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Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills

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Notice

The U.S. Environmental Protection Agency (EPA) through its Office of Research and Development performed and managed the research described in this report. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document. Any opinions expressed in this report are those of the author and do not, necessarily, reflect the official positions and policies of the EPA. Any mention of products or trade names does not constitute recommendation for use by the EPA.

Abstract

This document was prepared for U.S. EPA's Office of Research and Development in support of EPA's Office of Air Quality Planning and Standards (OAQPS). The objective is to summarize available data used to update emissions factors for quantifying landfill gas emissions and combustion by-products using more up-to-date and representative data for U.S. municipal landfills. This document provides background information used in developing a draft of the AP-42 section 2.4 which provides guidance for developing estimates of landfill gas emissions for national, regional, and state emission inventories. EPA OAQPS will be conducting the review of Section 2.4. Once comments are addressed, the AP-42 section will be updated and available through EPA's Technology Transfer Network (TTN) Clearinghouse for Inventories & Emissions (http://www.epa.gov/ttn/chief/ap42/). This report is considered a stand-alone report providing details of available data and analysis for developing landfill gas emission factors and combustion by-products for a wider range of pollutants and technologies.

The inputs that are described in this report are used in EPA's Landfill Gas Emission Model (LandGEM) for developing inputs for state, regional, and national emission inventories. Data from 62 LFG emissions tests from landfills with waste in place on or after 1992 were used to develop updated factors for use in LandGEM. This document also provides updated and additional emission factors for combustion by-products for control devices such as flares, boilers, and engines.

Of the 293 emissions tests submitted to EPA for this update, over 200 contained inadequate documentation or information for use in this update. The reports that were used included LFG composition data and, in some cases, emissions data on LFG combustion by-products. These emissions tests were screened for quality and compiled to create emission factors for non-methane organic compounds (NMOC), as well as speciated compounds in LFG. This update expands the list of emission factors for LFG constituents from 44 to 167 and provides many more "A" quality rated emission factors. Likewise, combustion by-product emission factors for dioxins/furans were added in this update, along with improved ratings of the other combustion by-product emission factors as a result of the addition of new data.

Updated information is provided of changes in the design and operation of U.S. MSW landfills along with updated statistics on the amount of waste being landfilled. Information on quantifying area source emissions (OTM10) is provided based on the use of Optical Remote Sensing technology and Radial Plume Mapping (ORS-RPM). The first-order equation used to estimate LFG emissions has been modified to add a factor to account for LFG capture efficiency. Due to the increase in the use of leachate recirculation, a gas production rate to characterize emissions from wet landfills has been added. The rate constant is based on an optimum moisture content using data from about 30 landfills using leachate recirculation. Information on air emission concerns regarding construction/demolition waste landfills and landfill fires have also been added to the AP-42 section.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

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 C. Gutierrez, Director
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1.0 INTRODUCTION

The document "Compilation of Air Pollutant Emission Factors" (AP-42) has been published periodically by the U.S. Environmental Protection Agency (EPA) since 1972. New emission source categories and updates to existing emission factors to supplement the AP-42 have been routinely published. These supplements are in response to the emission factor needs of the EPA, state, and local air pollution control programs, and industry. The prior update to this section was performed in 1998 (U.S. EPA, 1998).

This background information document describes the data analysis undertaken to develop updated emission factors and guidance for the AP-42 section for Municipal Solid Waste (MSW) Landfills. The data being used for this update is from industry-supplied information and additional data collected from state and local regulatory agencies. The most comprehensive set of data from measurements of five landfills of the header pipe gas and combustion by-products was also used in developing updated factors. This data is from a field study by EPA's Office of Research and Development (U.S. EPA, 2007a) which was co-funded by the Environmental Research and Education Foundation.

The data being used to update landfill gas emission factors is primarily from landfills with waste in place on or after 1992. Resource Conservation and Recovery Act (RCRA) Subtitle D regulations, specifically 40 CFR Part 258, were effective October 9, 1993, but applied to landfills accepting waste on or after October 9, 1991. It is, therefore, likely that landfills began instituting the provisions of Subtitle D during their operations around 1992. The regulatory provisions limited the types of waste that could be landfilled with municipal solid waste (MSW). For example, prior to RCRA Subtitle D, hazardous waste could be co-disposed with MSW. Therefore, a distinction is made between the landfill gas (LFG) constituents present in data from waste prior to 1992, and those that were measured at landfills with the majority of their waste in place on or after 1992. The previous update of AP-42 contained the data for LFG with waste in place on or before 1992. This document includes the addition of data for combustion by-products from flares, boilers, and engines (control data applies to both pre and post 1992 landfills). However, no additional data for gas turbines was received for this update. Therefore, the data present for turbines in the last AP-42 update were unchanged during this update. Chapter 2.7 presents the background information for the pre-1992 landfills, and supporting information from the previous version of the background information document is included as Appendix A for historical purposes. To assist the reader in determining where background information is located for a certain type of emission from a landfill or control device, the following table is provided to serve as a quick guide on where to go to obtain background information on the topics found in the AP-42 section:

AP-42 Chapter Topic:	Location in this Background Information Document:
Calculating Uncontrolled Landfill Gas Emissions	Chapter 2.1
Landfill Gas Constituents From Landfills with Waste in Place On or After 1992	Chapters 2.2 through 2.6
Landfill Gas Constituents From Landfills with Waste in Place Before 1992	Chapter 2.7
Control Device Emissions (for both pre and post-1992 Landfills)	Chapter 3.0
Mercury Emissions From Landfills with Waste in Place on or After 1992	Chapter 4.0
2008 Version of AP-42 Chapter 2.4 Municipal Solid Waste Landfills	Chapter 5.0

In addition to the new data analysis detailed in this background document, there were updates to the AP-42 chapter text which are briefly summarized below:

- The introduction to the AP-42 section contains a description of MSW landfills and related landfill statistics that were developed prior to the last update in 1998. This information has been updated including update updated statistics on U.S. waste disposal.

- Information was added on EPA's recommended approach for quantifying emissions from area sources (OTM 10; http://www.epa.gov/ttn/emc/tmethods.html). This approach uses optical remote sensing technology and radial plume mapping (ORS-RPM) to quantify uncontrolled emissions from landfills which includes leaks from header pipes, extraction wells, side slopes, and landfill cover material. (U.S. EPA, 2007b) Optical remote sensing technologies use an optical emission detector such as open-path Fourier transform infrared spectroscopy (FTIR), ultraviolet differential absorption spectroscopy (UV-DOAS), or open-path tunable diode laser absorption spectroscopy (OP-TDLAS); coupled with radial plume mapping software that processes path-integrated emission concentration data and meteorological data to yield an estimate of uncontrolled emissions. More information on ORS-RPM is described in the *Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology* (EPA/600/R-07/032). Ongoing research is helping to develop additional guidance using OTM 10 for landfill applications which can be more complex than other area source emissions such as waste lagoons and surface impoundments.

- Equation (1) in the AP-42 Section is used to estimate emissions from an uncontrolled landfill. In this update, a factor of 1.3 was added to Equation (1) to account for the fact that L_O is determined by the amount of gas collected by LFG collection systems. The design of these systems will typically result in a gas capture efficiency of only 75%. Therefore, 25% of the gas generated by the landfill is not captured and included in the development of L_O. The ratio of total gas to captured gas is a ratio of 100/75 or equivalent to 1.3. An analysis of the efficiency of typical LFG collection systems is presented in Appendix E. Previous equation being used did not account for total emissions which includes the quantity of gas that is collected plus any fugitive loss from leaks that can occur from header pipes, extraction wells, side slopes, and landfill cover material.

- There has been an increase in the occurrence of landfills that recirculate leachate to accelerate waste decomposition. An additional 'k' was added for use in the first-order equation to account for the increase in gas production from wet landfills. This was derived from a study that evaluated data from 29 wet landfills (Reinhart, 2005). For the purpose of AP-42, wet landfills are defined as landfills which add large amounts of liquid to the waste from recycled landfill leachate, condensate from LFG collection, and other sources of water such as treated wastewater.

- The use of petroleum contaminated soil or construction and demolition waste as daily cover may affect the characteristics of LFG. Primarily, non-methane organic compounds (NMOC) concentrations may be much higher in landfills where petroleum contaminated soil is used as daily cover. Likewise, sometimes elevated hydrogen sulfide concentrations are observed where wall board has been landfilled or recovered gypsum is used as daily cover

- Landfill fires, while uncommon, may occur from time to time. These fires may be significant sources of dioxins and other hazardous air pollutants resulting from incomplete combustion of material found in MSW.

References

Reinhart, Debra R., Ayman A. Faour, and Huaxin You, *First-Order Kinetic Gas Generation Model Parameters for Wet Landfills*, U. S. Environmental Protection Agency, (EPA-600/R-05/072), June 2005

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2.0 UNCONTROLLED LANDFILL GAS DATA ANALYSIS RESULTS

2.1 ESTIMATION OF UNCONTROLLED LANDFILL GAS EMISSIONS

To estimate uncontrolled emissions of the various compounds present in LFG, total uncontrolled LFG emissions must first be estimated. Emissions for uncontrolled LFG depend on several factors including: (1) the size, configuration, and operating conditions of the landfill; and (2) the characteristics of the refuse such as moisture content, age, and composition. Uncontrolled methane (CH_4) emissions may be estimated for individual landfills by using a theoretical first-order kinetic model of CH_4 production. This method of estimating emissions could result in conservative estimates of emissions, since it provides estimates of LFG generation and not LFG release to the atmosphere. Some capture and subsequent microbial degradation of organic LFG constituents within the landfill's surface layer may occur. However, LFG will take the path of least resistance so any leaks in the header pipe, extraction wells, side slopes, and cover material will be a potential source of fugitive loss. Although laboratory data is available, field test data on potential oxidation or biodegradation through the soil cover for individual constituents found in LFG was not available. Therefore the equation being used to estimate LFG emissions does not include a factor to account for potential reduction of emissions through soil cover.

The first-order kinetic model of CH_4 production in landfills is based on the following equation (U.S. EPA, 1991):

$$Q_{CH_4} = L_o\ R\,(e^{-kc} - e^{-kt}) \tag{1}$$

where:

Q_{CH_4} = Methane generation rate at time t, m^3/yr;

L_O = Methane generation potential, m^3 CH_4/Mg refuse;
R   = Average annual refuse acceptance rate during active life, Mg/yr;
e   = Base log, unitless;
k   = Methane generation rate constant, yr^{-1};
c   = Time since landfill closure, yrs (c = 0 for active landfills); and
t   = Time since the initial refuse placement, yrs.

Site-specific landfill information is generally available for variables R, c, and t. When refuse acceptance rate information is scant or unknown, R can be estimated by dividing the refuse in place by the age of the landfill (U.S. EPA, 1991). If a facility has documentation that a certain segment (cell) of a landfill has received only nondegradable refuse, then the waste from this segment of the landfill can be excluded from the calculation of R. Nondegradable refuse includes, but is not limited to, concrete, brick, stone, glass, plaster, piping, plastics, and metal objects. The average annual acceptance rate should only be estimated by this method when there is inadequate information available on the actual annual acceptance rate.

Values for the variables L_O and k must be estimated. The potential CH_4 generation capacity of refuse (L_O) is dependent on the organic (primarily cellulose) content of the refuse and can vary widely [6.2 to 270 m^3 CH_4/Mg refuse (200 to 8670 ft^3/ton)] (U.S. EPA, 1991). The value of the CH_4 generation constant (k) is dependent on moisture, pH, temperature, and other environmental factors, as well as landfill operating conditions (U.S. EPA, 1991).

A computer program that uses the theoretical model discussed above was developed by EPA and is known as Landfill Gas Emission Model or LandGEM (U.S. EPA, 2005). This model and User's Guide can be accessed from the Office of Air Quality Planning and Standards Technology Transfer Network

Website (OAQPS TTN Web) in the Clearinghouse for Inventories and Emission Factors (CHIEF) technical area (URL http://www.epa.gov/ttncatc1/products.html#software).

LandGEM includes both regulatory default values and recommended AP-42 default values for L_O and k (see below). The regulatory defaults, called "CAA factors," were developed for regulatory compliance purposes [New Source Performance Standards (NSPS), National Emissions Standards for Hazardous Air Pollutants (NESHAP) and Emission Guidelines (EG)] and provide conservative default values for municipal landfills. As a result, the regulatory L_O and k default values may not be representative of specific landfills, and may not be appropriate for use in an emissions inventory. Therefore, the LandGEM also includes a set of factors called "inventory factors" that are recommended for use when estimating LFG emissions for inventory purposes. LandGEM computes the total CH_4 generation based on the age of each landfill segment.

The recommended AP-42 defaults for k when estimating CH_4 emissions for inventory purposes are presented in Table 2-1. These recommendations are based on a comparison of gas-yield forecasts with LFG recovery data (U.S. EPA, 1991).

TABLE 2-1. RECOMMENDED VALUES OF k FOR USE IN MODELING UNCONTROLLED LANDFILL GAS EMISSIONS

Landfill Conditions	Inventory k Value
Areas receiving <25 inches/yr rainfall (U.S. EPA, 1991)	0.02
Areas receiving >25 inches/yr rainfall (U.S. EPA, 1991)	0.04
Wet landfills (Reinhart, 2005)	0.3

Based on work conducted in the late 1980's and early 1990's, a default L_O value of 100 m^3/Mg (3,530 ft^3/ton) refuse has been recommended for emission inventory purposes (Pelt, 1993). This L_O value was recommended because it provided the best agreement between emissions derived from empirical (measured) data to predicted emissions. The results of this comparison are depicted in Table 2-2. It must be emphasized that when complying with the NSPS and Emission Guideline, the regulatory defaults for k and L_O must be applied.

As part of this update of landfill emission factors, additional guidance is provided for estimating the flow rate of LFG from both controlled and uncontrolled landfills. The L_O value mentioned above of 100 m^3/Mg was based on data obtained by EPA from tests at 40 landfills conducted in the late 1980's and early 1990's (U.S. EPA, 1991). When the data from these landfills was used to develop the constants for the first order decay equation, the amount of gas that is uncontrolled was not accounted for in the equation. To correct for this, a factor has been added to estimate total emissions (both collected and uncontrolled).

The overall collection efficiency of a LFG collection system is affected by two factors: the specific collection efficiency of the gas collection system, and the portion and age of the waste that is excluded from the collection system. Specific collection efficiencies can range greatly based on the design of the landfill design and how well it is maintained and operated. A highly efficient collection system will include a liner under the waste and a cover over the waste that is comprised of a geomembrane and a thick layer of low-porosity clay. Each gas well in the high efficiency system is typically sealed to the geomembrane with a thick plug of bentonite clay material. Each gas well in the system is maintained under a strong vacuum and is monitored monthly. The landfill surface is also monitored frequently to identify leaks and initiate repairs immediately. Collection efficiencies as high as 95% have been reported for well designed and maintained LFG collection systems. However, the

collection efficiencies for a landfill that is unlined, has only a soil or porous clay cap and does not employ an aggressive operation and maintenance program might easily be as low as 50% to 60%.

