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Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide

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by

Amy Alexander, Clint Burklin, and Amanda Singleton
Eastern Research Group
Morrisville, NC

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Project Officer: Susan A. Thorneloe
Office of Research and Development
National Risk Management Research Laboratory
Air Pollution Prevention and Control Division
Research Triangle Park, NC 27711

U.S. Environmental Protection Agency
Office of Research and Development
Washington, DC 20460

Abstract

The Landfill Gas Emissions Model (LandGEM) is an automated estimation tool with a Microsoft Excel interface that can be used to estimate emission rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds, and individual air pollutants from municipal solid waste landfills. This guide provides step-by-step guidance for using this software application, as well as an appendix containing background information on the technical basis of LandGEM. LandGEM can use either site-specific data to estimate emissions or default parameters if no site-specific data are available. The model contains two sets of default parameters, CAA defaults and inventory defaults. The CAA defaults are based on federal regulations for MSW landfills laid out by the Clean Air Act (CAA) and can be used for determining whether a landfill is subject to the control requirements of these regulations. The inventory defaults are based on emission factors in EPA's *Compilation of Air Pollutant Emission Factors (AP-42)* and can be used to generate emission estimates for use in emission inventories and air permits in the absence of site-specific test data.

Foreword

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Acting Director
National Risk Management Research Laboratory

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Introduction

This document provides step-by-step guidance for using the Landfill Gas Emissions Model (LandGEM), a software application with a Microsoft Excel interface that estimates air pollutants and other gases from municipal solid waste (MSW) landfills. Using this document, you will learn how to

- Enter landfill-specific data,
- Choose between site-specific and default model parameters,
- Estimate emission rates, and
- View and print tabular and graphical results.

Overview of How LandGEM Works

LandGEM is an automated tool for estimating emission rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds (NMOCs), and individual air pollutants from MSW landfills. Landfill owners and operators can use LandGEM to determine if a landfill is subject to the control requirements of the federal New Source Performance Standards (NSPS) for new MSW landfills (40 CFR 60 Subpart WWW), the federal Emission Guidelines (EG) for existing MSW landfills (40 CFR Subpart Cc), or the National Emission Standards for Hazardous Air Pollutants (NESHAP) for MSW landfills (40 CFR Subpart AAAA).

LandGEM can use either site-specific data to estimate emissions or default parameters if no site-specific data are available. LandGEM contains two sets of default parameters.

CAA Defaults—The CAA defaults are based on requirements for MSW landfills laid out by the Clean Air Act (CAA), including the NSPS/EG and NESHAP. This set of default parameters yields conservative emission estimates and can be used for determining whether a landfill is subject to the control requirements of the NSPS/EG or NESHAP.

Inventory Defaults—With the exception of wet landfill defaults, the inventory defaults are based on emission factors in the U.S. Environmental Protection

Agency's (EPA's) *Compilation of Air Pollutant Emission Factors* (*AP-42*). This set of defaults yields average emissions and can be used to generate emission estimates for use in emission inventories and air permits in the absence of site-specific test data.

The default parameters in Version 3.02 of LandGEM represent values specified by NSPS/EG and NESHAP for determining applicability of CAA requirements. Also included are values specified in AP-42 for developing national and state emission inventories. The AP-42 values are being updated with new information that has been collected by EPA from more recent field tests. In addition, research is underway to obtain data for developing emission factors for wet/bioreactor landfills where leachate and other liquids are added to accelerate waste decomposition.

Section 1.
Understanding LandGEM

LandGEM is based on a first-order decomposition rate equation for quantifying emissions from the decomposition of landfilled waste in MSW landfills. The software provides a relatively simple approach to estimating landfill gas emissions. Model defaults are based on empirical data from U.S. landfills. Field test data can also be used in place of model defaults when available. Further guidance on EPA test methods, CAA regulations, and other guidance regarding landfill gas emissions and control technology requirements can be found at http://www.epa.gov/ttnatw01/landfill/landflpg.html.

LandGEM is considered a screening tool—the better the input data, the better the estimates. Often, there are limitations with the available data regarding waste quantity and composition, variation in design and operating practices over time, and changes occurring over time that impact the emissions potential. Changes to landfill operation, such as operating under wet conditions through leachate recirculation or other liquid additions, will result in generating more gas at a faster rate. Defaults for estimating emissions for this type of operation are being developed to include in LandGEM along with defaults for conventional landfills (no leachate or liquid additions) for developing emission inventories and determining CAA applicability. Refer to the Web site identified above for future updates to LandGEM.

Appendix A provides further background information regarding the technical basis of LandGEM and how it relates to landfill emissions, methane, carbon dioxide, NMOCs, and air pollutants.

1.1 Spreadsheet Design

LandGEM consists of nine worksheets within a Microsoft Excel spreadsheet. The worksheet names and their functions are listed in Table 1.

Table 1. Worksheet Names and Functions in LandGEM

Worksheet Name	Function
INTRO	Contains an overview of the model and important notes about using LandGEM
USER INPUTS	Allows users to provide landfill characteristics, determine model parameters, select up to four gases or pollutants (total landfill gas, methane, carbon dioxide, NMOCs, and 46 air pollutants), and enter waste acceptance rates
POLLUTANTS	Allows users to edit air pollutant concentrations and molecular weights for existing pollutants and add up to 10 new pollutants
INPUT REVIEW	Allows users to review and print model inputs
METHANE	Calculates methane emission estimates using the first-order decomposition rate equation
RESULTS	Shows tabular emission estimates for up to four gases/ pollutants (selected in the USER INPUTS worksheet) in megagrams per year, cubic meters per year, and user's choice of a third unit of measure (average cubic feet per minute, cubic feet per year, or short tons per year)
GRAPHS	Shows graphical emission estimates for up to four gases/ pollutants (selected in the USER INPUTS worksheet) in megagrams per year, cubic meters per year, and user's choice of a third unit of measure (selected in the RESULTS worksheet)
INVENTORY	Displays tabular emission estimates for all gases/pollutants for a single year specified by users
REPORT	Allows users to review and print model inputs and outputs in a summary report

1.2 First-Order Decomposition Rate Equation

LandGEM uses the following first-order decomposition rate equation to estimate annual emissions over a time period that you specify. The model parameters k and L_o used by this decomposition equation are described further in Section 3.0.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_o \left(\frac{M_i}{10} \right) e^{-kt_{ij}}$$

where

Q_{CH4} = 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 ($year^{-1}$)

L_o = potential methane generation capacity (m^3/Mg)

M_i = mass of waste accepted in the ith year (Mg)

t_{ij} = age of the jth section of waste mass M_i accepted in the ith year (decimal years, e.g., 3.2 years)

1.3 Software Requirements

LandGEM requires Microsoft Excel 97 or a more recent version of Excel. Earlier versions of Excel are unable to properly run the model because macros are embedded in the software.

Enable Macros—You **must** select *Enable Macros* when prompted (immediately after opening the file) to allow the LandGEM software to use macros embedded in the file. LandGEM has been carefully screened and is free of any viruses.

Macro Security—If you are using Microsoft Excel 2000 or Excel 2002 (within the Microsoft Office XP software package), you must set your *Macro Security Level* to *Medium* prior to opening the software to allow the *Enable Macros* option to be selected. If your *Macro Security Level* is set to *High* when the model is opened, then the warning message shown in Image 1 will appear, and the embedded macros needed to run LandGEM properly will be disabled. You can adjust the *Macro Security Level* in Excel by selecting *Macro...Security* from the *Tools* menu and clicking on the *Medium* radio button. Although LandGEM can operate with the *Macro Security Level* set to *Low*, this setting is not recommended by Microsoft.

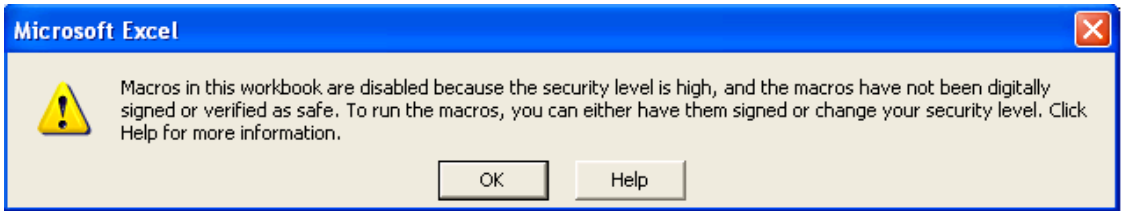


Image 1. Macro Security Warning Message.

Memory Requirements—You should have a minimum of 64 megabytes of random access memory (RAM). In addition, you will need a minimum of 2 megabytes of free space on your hard drive to accommodate the LandGEM software.

***Read Only* Feature**—LandGEM has been specified as a *Read Only* file. You save a copy of LandGEM under a new file name when running each landfill scenario. The *Read Only* restriction is intended to protect the original file from being inadvertently over-written. If necessary, you can remove this restriction by changing the file properties via a file management program (e.g., Windows Explorer).

Password Protection Feature—To avoid user modifications from occurring within the model, all of the worksheets contained in LandGEM and the Microsoft Excel workbook itself have been password protected.

Screen Resolution—The optimum screen resolution for viewing LandGEM is 1024 by 768 pixels. To change the screen resolution, you can open the *Control Panel* from the *Start* menu, open the *Display* folder, select the *Settings* tab at the top of the window, and adjust the *Screen resolution* or *Screen area* option (depending on your version of Windows) accordingly.

1.4 Significant Differences Between Model Versions

LandGEM Version 3.02 replaces Versions 2.01 and 3.01. Significant differences between Versions 2.01 and 3.02 of LandGEM include:

- Version 3.02 uses a revised first-order decomposition rate equation that improves the accuracy of emission estimates over time, especially for landfills being modeled using higher methane generation rate (k) values. The equation used in Version 2.01 integrates emissions over each year, whereas the revised equation in Version 3.02 integrates emissions over a 0.1 year time increment. This revision is considered an improvement over the previous calculation methodology. This new equation in Version 3.02 results in slightly lower emission estimates than previous versions for typical k values. For example, Version 3.02 emission estimates are 2% lower for a k of 0.05 year^{-1} (CAA Conventional) and 1% lower for a k of 0.02 year^{-1} (CAA Arid Area). Version 3.02 estimates significantly lower emissions for higher k values—for example, 25% lower for a k of 0.7 year^{-1} (Inventory Wet).

- Version 3.02 allows users to model emissions of total landfill gas, which can be calibrated using a user-specified methane content other than 50 percent. In Version 2.01, users cannot estimate total landfill gas emissions directly and must calculate total landfill gas off-line using methane emission estimates.

- Version 2.01 uses metric units of measure exclusively, whereas Version 3.02 allows users to choose between several English (e.g., short tons, cubic feet) and metric (e.g., megagrams, cubic meters) units of measure for model inputs and outputs.

- Version 2.01 reports emissions for 200 years past closure year of the landfill, whereas Version 3.02 reports emissions for 140 years total.

