impermeable to the passage of ground gas; however, the technique relies upon the barrier providing a greater resistance to gas migration than the surrounding ground so that gases are encouraged to migrate in another direction away from the building.	The permeabilities of many materials, particularly clays and cements, can vary due to changes in pore size and pore distribution caused by changes in the ground (e.g. decreased or increased water content). The design of any barrier should take into account these effects and allow for potential changes in permeability of either the surrounding ground or the barrier itself
		Membranes	Membranes work on the same principle as barriers, except a polyethylene, LDPE or modified bitumen/LDPE layer is installed to prevent gas ingress on top of a high permeability layer. The minimum recommended standard of membrane is 300 micrometers (1200 gauge) (BRE 212). A single membrane, if carefully designed and selected, may satisfy both the requirements of a damp proofing course and gas.	Membranes are usually installed in conjunction with passive or active venting. Of concern is whether the membrane can withstand the construction process because, once torn or damaged, the membrane will cease to operate as an effective barrier. Adequate quality control during the laying of the membrane is extremely important and the membrane should be protected.

Strategies				Description	Comments
Barriers (continued)	In-ground	In ground Barriers	Vertical Barriers	Vertical barriers are used to prevent lateral gas migration towards the development. A high permeability trench should be installed on the gassing source side of the vertical barrier to ensure gases are vented to the atmosphere and do not build up. Vertical barriers are only suitable where a low permeability material horizon is present at depth, where the vertical barrier is 'keyed' in. In some situations, the groundwater table can be considered to be an effective impermeable horizon to prevent ground gas migration. Vertical barriers can be constructed to surround a gassing source or, if the source is remote, in between the source and development to prevent and intercept migration.	The barrier has to remain in place for a considerable time period (50 or even 100 years) and the integrity of the barrier used must be complete. If concrete materials are to be used, the ground regime should be understood and the presence of concrete aggressive materials should be pre-designed for. Tolerance to ground movements (e.g. from mining subsidence) should also be guaranteed. If the groundwater table is identified as a suitable impermeable horizon, care should be taken to ensure that all fluctuations in its level are identified so that gaps between the groundwater and vertical barrier are not created, which could allow ground gas migration to occur. Vertical barriers could induce changes in the groundwater regime (e.g. flow direction), which could result in groundwater level rises upstream of the barrier. This could also alter the ground gas regime upstream, which could increase ground gas generation and affect existing or future development design. The presence, location and depth of the horizontal barrier should be made known so that any future services installed do not pass through and render if obsolete.

Strategies				Description	Comments
			Horizontal Barriers	Horizontal barriers are used to prevent ground gas migration from sources directly beneath the development. The barrier, which can be constructed from a range of materials including clay, mass concrete or synthetic liners, is carefully placed and sealed around services, foundations and structures. Usually, a venting blanket or gas drainage layer will underlie the horizontal barrier. Injection or jet grouting can also provide horizontal barriers to prevent gas migration through a low permeability horizon at depth beneath a site, which is known as "bottom sealing" or " under sealing"	The barrier has to remain in place for a considerable time period (50 or even 100 years) and the integrity of the barrier used must be complete. If concrete materials are to be used the ground regime should be understood and the presence of concrete aggressive materials should be pre-designed. Tolerance to ground movements (e.g. from mining subsidence) should also be guaranteed. Suitable drainage measures should be built into the ground above the horizontal barrier to prevent the areas becoming a quagmire. The presence, location and depth of the horizontal barrier should be made known so that any future services installed do not pass through and render it obsolete.

Strategies			Description	Comments
Dilution and Dispersion	Buildings	Passive or Natural Venting	This technique relies on the natural movement of air through buildings and/or structure fabric by the action of natural climatic conditions by the processes of gas diffusion and advection. Therefore, passive venting is suitable in situations where precise control over the air quality and volume flow rate of fresh air is not critical to dilute gas concentrations to safe acceptable levels. Passive venting to a development that is affected by ground gases can be applied in two ways: • Dilution of gas within the building fabric by providing adequate volume flow rate of fresh air to disperse gas; and • Dilution of gas before entering the building, i.e. reducing the concentration to safe acceptable levels so that ingress of gas into the building fabric, if any, will have no adverse effect.	Dispersion will not necessarily reduce gas concentration since gas may still be present or continue to arrive from a gassing source. Indeed, by providing an easier flow path the rate of gas entry may increase in gas concentration if the rate of release to the atmosphere is low. Other protection measures may have to be considered to either replace or supplement a passive venting system. It is generally considered good practice in the absence of reliable gas monitoring information to assume that active venting is required for gas protection measures until proven otherwise. Gas diffusion beneath or within the confined space of a building can be extremely slow and generally cannot be relied upon to provide adequate dilution and dispersion. Therefore, passive venting is normally designed on the basis of advection and the application of a pressure gradient to cause gas dilution and dispersion.