TABLE 2-2. COMPARISON OF MODELED AND EMPIRICAL LFG GENERATION DATA WHEN L_O IS SET AT 100 m³/Mg[a]

Landfill[b]	Predicted CH$_4$ (10^6 m³/yr)	Predicted/ Empirical CH$_4$	Landfill[b]	Predicted CH$_4$ (10^6 m³/yr)	Predicted/ Empirical CH$_4$
a	37.6	0.68	u	4.62	0.63
b	39.9	0.77	v	10.5	1.44
c	31.8	0.73	w	4.28	0.72
d	49.8	1.51	x	5.62	0.96
e	12.1	0.53	y	2.39	0.44
f	17.3	0.82	z	9.59	1.84
g	23.6	1.28	aa	5.08	1.08
h	8.61	0.49	bb	4.93	1.15
i	14.9	0.93	cc	3.93	0.93
j	14.5	0.94	dd	2.74	1.03
k	14.2	0.96	ee	8.37	3.23
l	7.16	0.50	ff	117	0.83
m	18.0	1.31	gg	14.4	0.58
n	8.57	0.76	hh	23.0	1.44
o	4.56	0.48	ii	29.6	2.19
p	17.4	1.87	jj	19.3	1.47
q	10.2	1.21	kk	22.4	1.71
r	6.95	0.87	ll	41.3	4.00
s	2.29	0.29	mm	7.14	0.81
t	3.49	0.45	nn	1.07	0.29
Average					1.10
Maximum					3.23
Minimum					0.29
Standard Dev.					0.73

[a] k = 0.04
[b] Landfill names are considered to be confidential.

The second factor which has a very significant influence on collection efficiency is the portion and age of the waste that is excluded from the gas collection system. There is normally a lag time between the placement of waste in a new landfill cell and the installation of a gas collection system in the cell. Landfills that have reached a sufficient size (i.e., waste in place is equal or greater than 2.5 million tons of waste) and NMOC emissions equal or exceed 50 megagrams per year are required by NSPS and EG to install a gas collection system. The time table specified in the NSPS/EG is that gas collection is to

be installed in open cells within five years of initial waste placement and in cells that have been closed for two or more years. As a result, a typical landfill will not have the most recent two to five years of waste included within its gas collection system. The impact of excluding the most recent portions of their waste mass from the collection system is magnified by the fact that the LFG emission rate is greatest in the first years of the waste's life and drops rapidly with time.

Therefore, a system capable of collecting 90% of the gas generated from the landfill cells in which it is installed is operating at reduced landfill-wide collection efficiency (i.e., less than 90%) due to the loss of uncollected gas from cells that have yet to be capped and connected to the collection system. All active landfills contain open cells and waste cells that have yet to be capped and fitted with a gas collection system. Table 2-3 demonstrates the impact of the delay in collecting gas from newer cells. The values in this table were generated using the first order decay model (Pelt, 1993) and assuming a L_O of 100 and a k of 0.04. The landfill was assumed to be operating (i.e., accepting waste) over a 20 year timeframe.

The years of delay between the placement of waste in a cell and the installation of wells in the cell are presented in the first column of Table 2-3. The effective landfill-wide collection efficiency of the gas collection system is presented in the second and third columns for gas collection systems with efficiencies of 90% and 85%, respectively. Large active landfills will typically install gas collection systems within two to five years after waste placement in a given cell, as required by the NSPS. As shown in Table 2-3, the effective landfill-wide collection efficiency of a gas collection system which is installed in waste cells two to five years after they are filled varies from 57% to 77% for systems with 85% to 90% efficiency. If a landfill is closed, all cells will be capped and the landfill-wide collection efficiency will be the same as the specific efficiency of the collection system, or 85% to 90%.

TABLE 2-3. IMPACT OF DELAYS IN COLLECTING GAS FROM NEWER LANDFILL CELLS

Time Between Waste Placement and Initial Gas Collection for Individual Cells (years)	Effective Landfill-wide Gas Collection Efficiency	
	System Collection Efficiency 90%	System Collection Efficiency 85%
1	84	79
2	77	73
3	72	68
4	66	62
5	60	57
6	55	52

It is assumed that the landfills used to develop L_O and k for use in the first order decay LFG generation equation included a similar number of both open and closed landfills. Typically these landfills in the late 1980's and early 1990's would have had specific collection efficiencies of 85% to 90% for the closed cells where the system was installed. The closed landfills might have an overall efficiency of 85%-90% and the open landfills might have an efficiency ranging from 57% to 77%. Based on these assumptions, the overall set of landfills used to develop L_O and k would have had overall collection efficiencies ranging from 57% to 90% and possibly averaging 75%.

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Using the analysis presented on the range in gas collection efficiency, a factor is added to account for the gas that is not collected given that empirical data was used to develop input for the first-order decomposition rate equation. If on average 75% gas generated at the landfills listed in Table 2-2 is collected, then actual gas production from landfills would then be 100/75 or 1.3 times greater than the gas flow measured in the gas collection systems. The first order decay model developed by the EPA (Pelt, 1993) would then be expressed as:

$$Q_{CH_4} = 1.3 L_o\ R\ (e^{-kc} - e^{-kt})$$
(2)

where:

Q_{CH_4} = Methane generation rate at time t, m^3/yr;
L_o = Methane generation potential, $m^3\ CH_4/Mg$ of "wet" or "as received" refuse;
R = Average annual refuse acceptance rate during active life, Mg of "wet" or "as received" refuse /yr;
e = Base log, unitless;
k = Methane generation rate constant, yr^{-1};
c = Time since landfill closure, yrs (c = 0 for active landfills); and
t = Time since the initial refuse placement, yrs.

When annual refuse acceptance data is available, the following form of Equation (2) is used. This is the equation that is used in EPA's Landfill Gas Emissions Model (LandGEM). Due to the complexity of the double summation, Equation (2 alt) is normally implemented within a computer model. Equation (2 alt.) is more accurate because it accounts for the varying annual refuse flows and it calculates each year's gas flow in $^1/_{10th}$ year increments.

$$Q_{CH_4} = 1.3 \sum_{i=1}^{n} \sum_{j=0.1}^{1} k\ L_o \frac{R_i}{10} e^{-kt_{ij}}$$
(2 alternate)

where:

Q_{CH_4} = Methane generation rate at time t, m^3/yr;
L_o = Methane generation potential, $m^3\ CH_4/Mg$ of "wet" or "as received" refuse;
R_i = Annual refuse acceptance rate for year i, Mg of "wet" or "as received" refuse /yr;
e = Base log, unitless;
k = Methane generation rate constant, yr^{-1};
c = Time since landfill closure, yrs (c = 0 for active landfills); and
t = Time since the initial refuse placement, yrs.
i = year in life of the landfill
j = $^1/_{10th}$ year increment in the calculation.

Equations (2) and (2 alt) are different from the equations used previously by EPA in AP-42 and in other models such as LandGEM, by the addition of the constant 1.3 at the front of the equation. This 1.3 constant compensates the value of L_O that had been developed based on systems nominally collecting only an estimated 75% of the LFG emissions.

There is a significant level of uncertainty in Equation 2 and its recommended defaults values for k and L_o. The recommended defaults k and L_o for conventional landfills, based upon the best fit to 40 different landfills, yielded predicted CH_4 emissions that ranged from ~30 to 400% of measured values and

had a relative standard deviation of 0.73 (Table 2-2). The default values for wet landfills were based on a more limited set of data and are expected to contain even greater uncertainty.

When gas generation reaches steady-state conditions, sampled LFG consists of approximately equal amounts of carbon dioxide (CO_2) and CH_4; and only trace amounts of NMOC (typically, less than two percent). Therefore, the estimate derived for CH_4 generation using the landfill model can also be used to estimate CO_2 generation (i.e., $CO_2 = CH_4$) (U.S. EPA, 1991). In addition, total LFG flow can be assumed to be equal to twice the CH_4 flow.

References

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2.2   DATA SUMMARY

A total of 293 emission tests were submitted to EPA that included LFG composition data. As listed in Table 2-4, a portion of these were not used because either the report did not present actual test data (they were based on emission models) or the test report was too incomplete to evaluate the quality of the data. Of the potentially useful tests, several (22) analyze LFG obtained through use of a "punch-probe," while 62 tests contain data for gas samples from LFG collection system headers. The emissions data from the collection system headers are assumed to be representative of the gas generated by the entire landfill and not selected locations, as may be the case with punch probe analyses. Therefore, in developing default emission factors for updating AP-42, only the emissions test data for the 62 tests taken from gas collection system headers are analyzed in this report.

The reference section to this chapter, and in the AP-42 chapter, lists the specific emission tests from which data were utilized. Appendix B contains the list of all 293 emission tests that were reviewed as part of this update.

TABLE 2-4. SUMMARY OF LANDFILL GAS EMISSIONS TESTS

Number of emission test reports	293
Number of reports that were not able to be used due to inadequate documentation or information	209
Number of punch-probe tests	22
Number of gas collection header tests	62

Landfill gas collection system header pipes were sampled for NMOC, reduced sulfur compounds, and speciated organics. Measured pollutant concentrations (i.e., as measured by EPA Reference Method 25C), must be corrected for air infiltration which can occur by two different mechanisms: LFG sample dilution and air intrusion into the landfill. These corrections require site-specific data for the LFG CH_4, CO_2, nitrogen (N_2), and oxygen (O_2) content. If the ratio of N_2 to O_2 is less than or equal to 4.0 (as found in ambient air), then the total pollutant concentration is adjusted for sample dilution by assuming that CO_2 and CH_2 are the primary (100 percent) constituents of LFG, and the following equation is used:

$$C_P \text{ (corrected for air infiltration)} = \frac{C_P \text{ x } (1 \times 10^6)}{C_{CO_2} + C_{CH_4}} \tag{3}$$

where:

C_P = Concentration of pollutant P in LFG (i.e., NMOC as hexane), ppmv;

C_{CO2} = CO_2 concentration in LFG, ppmv;

Q_{CH4} = CH_4 Concentration in LFG, ppmv; and

1×10^6 = Constant used to correct concentration of P to units of ppmv.

If the ratio of N_2 to O_2 concentrations (i.e., C_{N2}, C_{O2}) is greater than 4.0, then the total pollutant concentration should be adjusted for air intrusion into the landfill by using Equation (3) and adding the concentration of N_2 (i.e., C_{N2}) to the denominator. Values for C_{CO2}, C_{CH4}, C_{N2}, C_{O2}, can usually be found in the source test report for the particular landfill along with the total pollutant concentration data.

Most of the tests contained data on O_2, CO_2, CH_4 and N_2 content of the gas, as shown in Table 2-5, so that corrected values may be calculated. (While no reports present corrected data, Table 2-5 contains those tests for which corrected values could be calculated.) Table 2-6 displays NMOC values both

uncorrected (i.e., as reported) and corrected for air infiltration. For simplicity, the AP-42 chapter and Table 2-7 of this section present the data that has been corrected for air infiltration only. A summary of uncorrected data is presented in Appendix C.

TABLE 2-5. SUMMARY OF TEST REPORT DATA CONTENTS
(COUNTS OF DATA POINTS WITHIN TEST)

Test Report ID	CH_4	CO_2	N_2	O_2	CO		NMOC (as hexane)		Speciated Organic and Sulfur Compounds		Total	
					C	UC	C	UC	C	UC	C	UC[a]
TR-076	0	0	1	1	0	0	0	1	0	0	0	3
TR-084	0	0	1	1	0	0	0	1	0	0	0	3
TR-086	0	0	1	1	0	0	0	1	0	0	0	3
TR-114	0	0	1	0	0	0	0	1	0	0	0	2
TR-115	0	0	0	0	0	0	0	1	0	0	0	1
TR-134	0	0	1	1	0	0	0	1	0	0	0	3
TR-141	0	0	1	1	0	0	0	1	0	0	0	3
TR-145	1	1	1	1	1	1	1	1	28	28	30	34
TR-146	1	1	1	1	0	0	1	1	3	3	4	8
TR-147	0	0	0	0	0	1	0	1	0	1	0	3
TR-148	1	1	1	1	1	1	1	1	15	15	17	21
TR-153	1	1	1	1	0	0	1	1	0	0	1	5
TR-156	1	1	1	1	0	0	1	1	0	0	1	5
TR-157	1	1	1	1	0	0	1	1	0	0	1	5
TR-159	1	1	1	1	0	0	1	1	0	0	1	5
TR-160	0	0	0	0	0	0	0	1	0	0	0	1
TR-165	1	1	1	1	0	0	1	1	27	27	28	32
TR-167	1	1	1	1	0	0	1	1	27	27	28	32
TR-168	1	1	1	1	0	0	1	1	27	27	28	32
TR-169	1	1	1	1	0	0	1	1	27	27	28	32
TR-171	1	1	1	1	0	0	1	1	27	27	28	32
TR-173	1	1	1	1	0	0	1	1	27	27	28	32
TR-175	1	1	1	1	1	1	1	1	27	27	29	33
TR-176	1	1	1	1	0	0	1	1	21	21	22	26
TR-178	1	1	1	1	0	0	1	1	27	27	28	32
TR-179	1	1	0	1	0	0	0	1	0	27	0	31
TR-181	1	1	1	1	0	0	1	1	27	27	28	32

TABLE 2-5 (CONTINUED). SUMMARY OF TEST REPORT DATA CONTENTS
(COUNTS OF DATA POINTS WITHIN TEST)

Test Report ID	CH₄	CO₂	N₂	O₂	CO		NMOC (as hexane)		Speciated Organic and Sulfur Compounds		Total	
					C	UC	C	UC	C	UC	C	UCᵃ
TR-182	1	1	1	1	0	0	1	1	27	27	28	32
TR-183	1	1	1	1	0	0	1	1	27	27	28	32
TR-187	1	1	1	1	0	0	1	1	47	47	48	52
TR-188	1	1	1	1	1	1	0	0	108	108	109	113
TR-189	1	1	1	1	1	1	0	0	113	113	114	118
TR-190	1	1	1	1	0	0	0	0	107	107	107	111
TR-191	1	1	1	1	0	0	0	0	107	107	107	111
TR-194	1	1	0	1	0	1	0	0	0	98	0	102
TR-195	0	0	0	0	0	0	0	0	0	526	0	526
TR-196	1	1	1	1	0	0	1	1	27	27	28	32
TR-199	1	1	1	1	0	0	1	1	23	23	24	28
TR-205	1	1	1	1	0	0	1	1	27	27	28	32
TR-207	1	1	1	1	0	0	1	1	25	25	26	30
TR-209	1	1	1	1	0	1	1	1	28	28	29	34
TR-220	1	1	1	1	0	0	1	1	22	22	23	27
TR-226	1	1	1	1	1	1	1	1	0	0	2	6
TR-229	1	1	1	1	0	0	1	1	30	30	31	35
TR-236	0	0	0	0	0	0	0	0	0	7	0	7
TR-241	1	1	1	1	0	0	0	0	5	5	5	9
TR-251	1	1	1	1	0	0	1	1	27	27	28	32
TR-253	1	1	1	1	0	0	1	1	27	27	28	32
TR-255	1	1	1	1	0	0	1	1	27	27	28	32
TR-258	0	0	0	0	0	0	0	1	0	0	0	1
TR-259	1	1	1	1	0	0	1	1	27	27	28	32
TR-260	1	1	1	1	0	0	1	1	26	26	27	31
TR-261	1	1	1	1	0	0	1	1	27	27	28	32
TR-264	1	1	1	1	0	0	1	1	27	27	28	32
TR-266	1	1	0	1	0	1	1	1	9	9	10	14
TR-272	2	2	1	1	0	0	1	1	68	68	69	75
TR-273	2	2	1	1	0	0	1	1	67	67	68	74
TR-284	2	2	1	1	0	0	1	1	56	56	57	63
TR-287	2	2	1	1	0	0	1	1	56	56	57	63
TR-290	1	1	1	1	0	0	1	1	27	27	28	32

**TABLE 2-5 (CONTINUED). SUMMARY OF TEST REPORT DATA CONTENTS
(COUNTS OF DATA POINTS WITHIN TEST)**

Test Report ID	CH_4	CO_2	N_2	O_2	CO		NMOC (as hexane)		Speciated Organic and Sulfur Compounds		Total	
					C	UC	C	UC	C	UC	C	UC[a]
TR-292	2	2	1	1	0	0	1	1	33	33	34	40
TR-293a	1	1	1	1	0	0	1	1	30	30	31	35
TR-293b	1	1	1	1	0	0	1	1	26	26	27	31
Total	**56**	**54**	**52**	**54**	**6**	**10**	**44**	**55**	**1,537**	**2,196**	**1,585**	**2,473**

C = Corrected for air infiltration
UC = Uncorrected
[a] Uncorrected Total includes CH_4, CO_2, N_2, and O_2 data points.