- Version 2.01 does not allow waste to be accepted in the closure year. To provide users with more flexibility when entering inputs, Version 3.02 was changed to allow waste to be accepted in the closure year.

- Version 2.01 contains AP-42 default values and air pollutant concentrations and molecular weights that were current as of September 1997 (Supplement C of the 5th Edition). Version 3.02 contains revised AP-42 default values (within the inventory defaults), air pollutant concentrations, and molecular weights that are current as of November 1998 (Supplement E of the 5th Edition).

- Version 3.02 incorporates inventory default k and L_o values for wet landfills (such as bioreactors).

- Version 3.02 replaces Version 3.01 by correcting an error when av ft^3/min or ft^3/year is selected as the user-specified unit in the RESULTS worksheet.

1.5 Differences Between the Model and AP-42

Significant differences between Version 3.02 of LandGEM and EPA's *Compilation of Air Pollutant Emission Factors* (*AP-42*) include:

- The inventory default values for NMOC concentration and several air pollutant concentrations used in Version 3.02 of LandGEM differ slightly from those in the November 1998 version (Supplement E of the 5th Edition) of AP-42. These minor differences are due to rounding of the concentration values to more accurately reflect their relative uncertainty. These rounding differences are expected to be rectified in

an upcoming revision of AP-42 for MSW landfills because the uncertainty of the values within the current version of AP-42 do not accurately correspond with the inherent uncertainty of the NMOC and air pollutant concentrations.

- Due to a revision in the first-order decomposition rate equation used in Version 3.02 of LandGEM (Section 1.4), the methane generation equation (Equation 1) within AP-42 no longer matches the equation used by LandGEM. Differences between the two calculation methodologies are expected to be rectified in an upcoming revision of AP-42 for MSW landfills.

Section 2.
Providing Landfill Characteristics

Enter data on the USER INPUTS worksheet that relate to the identity and size of the landfill being modeled.

- Landfill name or identifier,
- Landfill open year,
- Landfill closure year,
- Option to have model calculate closure year, and
- Waste design capacity.

Image 2 shows these inputs as they appear on the USER INPUTS worksheet. To clear all of the landfill characteristic inputs, gas/pollutant selections (see Section 4.0), and waste acceptance rate data (see Section 5.0), click on *Clear ALL Non-Parameter Inputs/Selections* in the USER INPUTS worksheet. These inputs will then return to their defaults.

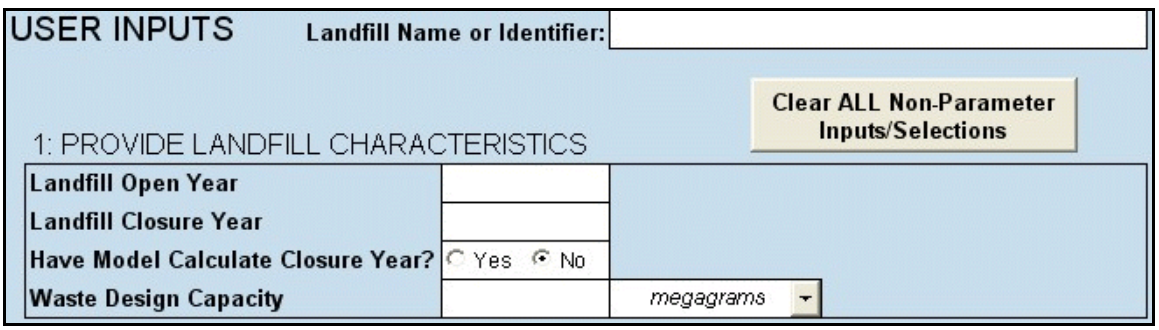


Image 2. Landfill Characteristics Inputs.

2.1 Landfill Name or Identifier

Use the *Landfill Name or Identifier* to enter a landfill's name and scenario information (for example, "Landfill A - Closed Cells" or "Landfill A - Leachate Recirculation Cells"). You can also enter information about the landfill as it relates to the types of model parameters chosen (for example, "Landfill B - NSPS/EG Conventional k Value" or "Landfill B - User-specified k = 0.06"). Model parameters are discussed further in Section 3.0. The *Landfill Name or Identifier* entry box is limited to 50 characters.

The *Landfill Name or Identifier* you enter on the USER INPUTS worksheet is shown in the same location on other worksheets within LandGEM. You are not required to enter information into the *Landfill Name or Identifier* entry box. The *Landfill Name or Identifier* entry box is not affected by the *Clear ALL Non-Parameter Inputs/Selections* button.

2.2 Landfill Open Year

Landfill Open Year is a required input and represents the year that the landfill began accepting waste. The open year should be in a four-digit year format (e.g., 2004).

2.3 Landfill Closure Year

Landfill Closure Year represents either of the following in LandGEM:

- Final year the landfill accepted waste, or
- Year the landfill is expected to reach *Waste Design Capacity*.

LandGEM uses the closure year of the landfill to determine the final year the landfill has accepted or is planning to accept waste. The "permitted" closure year of the landfill does not always represent the same year the landfill ceases to accept waste.

Landfill Closure Year is not a required input. However, if *Landfill Closure Year* is unknown, then you **must** select *Yes* for the *Have Model Calculate Closure Year?* option, AND you **must** enter *Waste Design Capacity*. If you enter a closure year, but still select *Yes* for the option to have the model calculate closure year, then the model will disregard the closure year you entered and automatically calculate closure year for you.

The model limits the number of years for entering *Waste Acceptance Rates* to 80 years (see Section 5.0 for further discussion about *Waste Acceptance Rates*). If the *Landfill Closure Year* entered is greater than 80 years from the *Landfill Open Year* entered (i.e., over 80 years of waste acceptance), then the model will disregard the *Landfill Closure Year* entered and will assign the 80th year past the *Landfill Open Year* as the final year of waste acceptance (or the closure year) used by the model to estimate emissions. For example, if you enter a *Landfill Open Year* of 1940, a *Landfill Closure Year* of 2030, and *Waste Acceptance Rates* for 1940-2004, then the model will only allow *Waste Acceptance Rates* to be entered for 2005 to 2019 and will calculate emissions as though the landfill closed in 2019. See Section 2.6 for instructions on estimating total emissions properly for scenarios where landfills accept waste beyond the waste acceptance limit of 80 years.

2.4 Have Model Calculate Closure Year?

If *Landfill Closure Year* is unknown, select *Yes* for the option to have the model calculate closure year. The default option is *No*. You **must** enter the *Waste Design Capacity* if you want the model to calculate closure year for you. *Waste Design Capacity* is discussed further in Section 2.5.

If you allow LandGEM to determine the closure year, it does so based on *Landfill Open Year*, *Waste Design Capacity*, and *Waste Acceptance Rates* you entered. Essentially, LandGEM calculates the closure year by summing the *Waste Acceptance Rates* entered, subtracting this "waste-in-place" amount from the *Waste Design Capacity* entered, and then dividing by the final (or most recent) acceptance rate entered. The model assumes that your final waste acceptance rate entered will continue to be the annual amount of waste accepted until closure of the landfill or until there are 80 years of waste acceptance, whichever scenario comes first (see Section 5.0 for further discussion about *Waste Acceptance Rates*).

Example 1 illustrates how the model calculates the closure year if it is unknown.

Example 1. Scenario for Unknown *Landfill Closure Year*

Landfill open year = 1970
Landfill closure year = ?
Have model calculate closure year? = Yes
Waste design capacity = 5,000,000 short tons
Waste acceptance rate from 1970 to 1990 = 100,000 short tons/year
Waste acceptance rate from 1991 to 2000 = 200,000 short tons/year

$$\textbf{Calculated landfill closure year} = \left[\frac{(\textbf{Waste design capacity} - \Sigma(\textbf{Waste acceptance rates}))}{\textbf{Final waste acceptance rate in 2000}}\right] + \textbf{Year of final waste acceptance rate}$$

$$\textbf{Calculated landfill closure year} = \left[\frac{(\textbf{5,000,000 short tons} - \textbf{4,100,000 short tons})}{\textbf{200,000 short tons}}\right] + \textbf{2000}$$

$$= \textbf{2005}$$

The model limits the number of years for entering *Waste Acceptance Rates* to 80 years (see Section 5.0 for further discussion about *Waste Acceptance Rates*). If the *Waste Design Capacity* has not been reached by the 80th year of waste acceptance, then the model will assign the 80th year past the *Landfill Open Year* entered as the final year of waste acceptance (or the closure year) used by the model to estimate emissions. For example, if you allow the

model to calculate closure year and enter a *Landfill Open Year* of 1960, a *Waste Design Capacity* of 10,000,000 Mg, and *Waste Acceptance Rates* of 100,000 Mg/year for 1960–2004, then the model will calculate emissions as though the landfill closed in 2039 because that is when it will reach the 80-year limit of waste acceptance. See Section 2.6 for instructions on estimating total emissions properly for scenarios where landfills accept waste beyond the waste acceptance limit of 80 years.

2.5 Waste Design Capacity

Waste Design Capacity represents the total amount of waste that can be disposed of in the landfill, or the amount of "waste-in-place" upon closure. Enter *Waste Design Capacity* only when you select *Yes* for the *Have Model Calculate Closure Year?* option. If you enter *Waste Design Capacity* without selecting *Yes*, the model will simply disregard the capacity amount you entered.

Waste Design Capacity can be entered in metric units of megagrams or English units of short tons. (Note: One megagram is equivalent to one metric ton.) Select the units of measure using the drop-down menu. The default unit of measure for *Waste Design Capacity* is megagrams.

Landfill gas emission factors were developed using empirical data from U.S. MSW landfills. The composition of waste in the landfills reflects U.S. waste composition including MSW, inert material, and other non-hazardous waste streams. If a portion of the landfill contains primarily non-biodegradable waste (i.e., inert material), such as ash from waste combustion, this portion may be subtracted from the *Waste Design Capacity*, depending upon documentation and approval from a regulatory authority. However, this is not recommended for sites that are typical of MSW landfills, which contain a range of waste that may or may not be degradable. This is because the emission factors were developed relating total waste quantity to total quantity of landfill gas.

2.6 Landfills Accepting Waste Over 80 Years

Sections 2.3 and 2.4 explain scenarios where LandGEM will implement a waste acceptance limit of 80 years in order to estimate emissions properly. If you are modeling a landfill that either has accepted or will accept waste for over 80 years, then multiple model runs are required to calculate emissions for the entire waste acceptance lifetime of the landfill. You should associate a unique file name and *Landfill Name or Identifier* in the USER INPUTS worksheet for each model run to properly identify the order of the model runs ("Landfill X - Run 1 of 2" and "Landfill X - Run 2 of 2," for example).

When the 80-year waste acceptance limit is exceeded, the INPUT REVIEW worksheet reports the actual landfill closure year that would be reached in absence of the 80-year limit. The additional years of waste acceptance can be modeled in a successive model run in order to capture the total emissions from the actual waste acceptance lifetime. The METHANE worksheet provides the waste-in-place amount at the end of the initial 80 years and remaining waste capacity from the final year of the initial model run if you have chosen to have model calculate closure year. These values can be used as inputs for the second model run. Once both model runs have been completed, then the emissions on the RESULTS worksheet from each run can be summed together by year for each gas/pollutant to result in total emissions for the actual waste acceptance lifetime of the landfill.