Strategies				Description	Comments
		Active venting	Mechanical extraction / natural supply	This is the simplest form of venting system and comprises one or more fans, usually of the propeller type, installed in outside walls or in the roof. Air is extracted from the confined space of a building so to draw in fresh air.	It is essential that provision for replacement air is made and consideration given to the location and size of the inlet. Too high a flow rate of gas ingress may cause excessive heat loss within the building. All mechanical and electrical components should be intrinsically safe. It is generally agreed that mechanical techniques SHOULD NOT be installed in residential properties due to maintenance issues
			Mechanical supply / natural extraction	This system is similar to mechanical extraction but arranged to deliver fresh air in the building. Such a system necessitates provision for the discharge of foul air by natural means. The system works better with a more controlled movement of air if a ducted system is installed.	An air-cleaning device and air heater with automatic temperature control will normally be required. Too high a flow rate of gas ingress may cause excessive heat loss. All mechanical and electrical components should be intrinsically safe. It is generally agreed that mechanical techniques SHOULD NOT be installed in residential properties due to maintenance issues.

Strategies				Description	Comments
			Combined mechanical supply and extraction	This system combines the other active venting systems discussed above and comprises supply and exhaust ductwork systems or may employ a fan with fresh air inlet on the low-pressure side of the building.	These systems are generally not suitable for gas protection since they could potentially involve the recirculation of gases. Locating the inlet and outlet vents on opposite sides of the building could possibly alleviate this, although detailed design would have to ensure this. All mechanical and electrical components should be intrinsically safe. It is generally agreed that mechanical techniques SHOULD NOT be installed in residential properties due to maintenance issues
Dilution and Dispersion (Continued)	In-ground	Passive venting		Passive venting is the controlled release and dispersal of gas from the ground to atmosphere via a preferential pathway through diffusion and advection of gas to surface outlets to release ground gases to the atmosphere away from sensitive areas of a site. Such preferential pathways may be venting trenches, venting walls and drainage layers. Passive venting is generally of a relatively simple construction and can be: • Low maintenance; • Effective for a long time; and • Installed with minimal intrusion within a development	Passive venting should be designed to allow gas migration under all circumstances, irrespective of fluctuations in concentration or the emission rate of the gas or changes in the ambient atmospheric conditions, i.e. wind speed, temperature, barometric pressure and rainfall. Detailed knowledge of these variable parameters is required so that the ventilation system can be designed confidently. In addition, comprehensive monitoring data will be required. site investigation and gas

Strategies			Description	Comments
		Active Abstraction	Gas is collected via a system of perforated pipes laid on or in the ground and through installed wells by mechanical pumps. The pumps create an artificial pressure gradient in the venting system to draw the gas from the ground, which is then either released to the atmosphere via surface outlets away from sensitive areas of a site or is flared off if the abstracted gas is potentially combustible. Active abstraction is most effective in situations of high and variable gas concentrations and/or rates of emission	A trial pumping exercise should be undertaken in order to establish: • The mechanical pump capacity required • The zone of abstraction of individual gas wells (generally not more than 30 to 50m) • Spacing of gas wells. The system must be as airtight as possible (generally, a low permeability material covers the pipework), because if air is drawn into the system from the ground surface it can result in: • Loss of suction of ground gas and a diminished effectiveness of the abstraction system; and • A potentially flammable gas mixture and the potential risk of explosion within the system or even the ground. As a result, the active abstraction system can take a long time to design and install. In addition, it is rarely adequate as a sole means of protection.

Strategies		Description	Comments
Miscellaneous techniques	Chemical or biological	Such techniques may rely on chemical (e.g. formaldehyde, methanol, ferric iron salts) or biological control to inhibit gas generation, which in turn prohibits gas migration. Temporary inhibition of methanogenesis may be a useful and practical tool, especially in an emergency, before more permanent gas control measures can be installed.	Difficulties in the process include: • Difficulty in efficient and uniform dispersal; • May only be partially effective; • Chemicals may themselves be degraded and turned into ground gases and increased leachate generation; and • Impact on environment by adding toxic substances to ground

Source: *Modified from NHBC (2007). Guidance on Evaluation of Development Proposals on sites Where Methane and Carbon Dioxide are present.*

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