2.3   NMOC AND VOC

Fifty-four test reports contained NMOC data. Forty-three of these contained sufficient data to calculate a value corrected for air infiltration. The corrected values were calculated using Equation 2. The data from the 54 test reports, corrected value (if possible to calculate), and the test method are reported in Table 2-6. In addition, summary statistics are presented at the bottom of the table. Based on guidance contained in EPA's Procedures for Preparing Emission Factor Documents (U.S. EPA, 1997a), each of the tests with the corrected value calculated are assumed to be rated as "A," because the tests were performed by a sound methodology and reported in enough detail for adequate validation. None of the NMOC concentrations were below the detection limit (BDL).

Taking the mean value of the corrected NMOC data yields a default emission factor of 838 ppmv, which compares to the pre-1992 AP-42 default value of 595 ppmv for "No or Unknown co-disposal landfills" (see Table 2.4-2 in the AP-42 chapter, included as section 5.0 of this document). An overall emission factor ranking of "A" is recommended for NMOC. This rating exemplifies the fact that the default NMOC emission factors were developed using A-rated test data from a large number of facilities. The pre-1992 AP-42 default emission factor for NMOC at "No or Unknown co-disposal" landfills is ranked as "B."

To determine the volatile organic compound (VOC) emission factor, the compounds listed in 40 CFR 51.100(s)(1) which have negligible chemical photoreactivity were removed from the overall NMOC concentration. This determination was possible for 34 emission tests that contained both speciated data and NMOC data. Consistent with the previous AP-42 update background document (U.S. EPA, 1997b), the following compounds from 40 CFR 51.100(s)(1) were removed from the NMOC concentration to obtain a VOC fraction: ethane, chlorodifluoromethane, acetone, dichloromethane, 1,1,1-Trichloroethane (methyl chloroform), dichlorodifluoromethane, perchloroethylene. Note that 40 CFR 51.100(s)(1) contains more compounds than those listed above, but this list envelops the LFG constituents that are listed in 51.100(s)(1) that are most prevalent in LFG. Since NMOC is presented as hexane (i.e., six carbons), the non-VOC compound concentrations are converted to be on the same six-carbon basis also so that they may be subtracted from the NMOC concentration value. The data used to develop the VOC emission factor and the resulting VOC fraction calculations are presented in Appendix D.

The resulting fraction of NMOC that is VOC is 0.997, based on data from 34 emission test reports (see Appendix D for data and calculation). All of these test reports are considered to be "A" quality. This fraction was multiplied by the corrected NMOC concentration value to obtain a VOC emission factor of 835 ppmv. The recommended emission factor ranking is "A" because a large number of "A" quality tests were used to develop the emission factor. Appendix E presents statistical data graphs of the NMOC data.

TABLE 2-6. SUMMARY OF TESTING RESULTS FOR NON-METHANE ORGANIC COMPOUNDS (NMOC) – CORRECTED AND UNCORRECTED FOR AIR INFILTRATION

Test Report ID	Test Method	Corrected Average Concentration (ppm as hexane)	Average Concentration (ppm as hexane)
TR-076	EPA Method 25C		157
TR-084	EPA Method 25C / Method 3C		117
TR-086	EPA Method 25C / Method 3C		121

TABLE 2-6 (CONTINUED). SUMMARY OF TESTING RESULTS FOR NON-METHANE ORGANIC COMPOUNDS (NMOC) – CORRECTED AND UNCORRECTED FOR AIR INFILTRATION

Test Report ID	Test Method	Corrected Average Concentration (ppm as hexane)	Average Concentration (ppm as hexane)
TR-114	EPA Method 25C		53
TR-115	EPA Method 25C		82
TR-134	EPA Method 25C		944
TR-141	EPA Method 25C		180
TR-145	EPA Method 25C	635	628
TR-146	SCAQMD Method 25.2	927	922
TR-147	EPA Method 25C		298
TR-148	EPA Method 18 / EPA Method 25C	332	331
TR-153	EPA Method 25C	721	726
TR-156	EPA Method 25C	575	573
TR-157	EPA Method 25C	574	571
TR-159	NJATM 3.9	31	31
TR-160	EPA Method 18		421
TR-165	SCAQMD Method 25.2	713	698
TR-167	SCAQMD Draft Method 25.2	673	665
TR-168	SCAQMD Method 25.2	1,314	1,294
TR-169	SCAQMD Draft Method 25.2	1,389	1,349
TR-171	SCAQMD Draft Method 25.2	1,021	993
TR-173	SCAQMD Method 25.1	1,425	1,400
TR-175	SCAQMD Method 25.1	161	110
TR-176	SCAQMD Draft Method 25.2	623	577
TR-178	SCAQMD Method 25.1	1,947	1,882
TR-179	SCAQMD Method 25.1		1,244
TR-181	SCAQMD Draft Method 25.2	649	627
TR-182	SCAQMD Draft Method 25.2	596	578
TR-183	SCAQMD Method 25.1	734	717
TR-187	SCAQMD Method 25.2	870	847
TR-196	EPA Method 25 Modified	889	883
TR-199	SCAQMD Method 25.1	193	176
TR-205	SCAQMD Draft Method 25.2	647	627
TR-207	SCAQMD Method 25.1	617	560
TR-209	EPA Method TO-12 Modified	536	529
TR-220	SCAQMD Draft Method 25.2	704	668
TR-226	NJDEP Method 3.9 (Modified) / GC	167	145
TR-229	SCAQMD Draft Method 25.2	564	527
TR-251	SCAQMD Method 25.1	1,067	1,031
TR-253	SCAQMD Draft Method 25.2	583	573
TR-255	SCAQMD Method 25.1	1,122	1,104
TR-258	EPA Method TO-12		137
TR-259	SCAQMD Draft Method 25.2	1,349	1,286
TR-260	SCAQMD Draft Method 25.2	1,349	1,294
TR-261	SCAQMD Draft Method 25.2	1,321	1,279

TABLE 2-6 (CONTINUED). SUMMARY OF TESTING RESULTS FOR NON-METHANE ORGANIC COMPOUNDS (NMOC) – CORRECTED AND UNCORRECTED FOR AIR INFILTRATION

Test Report ID	Test Method	Corrected Average Concentration (ppm as hexane)	Average Concentration (ppm as hexane)
TR-264	SCAQMD Method 25.1	537	523
TR-266	SCAQMD Method 100.1 and EPA Methods 6C and 7E	245	151
TR-272	EPA Method 25C	386	374
TR-273	EPA Method 25C	526	355
TR-284	EPA Method 25C	5,387[a]	5,870[a]
TR-287	EPA Method 25C	868	1,006
TR-290	Fuel Gas Analysis (SCAQMD Draft 25.2)	972	954
TR-292	EPA Method 25C	242	233
TR-293a	EPA Method 25C	378	446
TR-293b	EPA Method 25C	297	317
Number of Test Reports		**44**	**55**
Minimum		**31**	**31**
Maximum		**5,387**	**5,870**
Mean		**838**	**731**
Standard Deviation		**811**	**824**
95% Confidence Interval		**± 240**	**± 218**

[a] The TR-284 landfill utilized petroleum-contaminated soil as daily cover, which helps illustrate the potential for increased emissions of NMOC when this daily cover is used at a landfill.

To estimate uncontrolled emissions of NMOC or other LFG constituents, such as those listed in Table 2-7, the following equation should be used:

$$Q_P = \frac{Q_{CH4} \times C_P}{C_{CH_4} \times (1 \times 10^6)}$$

(4)

where:

Q_P = Emission rate of pollutant P (i.e., NMOC), m^3/yr;
Q_{CH_4} = CH_4 generation rate, m^3/yr (from Equation 1);
C_P = Concentration of pollutant P in LFG, ppmv; and
C_{CH4} = Concentration of CH_4 in the LFG (assumed to be 50% expressed as 0.5)

Uncontrolled mass emissions per year of total NMOC (as hexane) and speciated organic and inorganic compounds can be estimated by the following equation:

$$UM_P = Q_P \times \frac{MW_P \times 1 \text{ atm}}{(8.205 \times 10^{-5} \text{ m}^3 - \text{atm/gmol} - {}^{\circ}K) \times (1000g/kg) \times (273 + T)}$$

(5)

where:

UM_P = Uncontrolled mass emissions of pollutant P (i.e., NMOC), kg/yr;
MW_P = Molecular weight of P, g/gmol (i.e., 86.18 for NMOC as hexane);
Q_P = Emission rate of pollutant P, m^3/yr; and

T   =   Temperature of LFG, $^{\circ}$C.

This equation assumes that the operating pressure of the system is approximately 1 atmosphere. If the temperature of the LFG is not known, a temperature of 25 $^{\circ}$C (77 $^{\circ}$F) is recommended.

2.4   SPECIATED ORGANICS AND REDUCED SULFUR COMPOUNDS

Forty-seven test reports contained speciated organic and reduced sulfur compound data that could be corrected for air infiltration. An additional 20 test reports contained data that were not able to be corrected. For the speciated organic data, EPA Method 25C was used to obtain the majority of the data. Other methods used to determine speciated organic concentrations were EPA Methods TO-14 and TO-15, and South Coast Air Quality Management District's (SCAQMD) Method 25.2. For reduced sulfur measurements, EPA Method 18 and SCAQMD Method 307 were used.

EPA's Procedures for Preparing Emission Factor Documents (U.S. EPA, 1997a), were followed when addressing BDL test runs. In most cases, there were some runs that were below detection limit and others that were above. However, for a few compounds, there were no tests (or individual runs) that measured above the detection limit. Per the EPA's guidance (U.S. EPA, 1997a), in these cases the emission factor recorded is "BDL," with a reference to the range of method detection limits (MDL) reported.

Table 2-8 presents the default emission factor information for the speciated organic compounds and reduced sulfur compounds that were corrected for air infiltration. As discussed earlier, these data will be presented in the AP-42 chapter. Therefore, only these data have recommended emission factor ratings. Since all of these tests are considered "A" quality, then the emission factor ranking becomes more of a function of the number of data points used for that compound. The following criteria, used in developing ratings in the 1997 AP-42 update (U.S. EPA, 1997b), were used to provide recommended default emission factor ratings. Statistical data graphs of several of the more prevalent speciated organic compounds and reduced sulfur compounds are presented in Appendix E.

TABLE 2-7. CRITERIA USED TO DETERMINE RECOMMENDED DEFAULT EMISSION FACTOR RATINGS

Factor Rating	# of Data Points
A	≥ 20
B	10-19
C	6-9
D	3-5
E	<3

Default emission factors for two compounds presented in Table 2-8 could not be calculated since the test values were all reported as BDL in the respective test reports. The data for acrylonitrile consisted of six BDL test values, and there was one BDL test value reported for hexachlorobutadiene. The acrylonitrile BDL data is consistent with information received from California Air Resources Board regarding testing for acrylonitrile at a San Diego landfill.

Appendix C presents the data summary for data that is not corrected for air infiltration. While this uncorrected data will not be presented in AP-42, it is shown here to document that it is available and was extracted from the test reports. If, in the future, some methodology for assuming a correction factor

is available or more information from specific tests is received, then these data may be corrected and incorporated into the final default emission factors.

2.5   METHANE, CARBON DIOXIDE, CARBON MONOXIDE, OXYGEN AND NITROGEN

Table 2-9 presents a summary of the CH_4, CO_2, carbon monoxide (CO), O_2 and N_2 data. AP-42 presents CO data, but not the other compounds. However, as discussed above, CH_4, CO_2, O_2 and N_2 are used to correct for air infiltration, per Equation 3. CO measurements were performed using various methods, including EPA Method 10, Modified Method TO-14. Ten emission tests contained data for CO (TR-145, TR-147, TR-148, TR-175, TR-188, TR-189, TR-194, TR-209, TR-226, TR-241, and TR-266) and six of these data points were correctable for air infiltration. The average of the emissions tests results in a CO default emission factor of 21 ppmv (corrected for air infilteration). Since there are only six data points, the recommended emission factor rating for CO is C.

2.6   HYDROGEN CHLORIDE

One test report (TR-147) contained data for hydrogen chloride (HCl) present in the raw LFG. However, due to the lack of data for CH_4, CO_2, N_2, and O_2 the HCl data point could not be corrected for air infiltration.

TABLE 2-8. LANDFILL GAS CONSTITUENTS

Compound	Number of Test Reports	Minimum (ppm)	Maximum (ppm)	Mean (ppm)	Standard Deviation (ppm)	95% Confidence Interval (± ppm)	Recommended Emission Factor Rating
1,1,1-Trichloroethane	33	5.15E-03	8.50E-01	2.43E-01	2.43E-01	8.30E-02	A
1,1,2,2-Tetrachloroethane	2	3.06E-02	1.04E+00	5.35E-01	7.14E-01	9.89E-01	E
1,1,2,3,4,4-Hexachloro-1,3-butadiene (Hexachlorobutadiene)	3	1.03E-03	7.91E-03	3.49E-03	3.83E-03	4.33E-03	D
1,1,2-Trichloro-1,2,2-Trifluoroethane (Freon 113)	9	2.06E-03	4.60E-01	6.72E-02	1.48E-01	9.64E-02	C
1,1,2-Trichloroethane	3	7.90E-03	4.08E-01	1.58E-01	2.18E-01	2.47E-01	D
1,1-Dichloroethane	36	2.56E-02	1.59E+01	2.08E+00	2.87E+00	9.38E-01	A
1,1-Dichloroethene (1,1-Dichloroethylene)	34	2.06E-03	1.28E+00	1.60E-01	2.60E-01	8.74E-02	A
1,2,3-Trimethylbenzene	3	2.69E-01	5.20E-01	3.59E-01	1.40E-01	1.58E-01	D
1,2,4-Trichlorobenzene	6	1.01E-03	7.71E-03	5.51E-03	2.70E-03	2.16E-03	C
1,2,4-Trimethylbenzene	13	1.95E-01	2.99E+00	1.37E+00	9.45E-01	5.14E-01	B
1,2-Dibromoethane (Ethylene dibromide)	11	1.37E-03	1.90E-02	4.80E-03	5.39E-03	3.18E-03	B
1,2-Dichloro-1,1,2,2-tetrafluoroethane (Freon 114)	12	7.90E-03	4.23E-01	1.06E-01	1.15E-01	6.51E-02	B
1,2-Dichloroethane (Ethylene dichloride)	34	1.03E-03	2.60E+00	1.59E-01	4.36E-01	1.46E-01	A
1,2-Dichloroethene	1			1.14E+01			E
1,2-Dichloropropane	4	7.35E-04	1.99E-01	5.20E-02	9.78E-02	9.58E-02	D
1,2-Diethylbenzene	3	1.38E-02	2.52E-02	1.99E-02	5.75E-03	6.51E-03	D