Example 2 outlines a scenario for running LandGEM multiple times in order to accurately represent the emissions for landfills accepting waste over 80 years.

Example 2. Scenario for Landfills Accepting Waste Over 80 Years

First Model Run Inputs on USER INPUTS Worksheet:
Landfill open year = 1940
Landfill closure year = ?
Have model calculate closure year? = Yes
Waste design capacity = 12,000,000 Mg
Waste acceptance rate from 1940 to 2000 = 100,000 Mg/year
Waste acceptance rate from 2001 to 2004 = 200,000 Mg/year

First Model Run Results on METHANE Worksheet:
Closure year (with 80-year limit) = 2019
Actual closure year (without limit) = 2030
Calculated waste acceptance rate from 2005 to 2019 = 200,000 Mg/year
Waste-in-place at start of next model run = 9,900,000 Mg
Capacity remaining at start of next model run = 2,100,000 Mg

Second Model Run Inputs on USER INPUTS Worksheet:
Landfill open year = 2020 [One year past closure year from the first model run]
Landfill closure year = ?
Have model calculate closure year? = Yes
Waste design capacity = 2,100,000 Mg [Capacity remaining from the first model run]
Waste acceptance rate for 2020 = 200,000 Mg/year [Calculated waste acceptance rate from the first model run]

Second Model Run Results on METHANE Worksheet:
Closure year (with 80-year limit) = Actual closure year (without limit) = 2030
Total annual emissions for each gas/pollutant = (Run 1 emissions) + (Run 2 emissions)
For example, methane emissions for 2021 = $2.586\times10^{7} + 1.662\times10^{6} = 2.752\times10^{7}$

Section 3.
Determining Model Parameters

LandGEM relies on several model parameters to estimate landfill emissions.

- Methane generation rate (k),
- Potential methane generation capacity (L_o),
- NMOC concentration, and
- Methane content.

Default values for the model parameter inputs on the USER INPUTS worksheet are shown in Image 3. Model parameters should be selected using consistent default options. For example, if "Inventory Conventional - 0.04" is chosen for k, then "Inventory Conventional - 100" should be selected for L_o and "Inventory No or Unknown Co-disposal - 600" or "Inventory Co-disposal - 2,400" should be selected for *NMOC Concentration*. When using LandGEM to determine whether a landfill is subject to the control requirements of the NSPS/EG or NESHAP, CAA defaults **must** be chosen for all four model parameters.

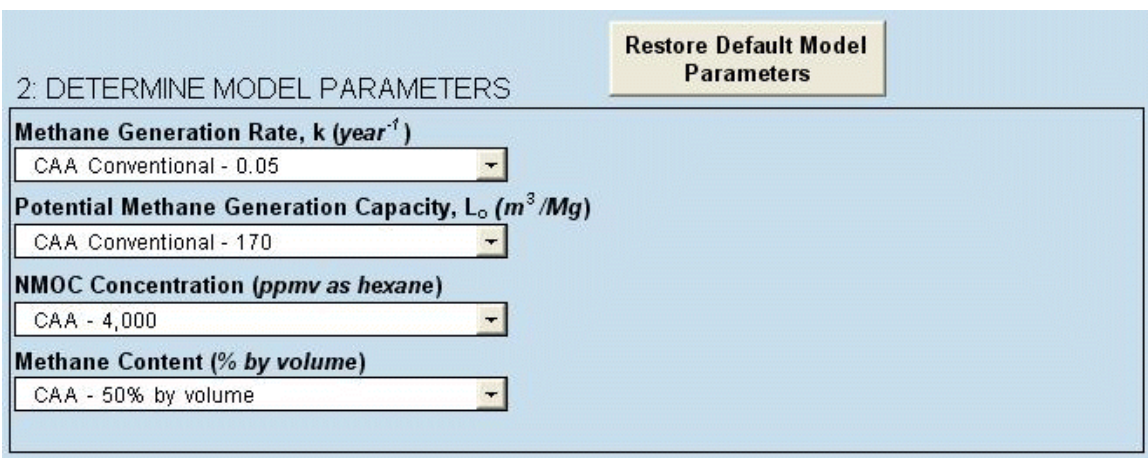


Image 3. Model Parameters Inputs.

You may select each of the model parameters from the drop-down menu. Alternatively, you may enter site-specific model parameter values other than the default values based on field

data or other information. Select *User-specified* for the model parameter for which you would like to enter site-specific data. A *User-specified value* entry box will appear to the right of that parameter and you can enter the site-specific value. *User-specified value* entry boxes only appear when *User-specified* is selected from the drop-down menu for a particular model parameter.

Clicking on *Restore Default Model Parameters* in the USER INPUTS worksheet resets all four of the model parameters back to their default values (shown in Image 3) and removes any user-specified values entered.

3.1 Methane Generation Rate (*k*)

The *Methane Generation Rate*, *k*, determines the rate of methane generation for the mass of waste in the landfill. The higher the value of *k*, the faster the methane generation rate increases and then decays over time. The value of *k* is primarily a function of four factors:

- Moisture content of the waste mass,
- Availability of the nutrients for microorganisms that break down the waste to form methane and carbon dioxide,
- pH of the waste mass, and
- Temperature of the waste mass.

Use EPA Method 2E to determine site-specific *k* values for user-specified data. The *k* value, as it is used in the first-order decomposition rate equation, is in units of 1/year, or year^{-1}. The five *k* values used by LandGEM are shown in Table 2. Arid area landfills are located in areas that receive less than 25 inches of rainfall per year. The default *k* value is the CAA *k* value for conventional landfills.

Table 2. Values for the Methane Generation Rate (*k*).

Default Type	Landfill Type	*k* Value year^{-1}
CAA	Conventional	0.05 (default)
CAA	Arid Area	0.02
Inventory	Conventional	0.04
Inventory	Arid Area	0.02
Inventory	Wet (Bioreactor)	0.7

3.2 Potential Methane Generation Capacity (L_o)

The *Potential Methane Generation Capacity*, L_o, depends only on the type and composition of waste placed in the landfill. The higher the cellulose content of the waste, the higher the value of L_o. The default L_o values used by LandGEM are representative of MSW. The L_o value, as it is used in the first-order decomposition rate equation, is measured in metric units of cubic meters per megagram to be consistent with the CAA. The five L_o values used by LandGEM are shown in Table 3. The default L_o value is the CAA L_o value for conventional landfills.

Table 3. Values for the Potential Methane Generation Capacity (L_o).

Emission Type	Landfill Type	L_o Value - m^3/Mg
CAA	Conventional	170 (default)
CAA	Arid Area	170
Inventory	Conventional	100
Inventory	Arid Area	100
Inventory	Wet (Bioreactor)	96

3.3 Nonmethane Organic Compound Concentration

The *NMOC Concentration* in landfill gas is a function of the types of waste in the landfill and the extent of the reactions that produce various compounds from the anaerobic decomposition of waste. *NMOC Concentration* is measured in units of parts per million by volume (ppmv) and is used by LandGEM only when NMOC emissions are being estimated. The *NMOC Concentration* for the CAA default is 4,000 ppmv as hexane. The *NMOC Concentration* for the inventory default is 600 ppmv where co-disposal of hazardous waste has either not occurred or is unknown and 2,400 ppmv where co-disposal of hazardous waste has occurred.

The default *NMOC Concentration* is the CAA value. If you use a site-specific value for NMOC concentration, then you must correct for air infiltration. EPA Method 25C is recommended for obtaining a site-specific concentration of NMOCs.

3.4 Methane Content

For LandGEM, landfill gas is assumed to be 50 percent methane and 50 percent carbon

dioxide, with additional, trace constituents of NMOCs and other air pollutants. When using LandGEM for complying with the CAA, *Methane Content* must remain fixed at 50 percent by volume (the model default value).

You may choose other methane amounts for the *Methane Content* using the *User-specified* selection if data exist to support using another concentration. However, using LandGEM at landfills that have methane content outside the range of 40 to 60 percent is not recommended. The first-order decomposition rate equation used by LandGEM to determine emissions may not be valid outside of this range.

The production of methane is determined using the first-order decomposition rate equation and is not affected by the concentration of methane. However, the concentration of methane affects the calculated production of carbon dioxide. The production of carbon dioxide (Q_{CO2}) is calculated from the production of methane (Q_{CH4}) and the methane content percentage (P_{CH4}) using the equation

$$Q_{CO2} = Q_{CH4} \times \left\{ \left[1 / \left(P_{CH4} / 100 \right) \right] - 1 \right\}$$

This equation is derived as follows:

$$\begin{aligned}
Q_{total} &= Q_{CH4} + Q_{CO2} \\
Q_{CH4} &= Q_{total} \times \left(P_{CH4} / 100 \right) \\
Q_{CO2} &= Q_{total} - Q_{CH4} = \left[Q_{CH4} / \left(P_{CH4} / 100 \right) \right] - Q_{CH4} \\
Q_{CO2} &= Q_{CH4} \times \left\{ \left[1 / \left(P_{CH4} / 100 \right) \right] - 1 \right\}
\end{aligned}$$

where Q_{total} is the total production of landfill gas.

Section 4.
Selecting Gases/Pollutants

You can choose four gases or air pollutants to be modeled at one time. The gases and pollutants to choose from and data associated with them are shown in Table 4.

Table 4. Gas/Pollutant Default Data Used in LandGEM.

Gas/Pollutant	Concentration (*ppmv*)	Molecular Weight	Notes
Gases			
Total landfill gas	Not applicable	30.03	
Methane	Not applicable	16.04	
Carbon dioxide	Not applicable	44.01	
NMOCs	4,000 for CAA	86.18	
	600 for Inventory No or Unknown Co-disposal		
	2,400 for Inventory Co-disposal		
Pollutants:			
1,1,1-Trichloroethane (methyl chloroform)	0.48	133.41	A
1,1,2,2-Tetrachloroethane	1.1	167.85	A, B
1,1-Dichloroethane (ethylidene dichloride)	2.4	98.97	A, B
1,1-Dichloroethene (vinylidene chloride)	0.20	96.94	A, B
1,2-Dichloroethane (ethylene dichloride)	0.41	98.96	A, B
1,2-Dichloropropane (propylene dichloride)	0.18	112.99	A, B
2-Propanol (isopropyl alcohol)	50	60.11	B
Acetone	7.0	58.08	
Acrylonitrile	6.3	53.06	A, B
Benzene	1.9 for No or Unknown Co-disposal	78.11	A, B
	11 for Co-disposal		
Bromodichloromethane	3.1	163.83	B
Butane	5.0	58.12	B
Carbon disulfide	0.58	76.13	A, B
Carbon monoxide	140	28.01	

Table 4. Gas/Pollutant Default Data Used in LandGEM (Concluded)

Carbon tetrachloride	4.0×10^{-3}	153.84	A, B
Carbonyl sulfide	0.49	60.07	A, B
Chlorobenzene	0.25	112.56	A, B
Chlorodifluoromethane	1.3	86.47	
Chloroethane (ethyl chloride)	1.3	64.52	A, B
Chloroform	0.03	119.39	A, B
Chloromethane	1.2	50.49	B
Dichlorobenzene	0.21	147	B, C
Dichlorodifluoromethane	16	120.91	
Dichlorofluoromethane	2.6	102.92	B
Dichloromethane (methylene chloride)	14	84.94	A
Dimethyl sulfide (methyl sulfide)	7.8	62.13	B
Ethane	890	30.07	
Ethanol	27	46.08	B
Ethyl mercaptan (ethanethiol)	2.3	62.13	B
Ethylbenzene	4.6	106.16	A, B
Ethylene dibromide	1.0×10^{-3}	187.88	A, B
Fluorotrichloromethane	0.76	137.38	B
Hexane	6.6	86.18	A, B
Hydrogen sulfide	36	34.08	
Mercury (total)	2.9×10^{-4}	200.61	A
Methyl ethyl ketone	7.1	72.11	A, B
Methyl isobutyl ketone	1.9	100.16	A, B
Methyl mercaptan	2.5	48.11	B
Pentane	3.3	72.15	B
Perchloroethylene (tetrachloroethylene)	3.7	165.83	A
Propane	11	44.09	B
t-1,2-Dichloroethene	2.8	96.94	B
Toluene	39 for No or Unknown Co-disposal 170 for Co-disposal	92.13	A, B
Trichloroethylene (trichloroethene)	2.8	131.40	A, B
Vinyl chloride	7.3	62.50	A, B
Xylenes	12	106.16	A, B

A. Hazardous air pollutants (HAP) listed in Title III of the 1990 Clean Air Act Amendments.
B. Considered volatile organic compounds (VOC), as defined by U.S. EPA in 40 CFR 51.100(s).
C. Source tests did not indicate whether this compound was the para- or ortho- isomer. The para- isomer is a Title III-listed HAP.

Concentrations, molecular weights, and notes for NMOCs and the 46 air pollutants contained in Table 4 are from Tables 2.4-1 and 2.4-2 of AP-42 (November 1998 version). These default pollutant concentrations have already been corrected for air infiltration, as stated in AP-42. If you use a site-specific value for *NMOC Concentration*, then you must

correct for air infiltration.

As discussed in Section 3.3, the *NMOC Concentration* for the inventory default is 600 ppmv where co-disposal of hazardous waste has either not occurred or is unknown and 2,400 ppmv where co-disposal of hazardous waste has occurred. Similarly, benzene and toluene have different concentrations depending upon the co-disposal status of the landfill. Both no or unknown co-disposal and co-disposal concentrations are shown in Table 4 for these pollutants.

The molecular weight of landfill gas was estimated using a weighted average of the molecular weights for methane and carbon dioxide. The molecular weight of 30.03 represents landfill gas as 50 percent methane and 50 percent carbon dioxide. If the *Methane Content* model parameter is changed to a value other than 50 percent, then the molecular weight of total landfill gas is adjusted to represent the appropriate methane content.

Image 4 shows where you can select four gases or pollutants on the USER INPUTS worksheet. Each of the gas or pollutant entries can be selected from the drop-down menus.

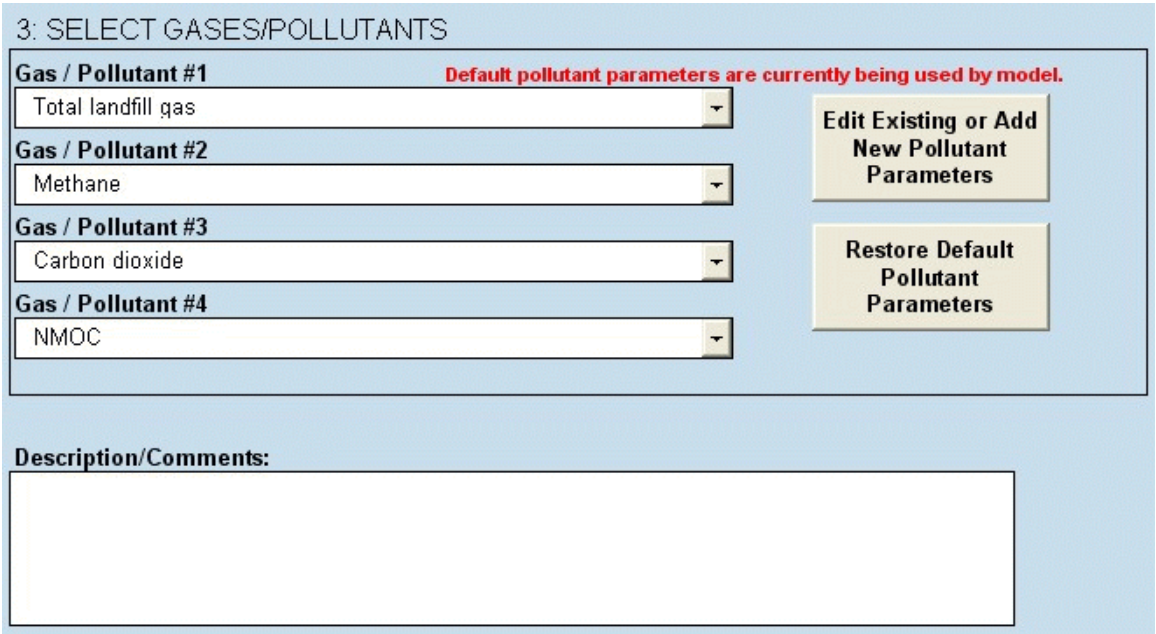


Image 4. Gas/Pollutant Inputs.

The *Edit Existing or Add New Pollutant Parameters* button in the USER INPUTS worksheet allows you to change the default pollutant parameters, including concentrations and molecular weights, for any of the 46 air pollutants listed on the drop-down menus, as well as add new pollutants and corresponding parameters. Clicking on the *Edit Existing or Add New Pollutant Parameters* button lets you view and edit the default parameters for existing pollutants in the POLLUTANTS worksheet. The default parameters shown on the POLLUTANTS worksheet are identical to the ones in Table 4. In addition, there are entry boxes at the bottom of the POLLUTANTS worksheet where you can enter new pollutants and corresponding concentrations and molecular weights. The *Enter New Pollutant Parameters* and *Edit Existing Pollutant Parameters* buttons at the top of the POLLUTANTS worksheet help guide you through this worksheet.

The model does not allow you to edit default parameters for total landfill gas, methane, carbon dioxide, or NMOCs, nor does it allow you to change names of existing pollutants. To restore the default pollutant parameters for existing pollutants and remove any new pollutants you may have added, click on the *Restore Default Pollutant Parameters* button in the USER INPUTS worksheet. Clicking this button also returns the gas/pollutant drop-down menus in the USER INPUTS worksheet to their default selections.

In the *Description/Comments* entry box, you can enter detailed information about the landfill or the scenario you are modeling. The *Description/Comments* entry box is limited to 450 characters.

To clear all of the gas/pollutant selections (but not the pollutant parameters) and the landfill characteristics and waste acceptance rate inputs (see Section 5.0), click on *Clear ALL Non-Parameter Inputs/Selections* in the USER INPUTS worksheet. The gas/pollutant drop-down menus will return to their default selections, as shown in Image 4. The *Description/Comments* box is not affected by the *Clear ALL Non-Parameter Inputs/Selections* button.

Section 5.
Entering Waste Acceptance Data

Waste Acceptance Rates **must** be entered in the USER INPUTS worksheet for LandGEM to properly estimate emissions. Enter annual acceptance rates for each year listed in the *Waste Acceptance Rates* table from the *Landfill Open Year* to the current year or the *Landfill Closure Year*. The *Waste Acceptance Rates* table is shown in Image 5. Once you enter the *Landfill Open Year*, the year column of the *Waste Acceptance Rates* table automatically shows the years for which acceptance rate data are needed.

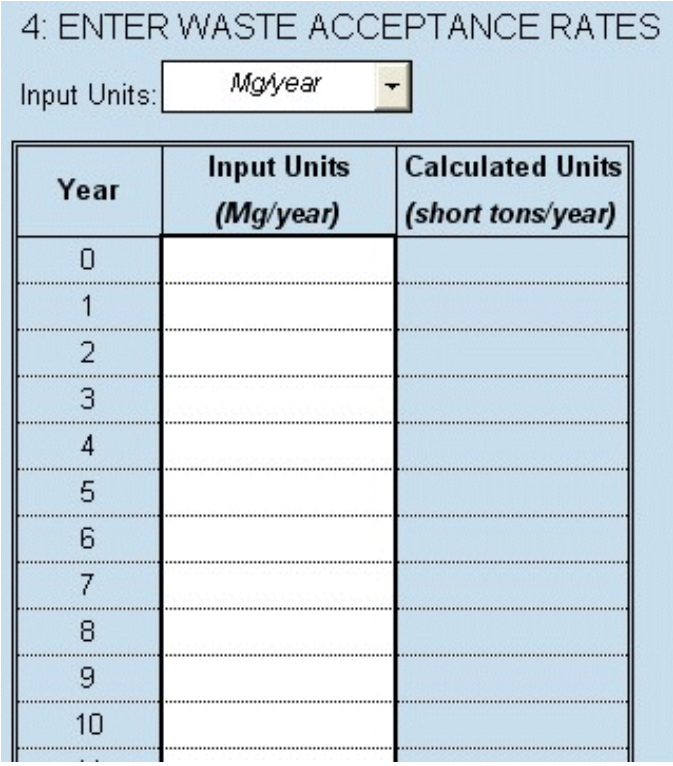


Image 5. Waste Acceptance Rate Inputs.

You may enter *Waste Acceptance Rates* in metric units of megagrams per year or English units of short tons per year by selecting from the drop-down menu. The default unit of measure for *Waste Acceptance Rates* is megagrams per year. If you enter acceptance rates in

units of megagrams per year, then LandGEM automatically calculates and displays the acceptance rates in units of short tons per year. Likewise, if you enter acceptance rates in short tons per year, then LandGEM automatically calculates and displays acceptance rates in megagrams per year.

The model makes the assumptions outlined in Table 5. regarding data entered in the *Waste Acceptance Rates* table.

Table 5. Acceptance Rate Input Options.

If you...	Then LandGEM will...
Enter acceptance rates beyond the *Landfill Closure Year* you entered,	Ignore the acceptance rates you entered past the *Landfill Closure Year*.
Enter acceptance rates through the current year but not up to the *Landfill Closure Year* you entered,	Apply the final (or most recent) acceptance rate you entered to the years between the current year and the *Landfill Closure Year*.
Enter acceptance rates through the current year and choose to have the model calculate closure year,	Apply the final (or most recent) acceptance rate you entered to each successive year not having an acceptance rate until the waste design capacity is reached. A smaller acceptance rate may be used the last year to achieve the exact design capacity. The final year the landfill receives waste becomes the closure year.