TABLE 2-8 (CONTINUED). LANDFILL GAS CONSTITUENTS

Compound	Number of Test Reports	Minimum (ppm)	Maximum (ppm)	Mean (ppm)	Standard Deviation (ppm)	95% Confidence Interval (± ppm)	Recommended Emission Factor Rating
1,3,5-Trimethylbenzene	9	1.51E-01	1.09E+00	6.23E-01	3.59E-01	2.35E-01	C
1,3-Butadiene (Vinyl ethylene)	7	2.27E-02	5.89E-01	1.66E-01	2.07E-01	1.53E-01	C
1,3-Diethylbenzene	4	2.37E-02	1.30E-01	6.55E-02	4.53E-02	4.44E-02	D
1,4-Diethylbenzene	4	9.50E-02	5.49E-01	2.62E-01	2.03E-01	1.99E-01	D
1,4-Dioxane (1,4-Diethylene dioxide)	5	2.09E-03	1.39E-02	8.29E-03	4.50E-03	3.94E-03	D
1-Butene / 2-Methylbutene	3	8.57E-01	1.42E+00	1.22E+00	3.12E-01	3.53E-01	D
1-Butene / 2-Methylpropene	1			1.10E+00			E
1-Ethyl-4-methylbenzene (4-Ethyl toluene)	7	1.21E-01	2.85E+00	9.89E-01	1.21E+00	8.97E-01	C
1-Ethyl-4-methylbenzene (4-Ethyl toluene) + 1,3,5-Trimethylbenzene	4	8.17E-02	8.42E-01	5.79E-01	3.54E-01	3.46E-01	D
1-Heptene	2	4.48E-01	8.03E-01	6.25E-01	2.51E-01	3.48E-01	E
1-Hexene / 2-Methyl-1-pentene	3	1.26E-02	2.22E-01	8.88E-02	1.16E-01	1.31E-01	D
1-Methylcyclohexene	4	1.32E-02	3.89E-02	2.27E-02	1.16E-02	1.14E-02	D
1-Methylcyclopentene	4	1.55E-02	4.62E-02	2.52E-02	1.45E-02	1.42E-02	D
1-Pentene	4	3.23E-02	4.83E-01	2.20E-01	1.95E-01	1.91E-01	D
1-Propanethiol (n-Propyl mercaptan)	22	1.46E-04	4.86E-01	1.25E-01	1.22E-01	5.11E-02	A
2,2,3-Trimethylbutane	4	4.80E-03	1.41E-02	9.19E-03	3.86E-03	3.79E-03	D
2,2,4-Trimethylpentane	5	3.21E-01	8.12E-01	6.14E-01	2.27E-01	1.99E-01	D
2,2,5-Trimethylhexane	4	9.44E-02	2.50E-01	1.56E-01	7.29E-02	7.14E-02	D
2,2-Dimethylbutane	4	9.56E-02	2.28E-01	1.56E-01	5.49E-02	5.38E-02	D
2,2-Dimethylpentane	4	4.42E-02	7.30E-02	6.08E-02	1.27E-02	1.25E-02	D
2,2-Dimethylpropane	1			2.74E-02			E
2,3,4-Trimethylpentane	4	1.78E-01	4.73E-01	3.12E-01	1.35E-01	1.32E-01	D
2,3-Dimethylbutane	4	1.43E-01	2.21E-01	1.67E-01	3.59E-02	3.52E-02	D
2,3-Dimethylpentane	4	2.03E-01	3.76E-01	3.10E-01	7.70E-02	7.54E-02	D
2,4-Dimethylhexane	4	1.74E-01	2.61E-01	2.22E-01	3.62E-02	3.54E-02	D
2,4-Dimethylpentane	4	6.55E-02	1.21E-01	1.00E-01	2.42E-02	2.37E-02	D
2,5-Dimethylhexane	4	1.33E-01	1.96E-01	1.66E-01	2.62E-02	2.57E-02	D
2,5-Dimethylthiophene	1			6.44E-02			E
2-Butanone (Methyl ethyl ketone)	8	2.81E-01	9.54E+00	4.01E+00	3.07E+00	2.12E+00	C
2-Ethyl-1-butene	4	1.02E-02	2.68E-02	1.77E-02	6.98E-03	6.84E-03	D
2-Ethylthiophene	1			6.29E-02			E
2-Ethyltoluene	4	1.38E-01	6.53E-01	3.23E-01	2.29E-01	2.25E-01	D

TABLE 2-8 (CONTINUED). LANDFILL GAS CONSTITUENTS

Compound	Number of Test Reports	Minimum (ppm)	Maximum (ppm)	Mean (ppm)	Standard Deviation (ppm)	95% Confidence Interval (± ppm)	Recommended Emission Factor Rating
2-Hexanone (Methyl butyl ketone)	2	5.73E-01	6.53E-01	6.13E-01	5.65E-02	7.83E-02	E
2-Methyl-1-butene	4	7.17E-02	3.47E-01	1.79E-01	1.18E-01	1.16E-01	D
2-Methyl-1-propanethiol (Isobutyl mercaptan)	1			1.70E-01			E
2-Methyl-2-butene	4	2.07E-01	4.12E-01	3.03E-01	1.03E-01	1.01E-01	D
2-Methyl-2-propanethiol (tert-Butylmercaptan)	1			3.25E-01			E
2-Methylbutane	4	2.80E-01	7.33E+00	2.26E+00	3.39E+00	3.32E+00	D
2-Methylheptane	4	6.01E-01	9.50E-01	7.16E-01	1.61E-01	1.57E-01	D
2-Methylhexane	4	5.58E-01	1.02E+00	8.16E-01	2.11E-01	2.07E-01	D
2-Methylpentane	4	5.51E-01	1.00E+00	6.88E-01	2.13E-01	2.09E-01	D
2-Propanol (Isopropyl alcohol)	6	1.17E-01	5.72E+00	1.80E+00	2.08E+00	1.66E+00	C
3,6-Dimethyloctane	4	5.38E-01	1.01E+00	7.85E-01	1.99E-01	1.95E-01	D
3-Ethyltoluene	4	3.55E-01	1.54E+00	7.80E-01	5.45E-01	5.34E-01	D
3-Methyl-1-pentene	3	4.33E-03	1.09E-02	6.99E-03	3.44E-03	3.89E-03	D
3-Methylheptane	4	6.25E-01	1.04E+00	7.63E-01	1.91E-01	1.87E-01	D
3-Methylhexane	4	7.44E-01	1.41E+00	1.13E+00	3.16E-01	3.10E-01	D
3-Methylpentane	4	5.72E-01	1.08E+00	7.40E-01	2.38E-01	2.34E-01	D
3-Methylthiophene	1			9.25E-02			E
4-Methyl-1-pentene	1			2.33E-02			E
4-Methyl-2-pentanone (MIBK)	7	7.77E-02	1.99E+00	8.83E-01	6.63E-01	4.91E-01	C
4-Methylheptane	4	1.90E-01	3.14E-01	2.49E-01	5.36E-02	5.25E-02	D
Acetaldehyde	5	2.19E-02	1.65E-01	7.74E-02	6.31E-02	5.53E-02	D
Acetone	9	3.38E-01	1.61E+01	6.70E+00	5.34E+00	3.49E+00	C
Acetonitrile	20	1.35E-01	2.56E+00	5.56E-01	5.19E-01	2.27E-01	A
Acrylonitrile	6			BDL[a]			C
Benzene	41	7.52E-02	2.20E+01	2.40E+00	3.69E+00	1.13E+00	A
Benzyl chloride	24	1.72E-03	2.96E-02	1.81E-02	8.16E-03	3.26E-03	A
Bromodichloromethane	2	2.75E-03	1.48E-02	8.78E-03	8.54E-03	1.18E-02	E
Bromomethane (Methyl bromide)	7	2.36E-03	6.77E-02	2.10E-02	2.32E-02	1.72E-02	C
Butane	9	4.31E-01	3.48E+01	6.22E+00	1.09E+01	7.10E+00	C
Carbon disulfide	34	2.92E-04	3.53E-01	1.47E-01	8.74E-02	2.94E-02	A
Carbon tetrachloride	30	8.55E-04	3.29E-02	7.98E-03	7.59E-03	2.72E-03	A
Carbon tetrafluoride (Freon 14)	1			1.51E-01			E
Carbonyl sulfide (Carbon oxysulfide)	29	1.04E-04	2.75E-01	1.22E-01	7.12E-02	2.59E-02	A

TABLE 2-8 (CONTINUED). LANDFILL GAS CONSTITUENTS

Compound	Number of Test Reports	Minimum (ppm)	Maximum (ppm)	Mean (ppm)	Standard Deviation (ppm)	95% Confidence Interval (± ppm)	Recommended Emission Factor Rating
Chlorobenzene	37	1.79E-02	7.44E+00	4.84E-01	1.21E+00	3.89E-01	A
Chlorodifluoromethane (Freon 22)	4	2.06E-01	1.39E+00	7.96E-01	5.00E-01	4.90E-01	D
Chloroethane (Ethyl chloride)	10	9.69E-02	2.79E+01	3.95E+00	8.60E+00	5.33E+00	B
Chloromethane (Methyl chloride)	11	1.24E-02	1.16E+00	2.44E-01	3.28E-01	1.94E-01	B
cis-1,2-Dichloroethene	17	5.27E-02	6.69E+00	1.24E+00	1.56E+00	7.40E-01	B
cis-1,2-Dimethylcyclohexane	4	5.68E-02	1.03E-01	8.10E-02	1.90E-02	1.86E-02	D
cis-1,3-Dichloropropene	4	2.33E-04	6.68E-03	3.03E-03	2.72E-03	2.66E-03	D
cis-1,3-Dimethylcyclohexane	4	3.78E-01	6.36E-01	5.01E-01	1.25E-01	1.23E-01	D
cis-1,4-Dimethylcyclohexane / trans-1,3-Dimethylcyclohexane	4	2.00E-01	2.91E-01	2.48E-01	3.97E-02	3.89E-02	D
cis-2-Butene	4	7.08E-02	1.58E-01	1.05E-01	3.94E-02	3.86E-02	D
cis-2-Heptene	1			2.45E-02			E
cis-2-Hexene	4	8.54E-03	2.51E-02	1.72E-02	7.16E-03	7.02E-03	D
cis-2-Octene	4	1.67E-01	2.78E-01	2.20E-01	5.66E-02	5.55E-02	D
cis-2-Pentene	4	2.14E-02	7.47E-02	4.79E-02	2.37E-02	2.32E-02	D
cis-3-Methyl-2-pentene	4	1.18E-02	2.43E-02	1.79E-02	5.92E-03	5.80E-03	D
CO	6	4.75E+00	7.81E+01	2.44E+01	2.85E+01	2.28E+01	C
Cyclohexane	10	1.19E-01	3.03E+00	1.01E+00	8.97E-01	5.56E-01	B
Cyclohexene	4	1.43E-02	2.56E-02	1.84E-02	5.19E-03	5.09E-03	D
Cyclopentane	4	1.27E-02	3.34E-02	2.21E-02	8.55E-03	8.38E-03	D
Cyclopentene	4	5.13E-03	2.78E-02	1.21E-02	1.07E-02	1.05E-02	D
Decane	4	1.85E+00	6.38E+00	3.80E+00	1.94E+00	1.90E+00	D
Dibromochloromethane	3	7.95E-03	2.38E-02	1.51E-02	8.02E-03	9.08E-03	D
Dibromomethane (Methylene dibromide)	2	6.37E-04	1.03E-03	8.35E-04	2.81E-04	3.89E-04	E
Dichlorobenzene	58	4.84E-04	5.54E+00	9.40E-01	1.32E+00	3.40E-01	A
Dichlorodifluoromethane (Freon 12)	13	1.17E-01	6.56E+00	1.18E+00	1.72E+00	9.34E-01	B
Dichloromethane (Methylene chloride)	42	5.09E-03	4.12E+01	6.15E+00	8.23E+00	2.49E+00	A
Diethyl sulfide	1			8.62E-02			E
Dimethyl disulfide	25	2.29E-04	4.35E-01	1.37E-01	1.03E-01	4.02E-02	A
Dimethyl sulfide	29	7.51E-03	1.47E+01	5.66E+00	3.83E+00	1.39E+00	A
Dodecane (n-Dodecane)	4	6.79E-02	4.64E-01	2.21E-01	1.70E-01	1.66E-01	D
Ethane	5	4.83E+00	1.40E+01	9.05E+00	4.23E+00	3.71E+00	D
Ethanol	5	2.03E-02	3.40E-01	2.30E-01	1.39E-01	1.21E-01	D
Ethyl acetate	6	1.63E-01	3.97E+00	1.88E+00	1.54E+00	1.23E+00	C

TABLE 2-8 (CONTINUED). LANDFILL GAS CONSTITUENTS

Compound	Number of Test Reports	Minimum (ppm)	Maximum (ppm)	Mean (ppm)	Standard Deviation (ppm)	95% Confidence Interval (± ppm)	Recommended Emission Factor Rating
Ethyl mercaptan (Ethanediol)	30	6.05E-05	8.35E-01	1.98E-01	1.97E-01	7.06E-02	A
Ethyl methyl sulfide	1			3.67E-02			E
Ethylbenzene	16	5.93E-01	8.80E+00	4.86E+00	2.58E+00	1.27E+00	B
Formaldehyde	5	3.40E-03	2.51E-02	1.17E-02	9.32E-03	8.17E-03	D
Heptane	10	1.29E-01	3.09E+00	1.34E+00	9.90E-01	6.14E-01	B
Hexane	17	1.19E-01	2.60E+01	3.10E+00	6.04E+00	2.87E+00	B
Hydrogen sulfide	36	1.02E-03	3.34E+02	3.20E+01	5.57E+01	1.82E+01	A
Indan (2,3-Dihydroindene)	4	2.38E-02	1.39E-01	6.66E-02	5.12E-02	5.02E-02	D
Isobutane (2-Methylpropane)	4	1.95E+00	1.66E+01	8.16E+00	6.73E+00	6.59E+00	D
Isobutylbenzene	4	1.66E-02	7.55E-02	4.07E-02	2.49E-02	2.44E-02	D
Isoprene (2-Methyl-1,3-butadiene)	3	1.16E-02	2.21E-02	1.65E-02	5.28E-03	5.97E-03	D
Isopropyl mercaptan	24	3.75E-05	1.22E+00	1.75E-01	2.60E-01	1.04E-01	A
Isopropylbenzene (Cumene)	5	7.61E-02	9.60E-01	4.30E-01	3.50E-01	3.07E-01	D
Methanethiol (Methyl mercaptan)	29	9.80E-04	4.05E+00	1.37E+00	9.55E-01	3.48E-01	A
Methyl tert-butyl ether (MTBE)	5	3.30E-03	2.61E-01	1.18E-01	1.21E-01	1.06E-01	D
Methylcyclohexane	4	1.00E+00	1.51E+00	1.29E+00	2.59E-01	2.54E-01	D
Methylcyclopentane	4	4.01E-01	8.17E-01	6.50E-01	1.77E-01	1.74E-01	D
Naphthalene	4	7.91E-03	2.65E-01	1.07E-01	1.19E-01	1.17E-01	D
n-Butylbenzene	4	2.24E-02	1.40E-01	6.80E-02	5.12E-02	5.02E-02	D
Nonane	4	1.62E+00	3.46E+00	2.37E+00	7.95E-01	7.79E-01	D
n-Propylbenzene (Propylbenzene)	5	1.32E-01	7.07E-01	4.13E-01	2.35E-01	2.06E-01	D
Octane	4	8.46E-01	1.38E+00	1.08E+00	2.73E-01	2.68E-01	D
p-Cymene (1-Methyl-4-lsopropylbenzene)	5	1.28E+00	8.16E+00	3.58E+00	3.10E+00	2.72E+00	D
Pentane	9	4.77E-01	2.44E+01	4.46E+00	7.56E+00	4.94E+00	C
Propane	9	4.79E+00	3.67E+01	1.55E+01	1.04E+01	6.80E+00	C
Propene	4	1.61E+00	4.80E+00	3.32E+00	1.41E+00	1.38E+00	D
Propyne	1			3.80E-02			E
sec-Butylbenzene	4	2.64E-02	1.21E-01	6.75E-02	4.04E-02	3.96E-02	D
Styrene (Vinylbenzene)	14	9.59E-03	1.21E+00	4.11E-01	4.49E-01	2.35E-01	B
Tetrachloroethylene (Perchloroethylene)	40	5.12E-03	8.28E+00	2.03E+00	1.89E+00	5.85E-01	A
Tetrahydrofuran (Diethylene oxide)	7	1.57E-01	1.78E+00	9.69E-01	5.63E-01	4.17E-01	C
Thiophene	2	1.25E-01	5.72E-01	3.49E-01	3.16E-01	4.38E-01	E
Toluene (Methyl benzene)	40	1.30E+00	9.08E+01	2.95E+01	2.30E+01	7.12E+00	A

TABLE 2-8 (CONTINUED). LANDFILL GAS CONSTITUENTS

Compound	Number of Test Reports	Minimum (ppm)	Maximum (ppm)	Mean (ppm)	Standard Deviation (ppm)	95% Confidence Interval (± ppm)	Recommended Emission Factor Rating
trans-1,2-Dichloroethene	8	3.09E-03	4.60E-02	2.87E-02	1.52E-02	1.05E-02	C
trans-1,2-Dimethylcyclohexane	4	3.19E-01	5.23E-01	4.04E-01	8.65E-02	8.47E-02	D
trans-1,3-Dichloropropene	5	3.30E-04	3.00E-02	9.43E-03	1.18E-02	1.03E-02	D
trans-1,4-Dimethylcyclohexane	4	1.68E-01	2.50E-01	2.05E-01	4.12E-02	4.04E-02	D
trans-2-Butene	4	5.41E-02	1.76E-01	1.04E-01	5.15E-02	5.05E-02	D
trans-2-Heptene	1			2.50E-03			E
trans-2-Hexene	4	1.11E-02	3.29E-02	2.06E-02	9.49E-03	9.30E-03	D
trans-2-Octene	4	1.69E-01	2.96E-01	2.41E-01	5.32E-02	5.21E-02	D
trans-2-Pentene	4	1.66E-02	5.09E-02	3.47E-02	1.41E-02	1.39E-02	D
trans-3-Methyl-2-pentene	4	9.91E-03	2.07E-02	1.55E-02	4.73E-03	4.63E-03	D
Tribromomethane (Bromoform)	4	4.36E-04	2.68E-02	1.24E-02	1.12E-02	1.09E-02	D
Trichloroethylene (Trichloroethene)	42	6.55E-03	3.18E+00	8.28E-01	6.88E-01	2.08E-01	A
Trichlorofluoromethane (Freon 11)	16	7.10E-03	7.14E-01	2.48E-01	2.22E-01	1.09E-01	B
Trichloromethane (Chloroform)	34	2.21E-03	6.82E-01	7.08E-02	1.46E-01	4.91E-02	A
Undecane	4	6.45E-01	3.10E+00	1.67E+00	1.04E+00	1.02E+00	D
Vinyl acetate	6	2.17E-02	1.02E+00	2.48E-01	3.86E-01	3.09E-01	C
Vinyl chloride (Chloroethene)	40	6.78E-03	1.72E+01	1.42E+00	2.88E+00	8.92E-01	A
Xylenes (*o*-, *m*-, *p*-, mixtures)	78	3.09E-01	3.56E+01	9.23E+00	8.84E+00	1.96E+00	A

[a] All tests below detection limit. Method detection limits are available for three tests, and are as follows: 2.00E-04, 4.00E-03, and 2.00E-02 ppm

TABLE 2-9. SUMMARY OF METHANE, CARBON MONOXIDE, CARBON DIOXIDE, NITROGEN, AND OXYGEN CONCENTRATIONS OF RAW LANDFILL GAS

Test Report ID	CH$_4$ (ppmv)	CH$_4$ (% v/v)	CO (ppmv)	CO (% v/v)	CO$_2$ (ppmv)	CO$_2$ (% v/v)	N$_2$ (ppmv)	N$_2$ (% v/v)	O$_2$ (ppmv)	O$_2$ (% v/v)
TR-076	NR[a]	NR	NR	NR	NR	NR	160,500	16.1	16,700	1.7
TR-084	NR	NR	NR	NR	NR	NR	100,000	10.0	24,000	2.4
TR-086	NR	NR	NR	NR	NR	NR	21,700	2.2	10,000	1.0
TR-114	NR	NR	NR	NR	NR	NR	140,000	14.0	NR	NR
TR-134	NR	NR	NR	NR	NR	NR	27,850	2.8	2,500	0.3
TR-141	NR	NR	NR	NR	NR	NR	50,100	5.0	20,500	2.1
TR-145	50,600	51.0	13	0.0	407,400	40.7	71,400	7.1	11,100	1.1
TR-146	525,000	52.5	NR	NR	413,000	41.3	56,900	5.7	4,280	0.4
TR-147	NR	NR	2.7	0.0	NR	NR	NR	NR	NR	NR
TR-148	529,000	52.9	4.7	0.0	402,000	40.2	66,000	6.6	2,700	0.3
TR-153	547,000	54.7	NR	NR	380,000	38.0	80,000	8.0	6,000	0.6
TR-156	389,000	38.9	NR	NR	349,000	34.9	258,000	25.8	24,000	2.4
TR-157	581,000	58.1	NR	NR	386,000	38.6	27,000	2.7	2,800	0.3
TR-159	480,000	48.0	NR	NR	374,000	37.4	141,000	14.1	5,300	0.5
TR-165	443,000	44.3	NR	NR	356,000	35.6	180,000	18.0	15,200	1.5
TR-167	450,000	45.0	NR	NR	360,000	36.0	178,000	17.8	14,400	1.4
TR-168	335,000	33.5	NR	NR	326,000	32.6	324,000	32.4	21,000	2.1
TR-169	316,000	31.6	NR	NR	316,000	31.6	340,000	34.0	22,000	2.2
TR-171	359,000	35.9	NR	NR	405,000	40.5	209,000	20.9	22,000	2.2
TR-173	481,000	48.1	NR	NR	382,000	38.2	121,000	12.1	17,400	1.7
TR-175	379,000	37.9	5.2	0.0	301,000	30.1	235,000	23.5	62,100	6.2
TR-176	318,000	31.8	NR	NR	265,000	26.5	344,000	34.4	73,300	7.3
TR-178	200,000	20.0	NR	NR	247,000	24.7	519,000	51.9	34,000	3.4
TR-179	459,000	45.9	NR	NR	331,000	33.1	NR	NR	32,800	3.3
TR-181	335,500	33.6	NR	NR	324,000	32.4	306,000	30.6	23,800	2.4
TR-182	351,000	35.1	NR	NR	332,000	33.2	287,000	28.7	21,800	2.2
TR-183	326,000	32.6	NR	NR	309,000	30.9	341,000	34.1	24,000	2.4

TABLE 2-9 (CONTINUED). SUMMARY OF METHANE, CARBON MONOXIDE, CARBON DIOXIDE, NITROGEN, AND OXYGEN CONCENTRATIONS OF RAW LANDFILL GAS

Test Report ID	CH$_4$ (ppmv)	CH$_4$ (% v/v)	CO (ppmv)	CO (% v/v)	CO$_2$ (ppmv)	CO$_2$ (% v/v)	N$_2$ (ppmv)	N$_2$ (% v/v)	O$_2$ (ppmv)	O$_2$ (% v/v)
TR-187	350,000	35.0	NR	NR	334,000	33.4	289,000	28.9	27,000	2.7
TR-188	435,000	43.5	77	0.0	355,000	35.5	196,000	19.6	13,700	1.4
TR-189	557,000	55.7	35	0.0	405,000	40.5	37,700	3.8	300	0.0
TR-190	502,000	50.2	NR	NR	395,000	39.5	103,000	10.3	200	0.0
TR-191	350,000	35.0	NR	NR	272,000	27.2	322,000	32.2	56,700	5.7
TR-194	611,000	61.1	65	0.0	389,000	38.9	NR	NR	1,000	0.1
TR-196	476,000	47.6	NR	NR	384,000	38.4	133,000	13.3	6,700	0.7
TR-199	275,000	27.5	NR	NR	212,000	21.2	427,000	42.7	86,000	8.6
TR-205	345,000	34.5	NR	NR	328,000	32.8	297,000	29.7	23,000	2.3
TR-207	183,000	18.3	NR	NR	219,500	22.0	506,000	50.6	91,800	9.2
TR-209	483,000	48.3	0.0	0.0	387,000	38.7	118,000	11.8	10,900	1.1
TR-220	350,000	35.0	NR	NR	295,000	29.5	304,000	30.4	50,500	5.1
TR-226	522,000	52.2	6.5	0.0	349,000	34.9	100,000	10.0	27,700	2.8
TR-229	309,000	30.9	NR	NR	250,000	25.0	374,000	37.4	72,200	7.2
TR-241	212,000	21.2	NR	NR	263,000	26.3	465,000	46.5	61,000	6.1
TR-251	410,000	41.0	NR	NR	366,000	36.6	190,000	19.0	35,000	3.5
TR-253	440,000	44.0	NR	NR	351,000	35.1	191,000	19.1	46,600	4.7
TR-255	445,000	44.5	NR	NR	375,000	37.5	164,000	16.4	16,000	1.6
TR-259	257,000	25.7	NR	NR	282,000	28.2	414,000	41.4	23,800	2.4
TR-260	260,000	26.0	NR	NR	284,000	28.4	415,000	41.5	24,000	2.4
TR-261	259,000	25.9	NR	NR	281,000	28.1	428,000	42.8	26,900	2.7
TR-264	446,000	44.6	NR	NR	374,000	37.4	154,000	15.4	26,500	2.7
TR-266	311,000	31.1	0.0	0.0	304,000	30.4	NR	NR	3,000	0.3
TR-272	467,000	46.7	NR	NR	374,000	37.4	131,000	13.1	17,000	1.7
TR-273	376,000	37.6	NR	NR	298,000	29.8	256,000	25.6	64,000	6.4
TR-284	520,000	52.0	NR	NR	411,000	41.1	159,000	15.9	16,000	1.6
TR-287	617,000	61.7	NR	NR	430,000	43.0	112,000	11.2	200	0.0

TABLE 2-9 (CONTINUED). SUMMARY OF METHANE, CARBON MONOXIDE, CARBON DIOXIDE, NITROGEN, AND OXYGEN CONCENTRATIONS OF RAW LANDFILL GAS

Test Report ID	CH_4 (ppmv)	CH_4 (% v/v)	CO (ppmv)	CO (% v/v)	CO_2 (ppmv)	CO_2 (% v/v)	N_2 (ppmv)	N_2 (% v/v)	O_2 (ppmv)	O_2 (% v/v)
TR-290	213,000	21.3	NR	NR	348,000	34.8	420,000	42.0	8,800	0.9
TR-292	495,000	49.5	NR	NR	333,000	33.3	136,000	13.6	25,700	2.6
TR-293a	607,000	60.7	NR	NR	438,000	43.8	137,000	13.7	26,000	2.6
TR-293b	432,000	43.2	NR	NR	374,000	37.4	262,000	26.2	24,000	2.4
Minimum	183,000	18.3	-	-	212,000	21.2	21,700	2.2	200	0.0
Maximum	617,000	61.7	77.0	0.0	438,000	43.8	519,000	51.9	91,800	9.2
Mean	408,000	40.8	20.9	0.0	342,000	34.2	219,000	21.9	25,400	2.5
Standard Deviation	113,000	11.3	28.4	0.0	54,800	5.5	135,000	13.5	22,100	2.2
95% Confidence Interval (±)	31,100	3.1	17.6	0.0	15,000	1.5	35,900	3.6	5,790	0.6

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2.7   LANDFILL GAS CONSTITUENT DATA FOR LANDFILLS WITH WASTE IN PLACE PRIOR TO 1992

The prior Municipal Solid Waste (MSW) Landfills section of AP-42 (U.S. EPA, 1998) contained uncontrolled LFG constituent default emission factors derived from landfills with the majority of their waste in place prior to 1992. This data is retained in the AP-42 section as Table 2.4-2. The following discussion, adapted from the 1997 emission factor documentation report (U.S. EPA, 1997b), documents the prior activities and analysis performed to derive these emission factors. The supporting raw data tables from the 1997 report are provided in Appendix A.

2.7.1 Data Gathering and Review

Data gathering was undertaken in advance of the 1998 AP-42 section update. This data gathering effort included an extensive literature search, contacts to identify ongoing projects within EPA, and electronic database searches. MSW landfill source test reports were collected during these efforts. After the data gathering was completed, a review of the information obtained was undertaken to reduce and synthesize the information for emission factor development.

Reduction of the collected literature and data into a smaller, more pertinent subset for development of the MSW Landfill AP-42 section was governed by the following:
- Only primary references of emissions data were used.
- Test report source processes were clearly identified.
- Test reports specified whether emissions were controlled or uncontrolled.
- Reports referenced for controlled emissions specify the control devices.
- Data support (i.e., calculation sheets, sampling and analysis description) was supplied in most cases. One exception is that some industry responses to the NSPS surveys were deemed satisfactory for inclusion.
- Test report units were convertible to selected reporting units.
- Test reports that were positively biased to a particular situation (i.e., test studies involving PCB analysis because of a known historical problem associated with PCB disposal in a specific MSW landfill) were excluded.

As delineated by EPA's Emission Inventory Branch (EIB), the reduced subset of emissions data was ranked for quality. The ranking/rating of the data was used to identify questionable data. Each data set was ranked as follows:

A -   When tests were performed by a sound methodology and reported in enough detail for adequate validation. These tests are not necessarily EPA reference method tests, although such reference methods were preferred.

B -   When tests were performed by a generally sound methodology, but lack enough detail for adequate validation.

C -   When tests were based on an untested or new methodology or are lacking a significant amount of background data.

D -   When tests were based on a generally unacceptable method but the method may provide an order-of-magnitude value for the source (U.S. EPA, 1993).

The selected rankings were based on the following criteria:

- Source operation. The manner in which the source was operated is well documented in the report. The source was operating within typical parameters during the test.

- Sampling procedures. If actual procedures deviated from standard methods, the deviations are well documented. Procedural alterations are often made in testing an uncommon type of source. When this occurs an evaluation is made of how such alternative procedures could influence the test results.

- Sampling and process data. Many variations can occur without warning during testing, sometimes without being noticed. Such variations can induce wide deviation in sampling results. If a large spread between test results cannot be explained by information contained in the test report, the data are suspect and are given a lower rating.

- Analysis and calculations. The test reports contain original raw data sheets. The nomenclature and equations used are compared with those specified by the EPA, to establish equivalency. The depth of review of the calculations is dictated by the reviewers' confidence in the ability and conscientiousness of the tester, which in turn is based on factors such as consistency of results and completeness of other areas of the test report (U.S. EPA, 1993).

2.7.2 Development of Default Concentrations

After review, there were 110 data sources (identified in the references as BID-1 to BID-110) used to develop the default concentrations. Appendix A lists the compounds presented in each reference. The Appendix also reflects the co-disposal history of the landfill, if known. Landfills known to have accepted non-residential wastes (i.e., co-disposal) and those known to have never accepted non-residential wastes are delineated. For most of these landfills, the disposal history is unknown. The data for co-disposal and no co-disposal or unknown disposal history are separated for NMOC, benzene, and toluene. There was no statistical difference among disposal history for any of the other LFG constituents presented (U.S. EPA, 1997b). As mentioned before, RCRA subtitle D requirements resulted in eliminating the practice of co-disposal in municipal solid waste landfills, so that co-disposal data segregation is not an issue for the landfills with waste in place on or after 1992.

Table 2-11 presents default concentration values for the speciated organic compounds and reduced sulfur compounds that were corrected for air infiltration. As discussed earlier, these data were presented in the previous version of the AP-42 chapter (U.S. EPA, 1998), and will be presented in the AP-42 chapter as default concentrations for landfills with waste in place prior to 1992. The following criteria, used in developing ratings in the 1997 AP-42 update (U.S. EPA, 1997b), were used to provide recommended default emission factor ratings.