The model limits the number of years for entering *Waste Acceptance Rates* to 80 years. See Section 2.6 for instructions on estimating total emissions properly for scenarios where landfills accept waste beyond the waste acceptance limit of 80 years.

Landfill gas emission factors were developed using empirical data from U.S. MSW landfills. The composition of waste in the landfills reflects U.S. waste composition including MSW, inert material, and other non-hazardous waste streams. For a landfill that may have a portion containing non-biodegradable waste (i.e., inert material), such as ash from waste combustion, this portion may be subtracted from the *Waste Acceptance Rates* depending on documentation and approval from a regulatory authority. However, this is not recommended for sites that are typical of MSW landfills containing a range of waste that may or may not be degradable. This is because the emission factors were developed relating total waste quantity to total quantity of landfill gas.

To clear all entries in the *Waste Acceptance Rates* table, in addition to landfill characteristics inputs and gas/pollutant selections, click on *Clear ALL Non-Parameter Inputs/Selections* in the USER INPUTS worksheet. The *Waste Acceptance Rates* table then returns to its defaults, as shown in Image 5.

Section 6.
Printing Inputs

To review your inputs as they will be used by LandGEM, go to the INPUT REVIEW worksheet. All data entered in the USER INPUTS worksheet as well as inputs determined by the model, such as calculated landfill closure year and waste acceptance rates as they are interpreted by LandGEM, appear on the INPUT REVIEW worksheet. Image 6 shows a scenario where closure year is unknown.

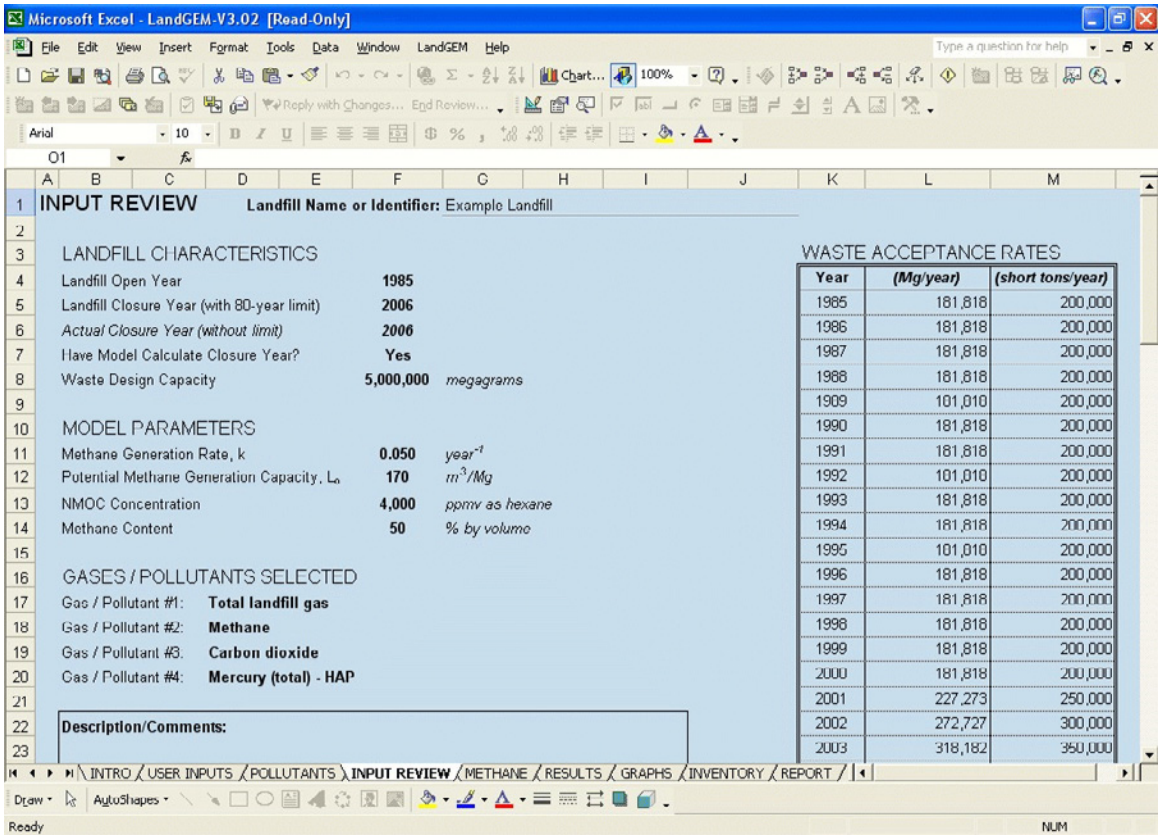
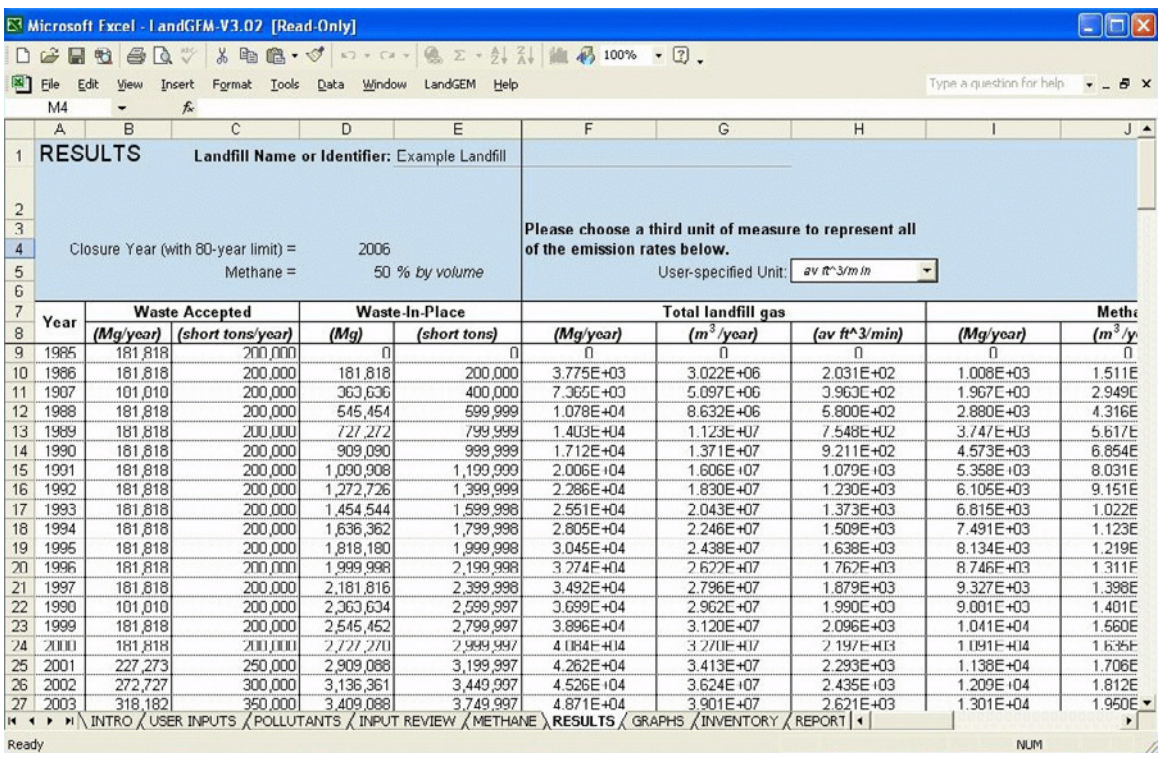


Image 6. INPUT REVIEW Worksheet.

To print the INPUT REVIEW worksheet, select *Print...* from the *File* menu. The INPUT REVIEW worksheet is set to print on one page. However, you may adjust this, as well as other print settings, by selecting *Page Setup...* from the *File* menu.

Section 7.
Viewing and Printing Tabular Results

To view emission estimates in a tabular format, go to the RESULTS worksheet. When comparing results from LandGEM with measurements of extracted gas collected at a site, the landfill owner or operator must adjust for air infiltration prior to any comparisons. Image 7 displays the RESULTS worksheet for the scenario shown in Image 6.



RESULTS — Landfill Name or Identifier: Example Landfill

Closure Year (with 80-year limit) = 2006

Methane = 50 % by volume

Please choose a third unit of measure to represent all of the emission rates below.

User-specified Unit: av ft^3/min

Year	Waste Accepted (Mg/year)	Waste Accepted (short tons/year)	Waste-In-Place (Mg)	Waste-In-Place (short tons)	Total landfill gas (Mg/year)	Total landfill gas (m^3/year)	Total landfill gas (av ft^3/min)	Meth (Mg/year)	Meth (m^3/y
1985	181,818	200,000	0	0	0	0	0	0	0
1986	181,818	200,000	181,818	200,000	3.775E+03	3.022E+06	2.031E+02	1.008E+03	1.511E
1907	101,010	200,000	363,636	400,000	7.365E+03	5.097E+06	3.963E+02	1.967E+03	2.949E
1988	181,818	200,000	545,454	599,999	1.078E+04	8.632E+06	5.800E+02	2.880E+03	4.316E
1989	181,818	200,000	727,272	799,999	1.403E+04	1.123E+07	7.548E+02	3.747E+03	5.617E
1990	181,818	200,000	909,090	999,999	1.712E+04	1.371E+07	9.211E+02	4.573E+03	6.854E
1991	181,818	200,000	1,090,908	1,199,999	2.006E+04	1.606E+07	1.079E+03	5.358E+03	8.031E
1992	181,818	200,000	1,272,726	1,399,999	2.286E+04	1.830E+07	1.230E+03	6.105E+03	9.151E
1993	181,818	200,000	1,454,544	1,599,998	2.551E+04	2.043E+07	1.373E+03	6.815E+03	1.022E
1994	181,818	200,000	1,636,362	1,799,998	2.805E+04	2.246E+07	1.509E+03	7.491E+03	1.123E
1995	181,818	200,000	1,818,180	1,999,998	3.045E+04	2.438E+07	1.638E+03	8.134E+03	1.219E
1996	181,818	200,000	1,999,998	2,199,998	3.274E+04	2.622E+07	1.762E+03	8.746E+03	1.311E
1997	181,818	200,000	2,181,816	2,399,998	3.492E+04	2.796E+07	1.879E+03	9.327E+03	1.398E
1990	101,010	200,000	2,363,634	2,599,997	3.699E+04	2.962E+07	1.990E+03	9.001E+03	1.401E
1999	181,818	200,000	2,545,452	2,799,997	3.896E+04	3.120E+07	2.096E+03	1.041E+04	1.560E
2000	181,818	200,000	2,727,270	2,999,997	4.084E+04	3.270E+07	2.197E+03	1.091E+04	1.636E
2001	227,273	250,000	2,909,088	3,199,997	4.262E+04	3.413E+07	2.293E+03	1.138E+04	1.706E
2002	272,727	300,000	3,136,361	3,449,997	4.526E+04	3.624E+07	2.435E+03	1.209E+04	1.812E
2003	318,182	350,000	3,409,088	3,749,997	4.871E+04	3.901E+07	2.621E+03	1.301E+04	1.950E

Image 7. RESULTS Worksheet.