TABLE 2-10. CRITERIA USED TO DETERMINE RECOMMENDED DEFAULT EMISSION FACTOR RATINGS

Factor Rating	# of Data Points
A	≥ 20
B	10-19
C	6-9
D	3-5
E	<3

TABLE 2-11. DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS FOR LANDFILLS WITH WASTE IN PLACE PRIOR TO 1992

Compound	Molecular Weight	Default Concentration (ppmv)	Emission Factor Rating
NMOC (as hexane)[e]	86.18		
Co-disposal (SCC 50300603)		2,420	D
No or Unknown co-disposal (SCC 50100402)		595	B
1,1,1-Trichloroethane (methyl chloroform)[a]	133.42	0.48	B
1,1,2,2-Tetrachloroethane[a]	167.85	1.11	C
1,1-Dichloroethane (ethylidene dichloride)[a]	98.95	2.35	B
1,1-Dichloroethene (vinylidene chloride)[a]	96.94	0.20	B
1,2-Dichloroethane (ethylene dichloride)[a]	98.96	0.41	B
1,2-Dichloropropane (propylene dichloride)[a]	112.98	0.18	D
2-Propanol (isopropyl alcohol)	60.11	50.1	E
Acetone	58.08	7.01	B
Acrylonitrile[a]	53.06	6.33	D
Benzene[a]	78.11		
Co-disposal (SCC 50300603)		11.1	D
No or Unknown co-disposal (SCC 50100402)		1.91	B
Bromodichloromethane	163.83	3.13	C
Butane	58.12	5.03	C
Carbon disulfide[a]	76.13	0.58	C
Carbon monoxide[b]	28.01	141	E
Carbon tetrachloride[a]	153.84	0.004	B
Carbonyl sulfide[a]	60.07	0.49	D
Chlorobenzene[a]	112.56	0.25	C
Chlorodifluoromethane	86.47	1.30	C
Chloroethane (ethyl chloride)[a]	64.52	1.25	B
Chloroform[a]	119.39	0.03	B
Chloromethane	50.49	1.21	B
Dichlorobenzene[c]	147	0.21	E
Dichlorodifluoromethane	120.91	15.7	A
Dichlorofluoromethane	102.92	2.62	D
Dichloromethane (methylene chloride)[a]	84.94	14.3	A
Dimethyl sulfide (methyl sulfide)	62.13	7.82	C
Ethane	30.07	889	C
Ethanol	46.08	27.2	E
Ethyl mercaptan (ethanethiol)	62.13	2.28	D
Ethylbenzene[a]	106.16	4.61	B
Ethylene dibromide	187.88	0.001	E
Fluorotrichloromethane	137.38	0.76	B

Table 2-11 (CONTINUED). DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS FOR LANDFILLS WITH WASTE IN PLACE PRIOR TO 1992

Compound	Molecular Weight	Default Concentration (ppmv)	Emission Factor Rating
Hexane[a]	86.18	6.57	B
Hydrogen sulfide	34.08	35.5	B
Mercury (total)[a,d]	200.61	2.92×10^{-4}	E
Methyl ethyl ketone[a]	72.11	7.09	A
Methyl isobutyl ketone[a]	100.16	1.87	B
Methyl mercaptan	48.11	2.49	C
Pentane	72.15	3.29	C
Perchloroethylene (tetrachloroethylene)[a]	165.83	3.73	B
Propane	44.09	11.1	B
t-1,2-dichloroethene	96.94	2.84	B
Toluene[a]	92.13		
Co-disposal (SCC 50300603)		165	D
No or Unknown co-disposal (SCC 50100402)		39.3	A
Trichloroethylene (trichloroethene)[a]	131.38	2.82	B
Vinyl chloride[a]	62.50	7.34	B
Xylenes[a]	106.16	12.1	B

NOTE: This is not an all-inclusive list of potential LFG constituents, only those for which test data were available at multiple sites.

[a] Hazardous Air Pollutants listed in Title III of the 1990 Clean Air Act Amendments.

[b] Carbon monoxide is not a typical constituent of LFG, but does exist in instances involving landfill (underground) combustion. Therefore, this default value should be used with caution. Of 18 sites where CO was measured, only 2 showed detectable levels of CO.

[c] Source tests did not indicate whether this compound was the para- or ortho- isomer. The para isomer is a Title III-listed HAP.

[d] No data were available to speciate total Hg into the elemental and organic forms.

[e] For NSPS/Emission Guideline compliance purposes, the default concentration for NMOC as specified in the final rule must be used. For purposes not associated with NSPS/Emission Guideline compliance, the default VOC content at co-disposal sites can be estimated by 85% by weight (2,060 ppmv as hexane); at No or Unknown sites can be estimated by 39% by weight (235 ppmv as hexane).

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3.0 CONTROLLED LANDFILL GAS DATA ANALYSIS RESULTS

Emission factors for control devices apply to landfills with waste in place both before and after 1992. Development of emission factors for each combustion control device type is discussed in the following sections.

3.1   FLARES

Landfill gas flare combustion by-product emissions data for a total of 35 landfills were submitted to EPA and utilized in emission factor development, comprising a total of 53flares contained in 41 test reports. Six of the test reports contained test data from two different landfills but represent six different flares (TR-181, TR-182, and TR-205 for one landfill, and TR-259, TR-260, and TR- 261 for another landfill). The manufacturer was specified for 23 of the flares (Table 3-1). These flares are assumed to be enclosed since sampling candle-stick flares is not typically done. Enclosed flares are designed to allow for performance testing to establish emission reduction capability and potential by-product emissions.

TABLE 3-1. SUMMARY OF NUMBER OF FLARES AND MANUFACTURERS FOR LANDFILL GAS FLARE COMBUSTION BY-PRODUCT EMISSIONS TEST DATA

Flare Manufacturer	Number of Emission Test Reports
Callidus	1
John Zink	14
LFG Specialties	1
McGill	2
Perennial Energy	3
SurLite	2
Not Specified	30
Total	53

Nitrogen oxides, carbon monoxide, and particulate matter emissions were sampled and reported in units of parts per million (ppm), pounds per hour (lb/hr), or pounds per day (lb/day). Total dioxin/furan emissions were reported in nanograms per dry standard cubic meter (ng/dscm). Twenty-five test reports contained emissions data for NO_X, CO, and PM. One test report contained data for NO_X, CO, and total dioxins/furans. Five test reports contained emissions data for both NO_X and CO, one test report contained only NO_X emission data, and five test reports contained only CO emissions data. Where possible, each of the emission data points were converted to kilograms per million dry standard cubic meters of CH_4 (kg/10^6 dscm CH_4) to result in comparable emissions for a variety of LFG flares (See Appendix G for sample calculation).

3.1.1 Nitrogen Oxides

The default NO_x emission factor was calculated from 36 test reports containing NO_X emissions data from a total of 48 flares.

The emission rate provided in TR-148 was excluded from the NO_X analysis because the flare inlet gas flow rate was reported in standard cubic feet per minute (scfm) and inlet gas moisture was not determined as part of the flare testing. Consequently, a NO_X emission factor could not be developed on the basis of dry standard cubic meters of inlet CH_4 for TR-148. The emission rate provided for TR-160

was excluded from the NO_X analysis because flare inlet gas composition data was not provided in the test report. As a result, an emission factor could not be calculated for TR-160.

One test report (TR-241) revealed NO_x emission rates below the method detection limit (<0.59 kg/hr or 392 kg/10^6 dscm CH_4) for all test runs. Based on guidance for detection limits contained in EPA's Procedures for Preparing Emission Factor Documents (U.S. EPA, 1997a), half of the method detection limit was used to represent this flare's average emission rate. Since there are detect values greater than this non-detect, the value is used in emission factor determination calculations

Two of the 36 test reports (TR-145 and TR-146) contained NO_X test data obtained from operating the flare under two different operating temperatures. For both cases, the data associated with the set of test runs that most closely matched the average testing temperature from the other 34 test reports (1,552 ºF) was used for the development of the default NO_X emission factor.

Emission rates for the 46 flares (excluding the two flares from TR-148 and TR-160) included in the analysis range from 211 to 1,373 kg/10^6 dscm CH_4. The arithmetic mean emission rate for NO_X for these LFG flares is 631 kg/10^6 dscm CH_4. This average rate was selected as the default emission factor to represent flare NO_X in the AP-42 update with an A quality rating. The previous AP-42 default factor (U.S. EPA, 1998) was 650 kg/10^6 dscm CH_4 with a quality rating of "C."

3.1.2 Carbon Monoxide

The CO default emission factor was calculated from 40 test reports containing emissions data from 52 flares.

The emission rate provided in TR-148 was excluded from the CO analysis because the flare inlet gas flow rate was reported in standard cubic feet per minute (scfm) and inlet gas moisture was not determined as part of the flare testing. Consequently, a CO emission factor could not be developed on the basis of dry standard cubic meters of inlet CH_4 for TR-148. The emission rate provided for TR-160 was excluded from the CO analysis because flare inlet gas composition data was not provided in the test report. As a result, an emission factor could not be calculated for TR-160.

Four test reports (TR-157, TR-175, TR-179, and TR-251) revealed CO emission rates below the method detection limits. Based on guidance for detection limits contained in EPA's Procedures for Preparing Emission Factor Documents (U.S. EPA, 1997a), half of the method detection limits were used to represent the average emission rate. Since there are detect values greater than the non-detect values, the values are used in emission factor determination calculations

Two of the 40 test reports (TR-145 and TR-146) contained CO test data obtained from operating the each flare under two different operating temperatures. For both cases, the data associated with the set of test runs that most closely matched the average testing temperature from the other 36 test reports (1,551 ºF) was used for the development of the default CO emission factor.

Carbon monoxide emission rates for the 50 flares (excluding the two flares from TR-148 and TR-160) included in the analysis range from 0 to 11,500 kg/10^6 dscm CH_4. The arithmetic mean emission rate for CO is 737 kg/10^6 dscm CH_4, which was selected as the default emission factor with an A quality rating for the AP-42 update. The prior default factor in AP-42 (U.S. EPA, 1998) was 12,000 kg/10^6 dscm CH_4 with a quality rating of "C." It is worth noting that the new default emission factor is based on over three times the amount of data as the previous emission factor, which may help explain the large difference between the default values.

3.1.3 Particulate Matter

The default PM emission factor was calculated from 28 test reports containing emissions data from 36 flares.

One of the test reports (TR-146) contained PM test data obtained from operating the flare under two different operating temperatures. The data associated with the set of test runs that most closely matched the average testing temperature from the other test reports (1,548 ºF) was used for the development of the default CO emission factor.

The emission rate provided in TR-148 was excluded from the PM analysis because the flare inlet gas flow rate was reported in standard cubic feet per minute (scfm) and inlet gas moisture was not determined as part of the flare testing. Consequently, a PM emission factor could not be developed on the basis of dry standard cubic meters of inlet CH_4.

The PM emission rates from the 35 flares (excluding the flare from TR-148) included in the analysis range between 84 and 735 $kg/10^6$ dscm CH_4. The arithmetic mean emission rate for PM is 238 $kg/10^6$ dscm CH_4 with an A quality rating. This average rate was selected as the default to represent PM in the AP-42 update. The prior version of the AP-42 section for MSW landfills (U.S. EPA, 1998) had a default PM emission factor of 270 $kg/10^6$ dscm CH_4 with a quality rating of "D."

3.1.4 Total Dioxin/Furan

One test report (TR-273) contained measurement data for dioxins/furans. The total dioxin/furan emission rate is 6.7 x 10^{-6} $kg/10^6$ dscm CH_4, which was selected as the default emission factor for the AP-42 update. The previous AP-42 section for MSW landfills (U.S. EPA, 1998) did not include dioxin/furan emission factors for LFG flares.

3.1.5 Flare Summary

Summaries of the NO_X, CO, PM, and total dioxin/furan combustion by-product data included in the LFG flare analysis for determining default emission factors for the update can be found in Tables 3-4, 3-5, and 3-6. In addition, the three tables provide the test methods used to measure these emissions data.

A data quality rating of A was assigned to each of the flare test reports listed in Tables 3-4, 3-5, and 3-6. All of the reports containing these data included adequate detail, the methodology appeared to be sound, and no problems were reported for the test runs. The following criteria, used in developing ratings in the 1998 AP-42 update, were used to provide recommended default emission factor ratings.

TABLE 3-2. CRITERIA USED TO DETERMINE RECOMMENDED DEFAULT EMISSION FACTOR RATINGS

Factor Rating	# of Data Points
A	≥ 20
B	10-19
C	6-9
D	3-5
E	<3

An overall data quality rating of A is recommended for the NO_X, CO, and PM combustion by-products from flares default emission factors. This rating exemplifies the fact that the default NO_X, CO, and PM emission factors were developed using A-rated test data and the emission factor ranking is more

of a function of the number of data points used to develop the default emission factor. Furthermore, no specific bias is evident for the NO_X, CO, and PM emission factors. An overall data quality rating of E is recommended for the total dioxin/furan combustion by-product default emission factor since the emission factor was developed from a single facility which does not represent a random sample of LFG flares (Table 3-3).

TABLE 3-3. RECOMMENDED DEFAULT EMISSION FACTOR RATINGS FOR NO_X, CO, PM, AND TOTAL DIOXIN/FURAN LANDFILL FLARE COMBUSTION BY-PRODUCTS

Flare Combustion By-Product	# of Data Points	Recommended Emission Factor Rating
NOx	30	A
CO	34	A
PM	23	A
Total Dioxin/Furan	1	E

TABLE 3-4. LANDFILL GAS FLARE NO_x EMISSIONS DATA USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS

Test Report	Test Method	Flare Combustion By-Product	Calculated Emission Factor ($kg/10^6$ dscm CH_4)
TR-145[a]	EPA Method 7E	NO_x	671
TR-146[a]	EPA Method 7E	NO_x	1,200
TR-159	EPA Method 7E	NO_x	634
TR-165	SCAQMD Method 100.1	NO_x	669
TR-168	SCAQMD Method 100.1	NO_x	341
TR-169	SCAQMD Method 100.1	NO_x	322
TR-171	SCAQMD Method 100.1	NO_x	608
TR-173	SCAQMD Method 100.1	NO_x	563
TR-175[b]	SCAQMD Method 100.1	NO_x	725
TR-176	SCAQMD Method 100.1	NO_x	656
TR-178	SCAQMD Method 100.1	NO_x	458
TR-179	SCAQMD Method 100.1	NO_x	502
TR-181, TR-182, TR-205[c]	SCAQMD Method 100.1	NO_x	320
TR-183	SCAQMD Method 100.1	NO_x	520
TR-187	SCAQMD Method 100.1	NO_x	430
TR-196	CARB Method 100/EPA Method 7E	NO_x	677
TR-199	SCAQMD Method 100.1	NO_x	449
TR-207	SCAQMD Method 100.1	NO_x	1,370
TR-209[d]	EPA Method 7E	NO_x	1,080
TR-229	SCAQMD Method 100.1	NO_x	823
TR-241[e]	EPA Method 7A	NO_x	392

TABLE 3-4 (CONTINUED). LANDFILL GAS FLARE NO$_X$ EMISSIONS DATA USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS

Test Report	Test Method	Flare Combustion By-Product	Calculated Emission Factor (kg/10^6 dscm CH$_4$)
TR-251	SCAQMD Method 100.1	NO$_x$	848
TR-253	SCAQMD Method 100.1	NO$_x$	846
TR-255	SCAQMD Method 100.1	NO$_x$	543
TR-258	CARB Method 100	NO$_x$	554
TR-259, TR-260, TR-261[c]	SCAQMD Method 100.1	NO$_x$	234
TR-264	SCAQMD Method 100.1	NO$_x$	939
TR-273	EPA Method 7E	NO$_x$	741
TR-287	EPA Method 7E	NO$_x$	596
TR-290	SCAQMD Method 100.1	NO$_x$	211
NO$_x$ Default Emission Factor			**631**
1998 AP-42 NO$_x$ Emission Factor[f]			**650**

[a] Average flare temperature for tests where the temperature was not varied is 1552ºF. For tests performed under multiple temperatures, the test where the operating temperature was closest to the average was included. See discussion for additional details.
[b] Emission factor calculated is based on the average emissions for three flares.
[c] Three test reports for three separate flares at the same landfill.
[d] Emission factor calculated is based on the average emissions for five flares.
[e] Based on guidance in EPA's Procedures for Preparing Emission Factor Documents for detection limits, half of the method detection limit was used to represent this landfill's average emission rate. Since there are detect values greater than this non-detect, the value is used in emission factor determination calculations.
[f] AP-42, Fifth Edition, Volume I, Section 2.4, Supplement E, November 1998.