Data on the RESULTS worksheet include

- Landfill closure year (provided on USER INPUTS worksheet or calculated),
- Methane content from USER INPUTS worksheet,
- Years of waste acceptance from open year to closure year of the landfill,
- Annual waste acceptance rates used by the model in megagrams per year and short

tons per year,

- Annual waste-in-place amounts based on acceptance rates used by the model, in megagrams and short tons,
- Annual emission estimates for the four gases/pollutants selected on the USER INPUTS worksheet in megagrams per year, cubic meters per year, and a third measurement unit that you may select from the drop-down menu. The third unit of measure options are average cubic feet per minute, cubic feet per year, and short tons per year. LandGEM uses average cubic feet per minute as the default third unit.

To print the RESULTS worksheet, select *Print...* from the *File* menu. The RESULTS worksheet is set to print on one page. However, you may adjust this as well as other print settings by selecting *Page Setup...* from the *File* menu.

Formatting of the values contained in the RESULTS worksheet is protected from user modification. To adjust the number formats of the values contained in the RESULTS worksheet, you will need to copy and paste the emission estimates into a new Microsoft Excel file by following the instructions below:

1. Highlight cells A7 to Q149 and select *Copy* from the *Edit* menu,
2. Open a new Microsoft Excel file by selecting *New...* (*Blank Workbook*) from the *File* menu,
3. Select *Paste Special...* from the *Edit* menu and click on the *Values* radio button in the *Paste Special* window that appears.
4. You can now change the number formats of these emission values by selecting *Cells...Number* from the *Format* menu.

It is important to note that when the *Methane Content* is assumed to be 50 percent by volume (default), then methane and carbon dioxide emission rates are identical on a volume basis (e.g., cubic meters per year, average cubic feet per minute, cubic feet per year) because carbon dioxide is also assumed to be 50 percent by volume. However, methane and carbon dioxide emission rates will differ from one another on a mass basis (e.g., megagrams per year, short tons per year) because methane and carbon dioxide have different molecular weights and, thus, different mass emissions.

Section 8.
Viewing and Printing Graphical Results

To view the emission estimates in a graphical format, go to the GRAPHS worksheet. Image 8 contains one of the three graphs generated on the GRAPHS worksheet for the scenario shown in Image 6.

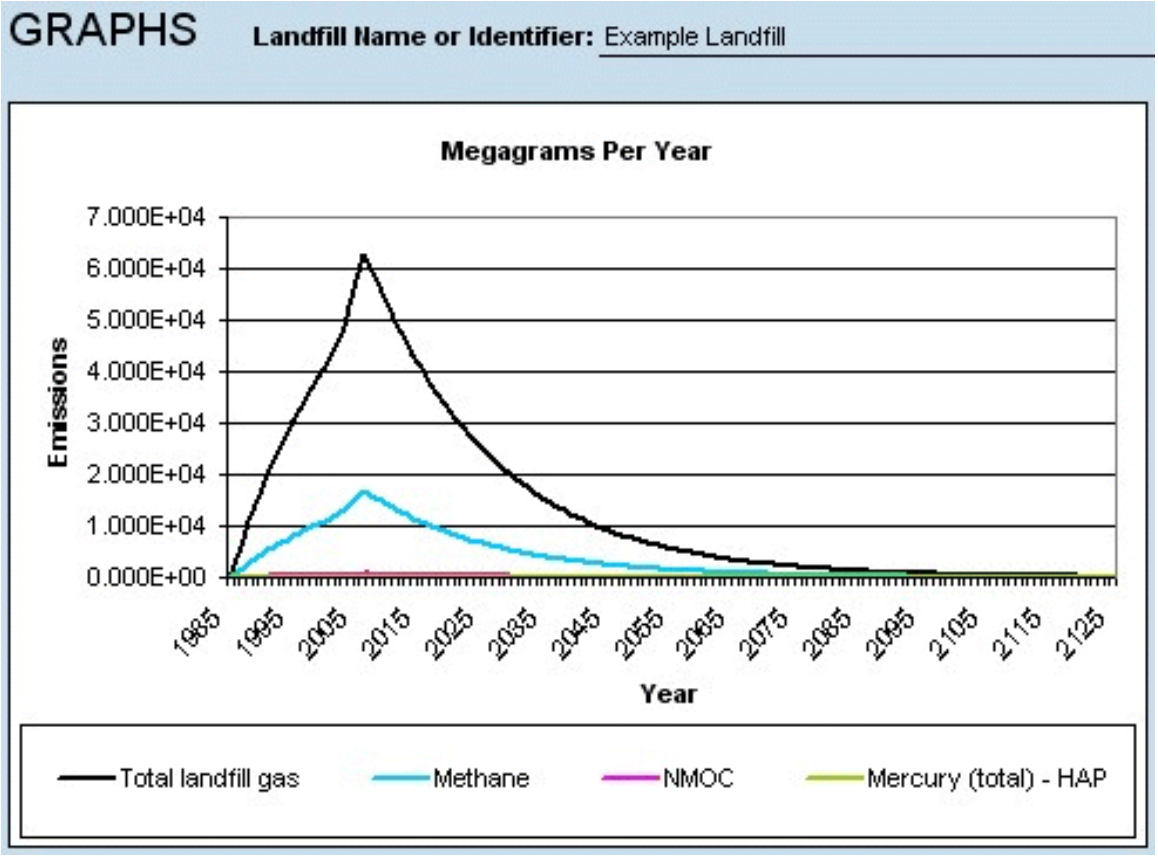


Image 8. Graphical Results in Units of Megagrams per Year.

A total of three graphs are generated for each scenario, one for each unit of measure of emissions on the RESULTS worksheet. The top two graphs are in units of megagrams per year and cubic meters per year, respectively. The third graph represents the units you

selected on the RESULTS worksheet (see Section 7.0 for further discussion), which defaults to average cubic feet per minute. The emission estimates for all four gases or pollutants are shown on each of the three graphs using a different color to represent each gas or pollutant's emissions.

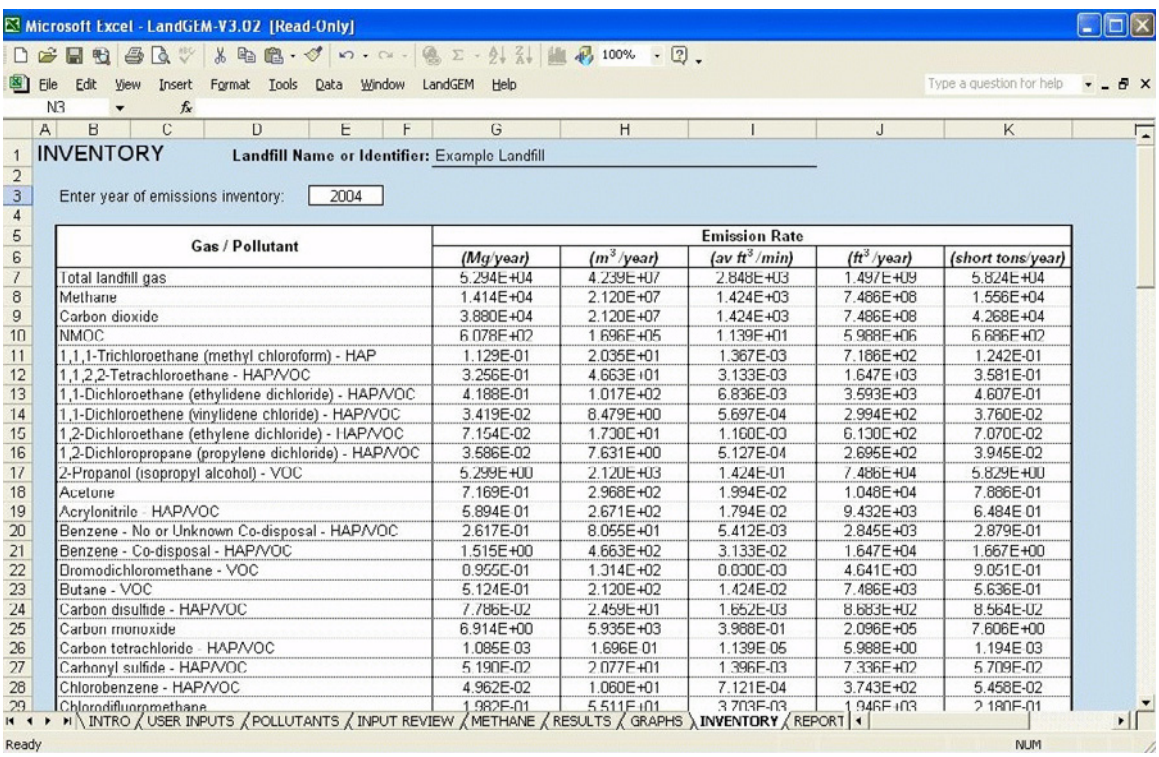
To print the GRAPHS worksheet, select *Print...* from the *File* menu. The GRAPHS worksheet is set to print on one page. However, you may adjust this as well as other print settings by selecting *Page Setup...* from the *File* menu.

Editing and formatting of the graphs are protected from user modification. To create graphs that can be edited or formatted, you will need to copy and paste the emission estimates from the RESULTS worksheet or the INVENTORY worksheet into a new Microsoft Excel file by following the instructions below.

1. Highlight the cells containing the values to be graphed and select *Copy* from the *Edit* menu.
2. Open a new Microsoft Excel file by selecting *New...* (*Blank Workbook*) from the *File* menu.
3. Select *Paste Special...* from the *Edit* menu and click on the *Values* radio button in the *Paste Special* window that appears.
4. You can now create graphs from these emission values by selecting *Chart...* from the *Insert* menu and following the instructions in the *Chart Wizard* window.

Section 9.
Viewing and Printing Inventory Results

To view emission estimates for use in emission inventories and air permits, go to the INVENTORY worksheet. This worksheet allows you to view and print emission estimates for a particular year for all gases or pollutants in megagrams per year, cubic meters per year, average cubic feet per minute, cubic feet per year, and short tons per year. You **must** enter a valid four-digit year in the designated entry box to obtain estimates for a particular year. The inventory year entered **must** be between the year after the *Landfill Open Year* entered and 140 years past the *Landfill Open Year*. Image 9 displays the INVENTORY worksheet for the scenario shown in Image 6.



INVENTORY Landfill Name or Identifier: Example Landfill

Enter year of emissions inventory: 2004

Gas / Pollutant	Emission Rate				
	(Mg/year)	(m^3/year)	(av ft^3/min)	(ft^3/year)	(short tons/year)
Total landfill gas	5.294E+04	4.239E+07	2.848E+03	1.497E+09	5.824E+04
Methane	1.414E+04	2.120E+07	1.424E+03	7.486E+08	1.556E+04
Carbon dioxide	3.880E+04	2.120E+07	1.424E+03	7.486E+08	4.268E+04
NMOC	6.078E+02	1.696E+05	1.139E+01	5.988E+06	6.686E+02
1,1,1-Trichloroethane (methyl chloroform) - HAP	1.129E-01	2.035E+01	1.367E-03	7.186E+02	1.242E-01
1,1,2,2-Tetrachloroethane - HAP/VOC	3.256E-01	4.663E+01	3.133E-03	1.647E+03	3.581E-01
1,1-Dichloroethane (ethylidene dichloride) - HAP/VOC	4.188E-01	1.017E+02	6.836E-03	3.593E+03	4.607E-01
1,1-Dichloroethene (vinylidene chloride) - HAP/VOC	3.419E-02	8.479E+00	5.697E-04	2.994E+02	3.760E-02
1,2-Dichloroethane (ethylene dichloride) - HAP/VOC	7.154E-02	1.730E+01	1.160E-03	6.130E+02	7.070E-02
1,2-Dichloropropane (propylene dichloride) - HAP/VOC	3.586E-02	7.631E+00	5.127E-04	2.695E+02	3.945E-02
2-Propanol (isopropyl alcohol) - VOC	5.299E+00	2.120E+03	1.424E-01	7.486E+04	5.829E+00
Acetone	7.169E-01	2.968E+02	1.994E-02	1.048E+04	7.886E-01
Acrylonitrile - HAP/VOC	5.894E-01	2.671E+02	1.794E-02	9.432E+03	6.484E-01
Benzene - No or Unknown Co-disposal - HAP/VOC	2.617E-01	8.055E+01	5.412E-03	2.845E+03	2.879E-01
Benzene - Co-disposal - HAP/VOC	1.515E+00	4.663E+02	3.133E-02	1.647E+04	1.667E+00
Bromodichloromethane - VOC	0.955E-01	1.314E+02	0.000E-03	4.641E+03	9.051E-01
Butane - VOC	5.124E-01	2.120E+02	1.424E-02	7.486E+03	5.636E-01
Carbon disulfide - HAP/VOC	7.786E-02	2.459E+01	1.652E-03	8.683E+02	8.564E-02
Carbon monoxide	6.914E+00	5.935E+03	3.988E-01	2.096E+05	7.606E+00
Carbon tetrachloride - HAP/VOC	1.085E-03	1.696E-01	1.139E-05	5.988E+00	1.194E-03
Carbonyl sulfide - HAP/VOC	5.190E-02	2.077E+01	1.396E-03	7.336E+02	5.709E-02
Chlorobenzene - HAP/VOC	4.962E-02	1.060E+01	7.121E-04	3.743E+02	5.458E-02
Chlorodifluoromethane	1.982E-01	5.511E+01	3.703E-03	1.946E+03	2.180E-01

Image 9. INVENTORY Worksheet.

To print the INVENTORY worksheet, select *Print...* from the *File* menu. The INVENTORY worksheet is set to print on one page. However, you may adjust this as well as other print settings by selecting *Page Setup...* from the *File* menu.

Formatting of the values contained in the INVENTORY worksheet is protected from user modification. To adjust the number formats of the values contained in the INVENTORY worksheet, you will need to copy and paste the emission estimates into a new Microsoft Excel file by following the instructions below:

1. Highlight cells B5 to K68 and select *Copy* from the *Edit* menu.
2. Open a new Microsoft Excel file by selecting *New...* (*Blank Workbook*) from the *File* menu.
3. Select *Paste Special...* from the *Edit* menu and click on the *Values* radio button in the *Paste Special* window that appears.
4. You can now change the number formats of these emission values by selecting *Cells...Number* from the *Format* menu.

Section 10.
Viewing and Printing the Summary Report

To view the summary report, go to the REPORT worksheet. Information contained in the summary report on the RESULTS worksheet includes

- A cover page showing the LandGEM title screen (pop-up introduction window that includes the model version and date), Landfill Name or Identifier and Description/Comments entered in the USER INPUTS worksheet, the current date, the first-order decomposition rate equation used to estimate emissions, and a general description of the model,
- Data contained in the INPUT REVIEW worksheet, including landfill characteristics, model parameters, gases/pollutants selected, waste acceptance rates, and yearly waste-in-place amounts,
- Emission estimates in graphical format, as shown on the GRAPHS worksheet, and
- Emission estimates in tabular format, from the RESULTS worksheet.

To print the REPORT worksheet, select *Print...* from the *File* menu. The REPORT worksheet is set to print on seven pages. However, you may adjust this as well as other print settings by selecting *Page Setup...* from the *File* menu.

Section 11.
Additional Information and References

Additional Information

For further information regarding landfill gas emissions, please access the following Web sites and documents:

- *Rules and Implementation Information for Standards of Performance for MSW Landfills*. EPA, Technology Transfer Network, Air Toxics Website: http://www.epa.gov/ttnatw01/landfill/landflpg.html.
  The following topics are included on this Web site:
  - Proposed and Promulgated Rules, including the NSPS/EG requirements,
  - Closely Related Rules, Policies or Program Guidance,
  - Technical Information, including Background Information Document (BID)/Response to Comments, Fact Sheets, and Risk Assessment,
  - Implementation and Enabling Documents,
  - Emission Estimation Tools, including the LandGEM software,
  - Source Identification and Location,
  - Outreach and Training Materials,
  - Permitting,
  - Compliance and Enforcement.

- *NESHAP Rule and Implementation Information for Municipal Solid Waste Landfills*. EPA, Technology Transfer Network, Air Toxics Website: http://www.epa.gov/ttnatw01/landfill/lndfillpg.html.
  The following topics are included on this Web site:
  - Proposed and Promulgated Rules, including the NESHAP requirements,
  - Closely Related Rules, Policies or Program Guidance,
  - Technical Information, including Background Information Document (BID)/Response to Comments, Fact Sheets, and Economic Analysis,
  - Implementation Documents,
  - Source Identification and Location,
  - Outreach and Training Materials,

- Permitting,
- Compliance and Enforcement.

- *Compilation of Air Pollutant Emission Factors (AP-42), Volume 1: Stationary Point and Area Sources, 5th ed., Chapter 2.4: Municipal Solid Waste Landfills*. EPA, Office of Air Quality Planning and Standards. Research Triangle Park, NC. http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s04.pdf.

- *Use of Landfill Gas Generation Model to Estimate VOC Emissions from Landfills*. Memorandum from Y.C. McGuinn, Radian Corporation, to Susan Thorneloe, EPA. June 21, 1988. Public Docket No. A-88-09.

- *Sensitivity Analysis of Landfill Gas Generation Model*. Memorandum from Y.C. McGuinn, Radian Corporation, to Susan Thorneloe, EPA. June 21, 1988. Public Docket No. A-88-09.

- *Methodology Used to Revise the Model Inputs in the Municipal Solid Waste Landfills Input Database (Revised)*. Memorandum from W.R. Pelt, Radian Corporation, to Municipal Solid Waste Landfills Docket A-88-09. April 28, 1993. Public Docket No. A-88-09.

- Methane Emissions from Landfills and Open Dumps, In *EPA Report to Congress on International Anthropogenic Methane Emissions: Estimates for 1990.* S.A. Thorneloe, M. Doorn, and M. Barlaz. EP A, Office of Policy, Planning and Evaluation. Washington, DC, 1994. EPA-230-R-93-010.

- *Landfill Gas Utilization – Options, Benefits, and Barriers, The Second United States Conference on Municipal Solid Waste Management, Arlington, VA*. S.A. Thorneloe. Published in Conference Proceedings, June 3–5, 1992.

- *Global Methane Emissions from Waste Management*. S.A. Thorneloe, M. A. Barlaz, R. Peer, L. C. Huff, L. Davis, and J. Mangino. Published in Atmospheric Methane: Sources, Sinks, and Role in Global Change, NATO ASI Series, Vol. 13, 1993.

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EPA, 1991b. *Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste Landfills,* proposed rule. Federal Register, 56 FR 24468, May 30.

EPA, 1991c. *Regulatory Package for New Source Performance Standards and III(d) Guidelines for Municipal Solid Waste Air Emissions,* Public Docket No. A-88-09 (proposed May 1991). U.S. Environmental Protection Agency, Research Triangle Park, NC.

EPA, 1996. *Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste Landfills*, final rule. Federal Register, 61 FR 9905, March 12.

EPA, 1998. *Compilation of Air Pollutant Emission Factors, AP-42, Volume 1: Stationary Point and Area Sources*, 5th ed., Supplement E, Chapter 2.4: Municipal Solid Waste Landfills. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, November.

McGuinn, Y.C., 1988a. Memorandum. Radian Corporation, to Susan Thorneloe, EPA. *Use of Landfill Gas Generation Model to Estimate VOC Emissions from Landfills*, Public Docket No. A-88-09, June 21.

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Thorneloe, S.A., A. Reisdorph, M. Laur, R. Pelt, R.L. Bass, and C. Burklin, 1999. The U.S. Environmental Protection Agency's Landfill Gas Emissions Model (LandGEM), Sardinia 99, Seventh International Waste Management and Landfill Symposium, Published in Proceedings, Volume IV, Pages 11–18, October 4–8.

Thorneloe, S.A. and J.G. Pacey, 1994. *Landfill Gas Utilization--Database of North American Projects*, Presented at the 17th Annual International Landfill Gas Symposium by the Solid Waste Association of North America, Long Beach, CA, March 22-24.

Thorneloe, S.A., M. Doorn, M. Barlaz, et al., 1994. Methane Emissions from Landfills and Open Dumps, In *EPA Report to Congress on International Anthropogenic Methane Emissions: Estimates for 1990*. EPA-230-R-93-010.

Appendix A
Technical Background

Introduction

The Landfill Gas Emissions Model (LandGEM) provides an automated estimation tool for quantifying air emissions from municipal solid waste (MSW) landfills. The model was developed by the Control Technology Center (CTC) of the U.S. Environmental Protection Agency and can be obtained by downloading from the TTNWeb (http://www.epa.gov/ttn/catc/products.html#software). It is also available from the National Technical Information Service (NTIS).

Air emissions from landfills come from landfill gas generated by the decomposition of waste in the landfill. Landfill gas is assumed by this model to be roughly half methane and half carbon dioxide with additional, relatively low, concentrations of other air pollutants. The following information is needed to estimate emissions from a landfill (see the Glossary of Terms at the end of Appendix A):

- The waste design capacity of the landfill,
- The amount of waste-in-place in the landfill or the annual waste acceptance rate for the landfill,
- The methane generation rate (k),
- The potential methane generation capacity (L_o),
- The concentration of total nonmethane organic compounds (NMOCs) and speciated NMOCs found in the landfill gas,
- The years the landfill has been in operation, and
- Whether the landfill has been used for disposal of hazardous waste (co-disposal).