TABLE 3-5. LANDFILL GAS FLARE CO EMISSIONS DATA USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS

Test Report	Test Method	Flare Combustion By-Product	Calculated Emission Factor (kg/10^6 dscm CH$_4$)
TR-145[a]	EPA Method 10, 40 CFR 60, Appendix A	CO	533
TR-146[a]	EPA Method 10, 40 CFR 60, Appendix A	CO	23
TR-147	EPA Method 10, 40 CFR 60, Appendix A	CO	13
TR-153	EPA Method 10, 40 CFR 60, Appendix A	CO	105
TR-156	EPA Method 10, 40 CFR 60, Appendix A	CO	53
TR-157[b]	EPA Method 10, 40 CFR 60, Appendix A	CO	12
TR-159	EPA Method 10, 40 CFR 60, Appendix A	CO	911
TR-165	SCAQMD Method 100	CO	1,550
TR-168	SCAQMD Method 100	CO	11
TR-169	SCAQMD Method 100.1	CO	15
TR-171	SCAQMD Method 100.1	CO	319
TR-173	SCAQMD Method 100.1	CO	263

TABLE 3-5 (CONTINUED). LANDFILL GAS FLARE CO EMISSIONS DATA USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS

Test Report	Test Method	Flare Combustion By-Product	Calculated Emission Factor (kg/10^6 dscm CH_4)
TR-175[b,d]	SCAQMD Method 100.1/SCAQMD Method 10.1 TCA/FID	CO	29
TR-176	SCAQMD Method 100.1	CO	13
TR-178	SCAQMD Method 100.1	CO	276
TR-179[b]	SCAQMD Method 100.1	CO	262
TR-181, TR-182, TR-205[e]	SCAQMD Method 100.1	CO	164
TR-183	SCAQMD Method 100.1	CO	541
TR-187	SCAQMD Method 100.1	CO	76
TR-196	CARB Method 100/EPA Method 10	CO	2,010
TR-199	SCAQMD Method 100.1	CO	11,500
TR-207	SCAQMD Method 100.1	CO	639
TR-209[c]	EPA Method 10, 40 CFR 60, Appendix A	CO	100
TR-226	EPA Method 10, 40 CFR 60, Appendix A	CO	67
TR-229	SCAQMD Method 100.1	CO	28
TR-251[b]	SCAQMD Method 25.1	CO	306
TR-253	SCAQMD Method 100.1	CO	13
TR-255	SCAQMD Method 100.1	CO	434
TR-258	CARB Method 100	CO	23
TR-259, TR-260, TR-261[e]	SCAQMD Method 100.1	CO	175
TR-264	SCAQMD Method 100.1	CO	780
TR-273	EPA Method 10, 40 CFR 60, Appendix A	CO	410
TR-287	EPA Method 10, 40 CFR 60, Appendix A	CO	3,420
TR-290	SCAQMD Method 100.1	CO	0
CO Default Emission Factor			**737**
1998 AP-42 CO Emission Factor[f]			**12,000**

[a] Average flare temperature for tests where the temperature was not varied is 1551°F. For tests performed under multiple temperatures, the test where the operating temperature was closest to the average was included. See discussion for additional details.

[b] Based on guidance in EPA's Procedures for Preparing Emission Factor Documents for detection limits, half of the method detection limit was used to represent this landfill's average emission rate. Since there are detect values greater than this non-detect, the value is used in emission factor determination calculations.

[c] Emission factor calculated is based on the average emissions for five flares.

[d] Emission factor calculated is based on the average emissions for three flares.

[e] Three test reports for three separate flares at the same landfill.

[f] AP-42, Fifth Edition, Volume I, Section 2.4, Supplement E, November 1998.

TABLE 3-6. LANDFILL GAS FLARE PM AND TOTAL DIOXIN/FURAN EMISSIONS DATA USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS

Test Report	Test Method	Flare Combustion By-Product	Calculated Emission Factor (kg/10^6 dscm CH_4)
TR-145	EPA Method 0050	PM	142
TR-146[a]	EPA Method 0050	PM	226
TR-165	SCAQMD Method 5.2	PM	187
TR-168	SCAQMD Method 5.1	PM	309
TR-171	SCAQMD Method 5.1	PM	735
TR-173	SCAQMD Method 5.1	PM	256
TR-175[b]	SCAQMD Method 5.1	PM	143
TR-176	SCAQMD Method 5.1	PM	165
TR-178	SCAQMD Method 5.1	PM	531
TR-179	SCAQMD Method 5.1	PM	251
TR-181, TR-182, TR-205[c]	SCAQMD Method 5.1	PM	84
TR-183	SCAQMD Method 5.1	PM	193
TR-187	SCAQMD Method 5.1	PM	249
TR-196	SCAQMD Method 5.1	PM	401
TR-199	SCAQMD Method 5.1	PM	184
TR-207	SCAQMD Method 5.2	PM	130
TR-229	SCAQMD Method 5.1	PM	313
TR-251	SCAQMD Method 5.1	PM	277
TR-253	SCAQMD Method 5.1	PM	131
TR-255	SCAQMD Method 5.1	PM	138
TR-259, TR-260, TR-261[c]	SCAQMD Method 5.1	PM	97
TR-264	SCAQMD Method 5.1	PM	205
TR-290	SCAQMD Method 5.1	PM	133
PM Default Emission Factor			**238**
1998 AP-42 PM Emission Factor[d]			**270**
TR-273	EPA Method 23	Dioxin/Furan	6.7E-06
Dioxin/Furan Default Emission Factor[e]			**6.76E-06**

[a] Average flare temperature for tests where the temperature was not varied is 1548ºF. For tests performed under multiple temperatures, the test where the operating temperature was closest to the average was included. See discussion for additional details.
[b] Emission factor calculated is based on the average emissions for three flares.
[c] Three test reports for three separate flares at the same landfill.
[d] AP-42, Fifth Edition, Volume I, Section 2.4, Supplement E, November 1998.
[e] New default emission factor. No emission factor for dioxin/furan is in the latest AP-42 update.

References

TR-145. Compliance Testing of a Landfill Flare at Browning-Ferris Gas Services, Inc.'s Facility in Halifax, Massachusetts, BFI Waste Systems of North America, Inc., May 1996.

TR-146. Compliance Source Testing of a Landfill Flare at Northern Disposal, Inc. East Bridgewater Landfill, Northern Disposal, Inc., June 1994.

TR-147. Compliance Emissions Test Program for BFI of Ohio, Inc., BFI of Ohio, Inc., 6/26/98.

TR-148. Compliance Testing of Landfill Flare at Browning-Ferris Gas Services, Inc.'s Fall River Landfill Flare, BFI Waste Systems of North America, Inc., March 1995.

TR-153. Results of the Emission Compliance Test on the Enclosed Flare System at the Carbon Limestone Landfill, Browning-Ferris Industrial Gas Services, Inc., 8/8/96.

TR-156. Results of the Emission Compliance Test on the Enclosed Flare System at the Lorain County Landfill No. 2, Browning-Ferris Industrial Gas Services, Inc., 9/5/96.

TR-157. Emission Compliance Testing Browning-Ferris Gas Services, Inc. Willowcreek Landfill, BFI-Willowcreek, 2/2/98.

TR-159. Compliance Stack Sampling Report, Monmouth County Reclamation Center, SCS Engineers (Reston, VA), 9/8/95.

TR-160. Source Emission Testing of an Enclosed Landfill Gas Ground Flare, SCS Engineers (Reston, VA), September 1997.

TR-165. 1997 Annual Compliance Source Testing Results for the Coyote Canyon Landfill Gas Recovery Facility Flare No. 1, Laidlaw Gas Recovery Systems, January 1998.

TR-168. Colton Sanitary Landfill Gas Flare No. 2 (John Zink) 1998 Source Tests Results, Bryan A. Stirrat & Associates, 9/29/98.

TR-169. Colton Sanitary Landfill Gas Flare No. 1 (McGill) 1998 Source Tests Results, Bryan A. Stirrat & Associates, 9/29/98.

TR-171. High Landfill Gas Flow Rate Source Test Results from One Landfill Gas Flare at FRB Landfill in Orange County, California, Bryan A. Stirrat & Associates, July 1997.

TR-173. Annual Emissions Test of Landfill Gas Flare #3 Bradley Landfill, Waste Management Recycling and Disposal Services of California, Inc., 4/12/99.

TR-175. Emissions Tests on Flares #2, #4 and #6 at the Lopez Canyon Landfill, City of Los Angeles, August 1997.

TR-176. Emissions Test Results on Flares #1, #4 and #9 Calabasas Landfill, County Sanitation Districts of Los Angeles County, February 1998.

TR-178. Annual Emission Test of Landfill Gas Flare #3 Bradley Landfill, Waste Management Recycling and Disposal Services of California, Inc., 5/21/98.

TR-179. Annual Emissions Test of Landfill Gas Flare #1 Bradley Landfill, Waste Management Recycling and Disposal Services of California, Inc., 4/13/99.

TR-181. The Mid-Valley Sanitary Landfill Gas Flare No.1 (McGill) 1998 Source Test Results, Bryan A. Stirrat & Associates, 9/29/98.

TR-182. The Mid-Valley Sanitary Landfill Gas Flare No.2 (SurLite) 1998 Source Test Results, Bryan A. Stirrat & Associates, 9/29/98.

TR-183. Annual Emissions Test of Landfill Gas Flare #2 Bradley Landfill, Waste Management Recycling and Disposal Services of California, Inc., 4/13/99.

TR-187. Emissions Test of a Landfill Gas Flare - Lowry Landfill/Denver-Arapohoe Disposal Site, Sur-Lite Corporation, February 1997.

TR-196. Results of the Biennial Criteria and AB 2588 Air Toxics Source Test on the Simi Valley Landfill Flare, Simi Valley Landfill and Recycling Center, April 1997.

TR-199. Emission Compliance Test on a Landfill Flare, City of Los Angeles, January 1999.

TR-205. The Mid-Valley Sanitary Landfill Gas Flare No. 3 (John Zink) 1998 Source Test Results, Bryan A. Stirrat & Associates, 9/29/98.

TR-207. Compliance Source Test Report Landfill Gas-fired Flare Stations I-4 and F-2, BKK Landfill, 12/12/97.

TR-209. Emission Test Report Volumes I and II - Source/Compliance Emissions Testing for Cedar Hills Landfill, King County Solid Waste Division, 1/20/05.

TR-226. Methane and Nonmethane Organic Destruction Efficiency Tests of an Enclosed Landfill Gas Flare, Newco Waste Systems, April 1992.

TR-229. Scholl Canyon Landfill Gas Flares No. 9, 10 11 and 12 Emission Source Testing April 1999, South Coast Air Quality Management District, April 1999.

TR-241. Performance Evaluation, Enclosed Landfill Gas Flare, Valley Landfill, Waste Energy Technology, November 1991.

TR-251. Emission Compliance Test on a Landfill Gas Flare - Flare #1, Frank R. Bowerman Landfill, Orange County, 1/25/99.

TR-253. Emission Source Testing on Two Flares (Nos. 3 and 6) at the Spadra Landfill, Los Angeles County Sanitation Districts, 7/21/98.

TR-255. Emission Compliance Test on a Landfill Gas Flare -Olinda Alpha Landfill, Orange County Integrated Waste Management Department, No Report Date Given.

TR-258. Source Test Report, City of Sacramento Landfill Gas Flare, City of Sacramento, 6/26/96.

TR-259. The Millikan Sanitary Landfill Gas Flare No. 1 (Surlite) 1998 Source Test Results, South Coast Air Quality Management District, 9/29/98.

TR-260. The Millikan Sanitary Landfill Gas Flare No. 2 (John Zink) 1998 Source Test Results, South Coast Air Quality Management District, 9/29/98.

TR-261. The Millikan Sanitary Landfill Gas Flare No. 3 (John Zink) 1998 Source Test Results, South Coast Air Quality Management District, 9/29/98.

TR-264. Emission Compliance Test on a Landfill Gas Flare, Orange County Integrated Waste Management Department, No Report Date Given.

TR-273. Source Testing Final Report - Landfill B, US EPA Air Pollution Prevention and Control Division, 10/6/05.

TR-287. Source Testing Final Report - Landfill D, US EPA Air Pollution Prevention and Control Division, 10/6/05.

TR-290. San Timoteo Sanitary Landfill 1998 Source Test Results, San Bernandino County Solid Waste Management, 9/29/98.

U.S. Environmental Protection Agency (1997a). Procedures for Preparing Emission Factor Documents ,EPA-454/R-95-015, Office of Air Quality Planning and Standards, Research Triangle Park, NC, November 1997.

U.S. Environmental Protection Agency (1998). Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: Stationary Point and Area Sources, Section 2.4 Municipal Solid Waste Landfills, Research Triangle Park, NC, November 1998.

3.2   BOILERS, ENGINES AND TURBINES

3.2.1 Boiler Combustion By-Product Emissions – Source Characterization, Test Methods and Results

Combustion by-product emissions data for LFG-fired boilers were submitted to EPA for a total of seven landfills. However, one boiler test report (TR-163) was excluded from the analysis because the report provided to EPA is incomplete and does not contain any test method or sampling information. Nitrogen oxide and carbon monoxide emissions were sampled and reported in units of parts per million (ppm), pounds per hour (lb/hr), pounds per day (lb/day), or grams per cubic meter of CH_4 (g/m^3 CH_4) for six boilers. Four of the test reports also contain particulate matter emissions data, given in lb/hr, lb/day, or g/m^3 CH_4. Five boiler test reports have total dioxin/furan emissions in nanograms per dry standard cubic meter (ng/dscm), picograms in toxicity equivalents (TEQ) per cubic meter (pg TEQ/m^3), or lb/hr. Where possible, each of the emission data points were converted to kilograms per million dry standard cubic meters of CH_4 ($kg/10^6$ dscm CH_4) to result in comparable emissions for a variety of LFG-fired boilers.

Of the six boiler test reports used in the analysis, three boilers (TR-167, TR-220, TR-291) are Zurn steam boilers. One of these boilers is equipped with dual Coen burners such that the LFG may be supplemented with natural gas in order to maintain acceptable Btu levels. One boiler (TR-292) is a Combustion Engineering Model 33-7KT-10, A-type package base-load steam boiler. The remaining two boilers did not specify the type of boiler tested. There were no "A" or "B" quality test reports available for boilers from the prior AP-42 update that could be utilized in this analysis.

3.2.1.1 Nitrogen Oxides

Five of the six test reports (TR-167, TR-188, TR-220, TR-268, TR-291, TR-292) containing NO_X emissions data were included in the analysis to determine a default emission factor. The emission rate provided for TR-188 was excluded from the NO_X analysis because samples were collected and analyzed using a portable combustion gas analyzer, which is not considered an acceptable test method for the AP-42 analysis.

The two lowest emission rates are represented by boilers (TR-167, TR-220) equipped with flue gas recirculation to reduce NO_X formation, although the difference between these two rates and the next two highest rates is not a significant amount.

Emission rates for the six boilers included in the analysis range from 563 to 1,040 $kg/10^6$ dscm CH_4. The arithmetic mean emission rate for NO_X for these LFG-fired boilers is 677 $kg/10^6$ dscm CH_4. This average rate was selected as the default emission factor to represent boiler NO_X in the AP-42 update with a D quality rating. The 1998 default factor in AP-42 (U.S. EPA, 1998) is 530 with a D quality rating.