The estimation method used by the model is a simple first-order decay equation. Because the data available for landfills (such as data on the quantity, age, and composition of the waste in the landfill) are limited, using a more sophisticated calculation method is not justified. The Landfill Gas Emissions Model estimates emissions of total landfill gas, methane, carbon dioxide (CO_2), NMOCs, and selected air pollutants. Information on the assumptions used in the model can be found in the background information document (EPA, 1991a) written to support the Standards of Performance for New Stationary Sources (NARA, 1997a) and Emission Guidelines for Control of Existing Sources (NARA, 1997b) and in the public docket (McGuinn, 1988a; McGuinn, 1988b; Pelt, 1993).

The Landfill Gas Emissions Model can be used with site-specific data for all the information needed to generate emission estimates, or it can be used with two different sets of default values. One set of default values (the CAA defaults) is for estimating emissions to determine the applicability of the Clean Air Act (CAA) regulations for MSW landfill emissions,

specifically the New Source Performance Standards (NSPS) for new MSW Landfills and the emission guidelines (EG) for existing MSW landfills. The NSPS/EG were initially proposed May 30, 1991 (EPA, 1991b), and the final rule was promulgated on March 12, 1996 (EPA, 1996).

The applicability of the NSPS/EG to a particular landfill can be determined based on emissions estimated using the CAA defaults in the model. The applicability of the NSPS/EG to a particular landfill is determined in tiers. There is, first, a size cutoff (i.e., 2.5 million tons or 2.5 million cubic meters of waste) below which landfills are not subject to the rule. After the size cutoff, the first tier of the applicability determination is to assess whether emissions of NMOCs exceed a cutoff value of 50 Mg of NMOCs/yr using LandGEM with all default values set for the CAA defaults. Landfills with emissions exceeding the cutoff value can choose to install emission controls or move to the second tier of the applicability determination, which is to test the landfill for landfill gas NMOC concentrations. If the revised NMOC concentrations result in NMOC emissions that still exceed the cutoff value, the landfill can choose to install emission controls or move to the third tier of the applicability determination, which is to perform another test to obtain a site-specific *k* value (the methane generation rate constant).

The CAA default values in the model provide emission estimates that would reflect the expected maximum emissions and generally would be used only for determining the applicability of the regulations to a landfill. To estimate actual emissions in the absence of site-specific data, a second set of default values (the inventory defaults) is provided in the model. The inventory default values in the model are based on emission factors from the U.S. Environmental Protection Agency's *Compilation of Air Pollutant Emission Factors*, *AP-42* (EPA, 1998). The inventory default values provide emission estimates that should reflect typical landfill emissions and are the values suggested for use in developing estimates for state inventories.

The EPA fully recognizes that modeling landfill air emissions accurately is difficult due to limitations in available information for inputs to the model. However, as new landfills are constructed and operated and better information is collected, the present modeling approach can be improved. As better data become available, including longer term data on landfill air emissions, better modeling approaches are expected to evolve. For example, several firms in the landfill gas industry have models for estimating landfill emissions that are regarded as proprietary. If this information is released to the public, the EPA can use it to improve the present emission estimation approach. In addition, as data become available through the

implementation of the NSPS/EG, the new data can be used to improve the modeling calculations.

Landfill Emissions

The Landfill Gas Emissions Model estimates the emissions resulting from the biodegradation of waste in landfills. The anaerobic decomposition of waste in MSW landfills causes emissions of landfill gas. As landfill gas passes through the waste, it sweeps NMOCs and other air pollutants present in the waste to the surface. The composition of MSW landfill emissions is estimated by the model to be about 50 percent methane (CH_4) and 50 percent carbon dioxide (CO_2), with additional, trace constituents of NMOCs, although, these default percentages can easily be changed. The concentration of total and speciated NMOCs can be estimated by the model using either default or site-specific concentrations. The pollutant regulated under the NSPS/EG is MSW landfill emissions, but the surrogate for measuring MSW landfill emissions for the applicability of and compliance with the regulations is NMOCs.

The EPA has determined that emissions from MSW landfills cause, or contribute significantly to, air pollution that may reasonably be anticipated to endanger public health or welfare. Some NMOCs are known or suspected carcinogens, or cause other noncancer health effects. Public welfare concerns include the odor nuisance from the landfill gas and the potential for CH_4 migration, both on-site and off-site, which may lead to explosions or fires. The CH_4 emitted from landfills is also a concern because it is a greenhouse gas and contributes to global climate change. It has been estimated that the United States contributed 8 to 16 Tg/yr of CH_4 to the atmosphere in 1990, about 40 percent of the worldwide amount emitted from landfills and open dumps (Thorneloe and Pacey, 1994; Thorneloe et al., 1994). The environmental and welfare concerns associated with MSW landfill air emissions are documented in the preamble to the proposed NSPS/EG (EPA, 1991c).

This computer model uses a first-order decomposition rate equation and estimates annual emissions over any time period specified by the user. Total landfill gas emissions are estimated by estimating CH_4 generation and doubling it (the landfill gas is assumed to be half CH_4 and half CO_2). Methane generation is estimated using L_o, the potential CH_4 generation capacity of the waste, and k, the CH_4 generation rate constant, which accounts for how quickly the CH_4 generation rate decreases once it reaches its peak rate. The CH_4 generation rate is assumed to be at its peak upon closure of the landfill or final placement of waste at the site. The model allows the user to enter L_o and k values derived using site-specific test data collected at the landfill (site-specific data may be collected using the test

methods specified in the NSPS/EG for MSW landfills), or to use the CAA or inventory default values.

The model estimates emission rates for total landfill gas, CH_4, CO_2, NMOCs, and a list of air pollutants expected to be emitted from landfills based on test data from AP-42 (EPA, 1998).

Methane and Carbon Dioxide

The NSPS/EG require only NMOC emission estimates, but the model provides estimates of all landfill gas constituents. Landfill gas is assumed to be half CH_4 and half CO_2. The model assumes that CO_2 emissions are the same as CH_4 emissions and that landfill gas emissions are twice the CH_4 emissions. The generation of CH_4 from a landfill is a function of k, the CH_4 generation rate constant, and L_o, the CH_4 generation potential.

The CH_4 generation rate constant, k, determines the rate of CH_4 generation for each submass of waste in the landfill. The higher the value of k, the faster the CH_4 generation rate increases and then decays over time. The value of k is a function of (1) waste moisture content, (2) availability of the nutrients for methanogens, (3) pH, and (4) temperature. The k values obtained from the data collected for the NSPS/EG range from 0.003 to 0.21 (EPA, 1991a). These values were obtained from theoretical models using field test data and from actual field test measurements. If no user-specified k value is entered into LandGEM, a default value is used. The default k value used by the model is 0.05 $year^{-1}$ for the CAA conventional landfills option (EPA, 1991a).

The value for the potential CH_4 generation capacity of waste (L_o) depends only on the type of waste in the landfill. The higher the cellulose content of the waste, the higher the value of L_o. The values of theoretical and obtainable L_o range from 6.2 to 270 m^3/Mg of waste (EPA, 1991c). If no user-specified L_o value is entered into LandGEM, a default value is used for L_o. The default L_o value used in the model is 170 m^3/Mg of waste for the CAA conventional landfills option (EPA, 1991a).

Air Pollutants

Landfill gas contains low concentrations of air pollutants from the leaching and decomposition of waste. The Landfill Gas Emissions Model can estimate emissions of such air pollutants if users choose to do so. Emissions of air pollutants are based on concentrations of air pollutants in the landfill gas. The model contains default concentrations for specific air pollutant compounds. The list of air pollutants expected to be emitted with

landfill gas and the concentrations of these air pollutants were taken from test data in AP-42 (EPA, 1998). The default air pollutants included in the model are designated as a hazardous air pollutant (HAP) or a volatile organic compound (VOC) with the HAP or VOC abbreviation after their chemical names. These designations are based on EPA HAP and VOC definitions that are current as of April 2004.

Because some air pollutant concentrations in the landfill gas are slightly higher for landfills that have been used for disposal of hazardous waste than for those that have not, there is a choice in the model between "Co-disposal," (i.e., landfills used for disposal of hazardous and non-hazardous waste), and "No or Unknown Co-disposal," (i.e., landfills that have not been used for disposal of hazardous waste or unknown disposal of hazardous waste). For example, concentrations in the model for benzene and toluene are different for landfills with hazardous waste "Co-disposal" than for landfills with "No or Unknown Codisposal."

Landfill sites that have hazardous waste co-disposal or Superfund sites should use the co-disposal option for estimating air pollutant emissions. In general, it is recommended that landfill owners and operators obtain actual test data for air pollutant concentrations in the landfill gas for their specific landfill.

Nonmethane Organic Compounds

The NMOC concentration in the landfill gas is a function of the types of waste in the landfill and the extent of the reactions that produce various compounds from the anaerobic decomposition of waste. To determine NMOC concentrations, NMOC data were collected from emission test reports from industry, state, and local regulatory agencies (Pelt, 1993). The NMOC concentrations from 23 landfills ranged from 240 to 14,300 ppmv. Three suggested default NMOC concentrations are used in the model: one for the CAA default option and two for the inventory default option (one for co-disposal and one for no or unknown co-disposal). For the CAA default option, the NMOC concentration as hexane is 4,000 ppmv. For the inventory default option, the NMOC concentration as hexane for co-disposal is 2,400 ppmv and is 600 ppmv for no or unknown co-disposal. The analysis of NMOC concentrations in landfill gas is documented in a memorandum (Pelt, 1993), which can be found in Public Docket No. A-88-09 and in AP-42 (EPA, 1998). Because the NMOC concentration in landfill gas varies from landfill to landfill, collection of site-specific data using EPA Method 25C will provide the most accurate estimates (EPA, 1991c).

GLOSSARY OF TERMS

Term	Definition
Co-disposal	Disposal of hazardous waste as well as other kinds of waste in a landfill.
Waste Design Capacity	The total amount of waste that can be disposed of in the landfill.
Landfill Gas	Landfill gas is a product of biodegradation of waste in landfills and consists of primarily CH_4 and CO_2, with trace amounts of NMOCs and air pollutants.
Methane Generation Rate (k)	k is a constant that determines the rate of landfill gas generation. The first-order decomposition rate assumes that k values before and after peak landfill gas generation are the same. k is a function of moisture content in the landfill waste, availability of nutrients for methanogens, pH, and temperature.
Nonmethane Organic Compounds (NMOCs)	NMOCs are specified in this program as the fraction of landfill gas containing nonmethane organic compounds, expressed as hexane. NMOCs include air pollutants and VOCs. NMOC concentration can be measured using guidance provided by EPA Method 25C.
Potential Methane Generation Capacity (L_o)	L_o is a constant that represents the potential capacity of a landfill to generate CH_4 (a primary constituent of landfill gas). L_o depends on the amount of cellulose in the waste.
Air Pollutants	Compounds found in landfill gas or emitted with landfill gas, some of which are listed as air pollutants under section 112 of the Clean Air Act (CAA). A total of 46 air pollutants emitted from landfills are included in the model.
Landfill Closure Year	The year in which the landfill ceases, or is expected to cease, accepting waste.