3.2.1.2 Carbon Monoxide

Four of the six test reports (TR-167, TR-188, TR-220, TR-268, TR-291, TR-292) containing CO emissions data were included in the analysis to determine a default emission factor. The emission rate provided for TR-188 was excluded from the CO analysis because samples were collected and analyzed using a portable combustion gas analyzer, which is not considered an acceptable test method for the AP-42 analysis. Another report (TR-291) reveals CO emission rates below the method detection limit (<0.03 kg/hr or 16 $kg/10^6$ dscm CH_4) for all test runs. Based on guidance for detection limits contained in EPA's Procedures for Preparing Emission Factor Documents (U.S. EPA, 1997a), half of the detection limit (0.014 kg/hr or 8 $kg/10^6$ dscm CH_4) should be used to represent the average CO emission rate. However,

the halved rate is greater than the detect value for the CO emission rate for another test report (TR-220). Therefore, as directed in the EPA procedures document, this halved emission rate was not used to determine a default CO emission factor.

Carbon monoxide emission rates range from 3 to 250 kg/10^6 dscm CH_4. The arithmetic mean emission rate for CO is 116 kg/10^6 dscm CH_4, which was selected as the default emission factor with a "D" quality rating for the AP-42 update. The prior default factor in AP-42 (U.S. EPA, 1998) is 90 kg/10^6 dscm CH_4 with a quality rating of "E."

3.2.1.3 Particulate Matter

Particulate matter emissions are provided in four boiler test reports (TR-167, TR-188, TR-220, TR-268). These four PM emission rates range between 10 and 71 kg/10^6 dscm CH_4. The arithmetic mean emission rate for PM is 41 kg/10^6 dscm CH_4. This average rate was selected as the default to represent PM in the AP-42 update, with a "D" quality rating. The previous AP-42 section for MSW landfills (U.S. EPA, 1998) has a default PM emission factor of 130 kg/10^6 dscm CH_4 with a quality rating of "D."

3.2.1.4 Total Dioxin/Furan

Five test reports (TR-188, TR-220, TR-268, TR-291, TR-292) contain measurement data for dioxins/furans. Emissions data for one boiler test report (TR-188) were excluded from the dioxin/furan analysis because data were only reported on a TEQ basis but total dioxin/furan on a mass basis was being used in the analysis to determine a default emission factor. Three test reports (TR-220, TR-268, TR-291) reveal total dioxin/furan emission rates below the method detection limit for all test runs. Based on guidance for detection limits contained in EPA's Procedures for Preparing Emission Factor Documents (U.S. EPA, 1997a), half of the detection limit was used to represent the average emission rate of total dioxin/furan for these boilers.

Total dioxin/furan emission rates range from 1.4×10^{-6} to 1.5×10^{-5} kg/10^6 dscm CH_4. The arithmetic mean emission rate for total dioxin/furan is 5.1×10^{-6} kg/10^6 dscm CH_4, which was selected as the default emission factor with a "D" quality rating for the AP-42 update. The prior AP-42 section for MSW landfills (U.S. EPA, 1998) does not include dioxin/furan emission factors for LFG-fired boilers.

3.2.1.5 Boiler Summary

Table 3-7 contains a summary of the combustion by-product data included in the LFG-fired boiler analysis for determining default emission factors for the AP-42 update. In addition, Table 3-7 provides the test methods used to measure these emissions data.

A data quality rating of "A" was assigned to each of the boiler test reports listed in Table 3-7. All of the reports containing these data included adequate detail, the methodology appeared to be sound, and no problems were reported for the test runs. However, an overall data quality rating of "D" is recommended for each of the four default emission factors representing combustion by-products from boilers. This rating exemplifies the fact that the default factors were developed using "A"-rated test data from a small number of facilities. Although no specific bias is evident, it is not clear if the boilers tested represent a random sample of the existing LFG-fired boilers in the U.S. given that five or fewer data points were used to determine each default emission factor.

**TABLE 3-7. LANDFILL GAS-FIRED BOILER EMISSIONS DATA
USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS**

Test Report Reference	Test Method	Boiler Combustion By-Product	Emission Rate (kg/10^6 dscm CH$_4$)	Emission Rate (lb/10^6 dscf CH$_4$)
TR-167	SCAQMD Method 100.1 sampling with a CEMS	NO$_X$	591	37
TR-220	SCAQMD Method 100.1 sampling with a CEMS	NO$_X$	563	35
TR-268	ARB Method 1-100	NO$_X$	1,040	65
TR-291	SCAQMD Method 100.1 sampling with a CEMS	NO$_X$	593	37
TR-292	EPA Method 7E (CEM)	NO$_X$	593	37
NO$_X$ Default Emission Factor			**677**	**42**
1998 NO$_X$ Default Emission Factor[a]			**530**	**33**
TR-167	SCAQMD Method 100.1 sampling with a CEMS	CO	94	6
TR-220	SCAQMD Method 100.1 sampling with a CEMS	CO	3	0.2
TR-268	ARB Method 1-100	CO	116	7
TR-292	EPA Method 10 (CEM)	CO	250	16
CO Default Emission Factor			**116**	**7**
1998 CO Default Emission Factor[a]			**90**	**5.7**
TR-167	SCAQMD Method 5.2	PM	48	3
TR-188	Environment Canada Report EPS 1/RM/8 "*Reference Method for Source Testing: Measurement of Releases of Particulate from Stationary Sources*"	PM	36	2
TR-220	SCAQMD Method 5.1	PM	10	1
TR-268	EPA Method 5	PM	71	4
PM Default Emission Factor			**41**	**3**
1998 PM Default Emission Factor[a]			**130**	**8.2**
TR-220	CARB Method 428	Total dioxin/furan	2.22x10^{-6}	1.38x10^{-7}
TR-268	Modified EPA Method 5 (ASME Semi-VOST)	Total dioxin/furan	1.36x10^{-6}	8.47x10^{-8}
TR-291	CARB Method 428	Total dioxin/furan	1.4x10^{-6}	8.93x10^{-8}
TR-292	EPA Method 23 and EPA Method 8290	Total dioxin/furan	1.53x10^{-5}	9.54x10^{-7}
Total Dioxin/Furan Default Emission Factor			**5.1x10^{-6}**	**3.2x10^{-7}**
1998 Total Dioxin/Furan Default Emission Factor[a]			**Not available**	**Not available**

[a] – Default emission factor from the November 1998 AP-42 chapter 2.4.

3.2.2 Internal Combustion (IC) Engine Combustion By-Product Emissions – Source Characterization, Test Methods and Results

Combustion by-product emissions data for LFG-fired IC engines were submitted to EPA for a total of six landfills. Nitrogen oxide and carbon monoxide emissions were sampled and reported in units of ppm, lb/hr, or g/m^3 CH$_4$ for all six engines. Three of the test reports also contain particulate matter emissions data, given in g/m^3 CH$_4$. Five engine test reports have total dioxin/furan emissions in pg TEQ/m^3, or grams per hour (g/hr). Where possible, each of the emission data points was converted to kilograms per million dry standard cubic meters of CH$_4$ (kg/10^6 dscm CH$_4$) to result in comparable emissions for a variety of LFG-fired engines.

Of the six engine test reports used in the analysis, five engines (TR-189, TR-190, TR-266, TR-272, TR-284) are Caterpillar gas engines. The remaining engine (TR-194) is a Waukesha gas engine.

In addition to the newly-submitted test reports described above, there were data from six engine test reports used in the prior AP-42 update that were "A" or "B" quality that were also used in this analysis. Six data points for NO_x, five for CO, and one for PM were used from the prior AP-42 update information.

3.2.2.1 Nitrogen Oxides

Three of the six test reports (TR-266, TR-272, TR-284) containing NO_X emissions data were included in the analysis to determine a default emission factor. The emission rates provided for TR-189, TR-190, and TR-194 were excluded from the NO_X analysis because samples were collected and analyzed using a portable combustion gas analyzer, which is not considered an acceptable test method.

The maximum emission rate of 60,600 kg/10^6 dscm CH_4 for one engine (TR-284) is a suspected outlier when compared to the other emission rates. However, this test was witnessed by EPA staff and was thoroughly audited. Therefore, this potential outlier was included in the analysis because no datum should be rejected solely on the basis of statistical tests since there is a risk of rejecting an emission rate that represents actual emissions.

Emission rates for the three engines included in the analysis, plus the six engines from the previous AP-42 update (BID-64, -67, -68, -98, -99, -101) range from 2,440 to 60,600 kg/10^6 dscm CH_4. The arithmetic mean emission rate for NO_X for these LFG-fired engines is 11,600 kg/10^6 dscm CH_4. This average rate was selected as the default emission factor to represent engine NO_X in the AP-42 update, with a quality rating of "C." However, the user should consider the impact of the individual data point that is influencing this average when applying the default emission factor. For comparison, the median value of the engine NOx data points results in a value of 4,740 kg/10^6 dscm CH_4, which compares more closely with the previous default factor in AP-42 (U.S. EPA, 1998). The previous default emission factor was 4,000 kg/10^6 dscm CH_4 with a quality rating of "D."

3.2.2.2 Carbon Monoxide

Three of the six engine test reports (TR-266, TR-272, TR-284) containing CO emissions data were included in the analysis to determine a default emission factor. The emission rates provided for TR-189, TR-190, and TR-194 were excluded from the CO analysis because samples were collected and analyzed using a portable combustion gas analyzer, which is not considered an acceptable test method for the AP-42 analysis. There are five emission data points from the prior AP-42 update that are included in this analysis (BID-64, -67, -98, -99, -101).

Carbon monoxide emission rates range from 6,400 to 11,700 kg/10^6 dscm CH_4. The arithmetic mean emission rate for CO is 8,460 kg/10^6 dscm CH_4, which was selected as the default emission factor with a "C" quality rating for the AP-42 update. The prior default factor in AP-42 (U.S. EPA, 1998) is 7,500 kg/10^6 dscm CH_4 with a quality rating of "C."

3.2.2.3 Particulate Matter

Particulate matter emissions are provided in three engine test reports (TR-189, TR-190, TR-194) and one data point from the prior AP-42 update (BID-98). These four PM emission rates range between 43 and 772 kg/10^6 dscm CH_4. The arithmetic mean emission rate for PM is 232 kg/10^6 dscm CH_4. This

average rate was selected as the default to represent PM in the AP-42 update, with a quality rating of "D." The 1998 AP-42 section for MSW landfills (U.S. EPA, 1998) has a default PM emission factor of 770 kg/10^6 dscm CH_4 with a quality rating of "E."

3.2.2.4 Total Dioxin/Furan

Five test reports (TR-189, TR-190, TR-194, TR-272, TR-284) contain measurement data for dioxins/furans. Emissions data for three engine test reports (TR-189, TR-190, TR-194) were excluded from the dioxin/furan analysis because data were only reported on a TEQ basis but total dioxin/furan on a mass basis was being used in the analysis to determine a default emission factor. Emission rates for the remaining two test reports (TR-272, TR-284) are below the method detection limit for all test runs using EPA Method 23. The emission rates for each of these reports are $<2.15 \times 10^{-10}$ kg/hr (1.73×10^{-6} kg/10^6 dscm CH_4) for TR-272 and $<1.12 \times 10^{-10}$ kg/hr (3.92×10^{-7} kg/10^6 dscm CH_4) for TR-284. Therefore, a proper analysis cannot be conducted for total dioxin/furan emissions from LFG-fired engines until additional data become available. The prior version of the AP-42 section for MSW landfills (U.S. EPA, 1998) does not include dioxin/furan emission factors for engines.

3.2.2.5 IC Engine Summary

Table 3-8 contains a summary of the combustion by-product data included in the LFG-fired IC engine analysis for determining default emission factors for the AP-42 update. In addition, Table 3-8 provides the test methods used to measure these emissions data.

A data quality rating of "A" (except for BID-99 and PM for BID-98, which have "B" ratings) was assigned to each of the IC engine test reports listed in Table B. All of the reports containing these data included adequate detail, the methodology appeared to be sound, and no problems were reported for the test runs. However, overall data quality ratings of "C" for NOx and CO, and "D" for PM, are recommended for default emission factors representing combustion by-products from engines. These ratings exemplify the fact that the default factors were developed using "A" and "B"-rated test data from a reasonable to small number of facilities. Although no specific bias is evident, it is not clear if the engines tested represent a random sample of the existing LFG-fired engines in the U.S. given that between four (PM) to nine (NO$_x$) data points were used to determine each default emission factor.

TABLE 3-8. LANDFILL GAS-FIRED IC ENGINE EMISSIONS DATA USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS

Test Report Reference	Test Method	IC Engine Combustion By-Product	Emission Rate (kg/10^6 dscm CH_4)	Emission Rate (lb/10^6 dscf CH_4)
TR-266	SCAQMD Method 100.1 and EPA Methods 6C and 7E	NO$_X$	8,170	510
TR-272	EPA Method 7E (CEM)	NO$_X$	5,680	355
TR-284	EPA Method 7E (CEM)	NO$_X$	60,600	3,780
BID-64	EPA Method 10 (CEM)	NO$_X$	2,470	154
BID-67	EPA Method 10 (CEM)	NO$_X$	2,500	156
BID-68	EPA Method 7E (CEM)	NO$_X$	2,440	152
BID-98	CARB Method 1-100	NO$_X$	4,540	283
BID-99	Unspecified	NO$_X$	4,740	296
BID-101	Phenoldisulfonic Acid (PDSA) method	NO$_X$	13,400	839

TABLE 3-8 (CONTINUED). LANDFILL GAS-FIRED IC ENGINE EMISSIONS DATA USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS

Test Report Reference	Test Method	IC Engine Combustion By-Product	Emission Rate (kg/10⁶ dscm CH₄)	Emission Rate (lb/10⁶ dscf CH₄)
	NO$_X$ Default Emission Factor		11,600	725
	1998 NO$_X$ Default Emission Factor[a]		4,000	250
TR-266	SCAQMD Method 100.1 and EPA Methods 6C and 7E	CO	11,100	693
TR-272	EPA Method 10 (CEM)	CO	11,700	728
TR-284	EPA Method 10 (CEM)	CO	7,680	479
BID-64	EPA Method 7E (CEM)	CO	8,150	508
BID-67	EPA Method 7E (CEM)	CO	9,280	579
BID-98	CARB Method 1-100	CO	6,810	425
BID-99	Unspecified	CO	6,400	399
BID-101	TCA method	CO	6,610	413
	CO Default Emission Factor		8,460	528
	1998 CO Default Emission Factor[a]		7,500	470
TR-189	Environment Canada Report EPS 1/RM/8 "*Reference Method for Source Testing: Measurement of Releases of Particulate from Stationary Sources*"	PM	56.6	3.5
TR-190	Environment Canada Report EPS 1/RM/8 "*Reference Method for Source Testing: Measurement of Releases of Particulate from Stationary Sources*"	PM	54.8	3.4
TR-194	Environment Canada Report EPS 1/RM/8 "*Reference Method for Source Testing: Measurement of Releases of Particulate from Stationary Sources*"	PM	43.1	2.7
BID-98	EPA Method 5	PM	772	48
	PM Default Emission Factor		232	14.5
	1998 PM Default Emission Factor[a]		770	48

[a] – Default emission factor from the November 1998 AP-42 chapter 2.4.

3.2.2.6 *Emission Factors in Alternate Units of Measure*

The preceding tables present the emission factors in the units used for updating the MSW Landfills section of AP-42 (U.S. EPA, 1998). However, EPA's Landfill Methane Outreach Program (LMOP) and other organizations may require emission factors presented in units more convenient to the LFG energy project or combustion device being studied. Therefore, Table 3-9 presents the boiler data in units of lb/MMBtu heat input and lb/MWh of electricity produced, and Table 3-10 presents the engine data in lb/MMBtu heat input, and lb/MWh and g/brake horsepower-hour (bhph). The heat rate assumed in these conversions is 10,700 Btu/kWh for boilers, and 11,100 Btu/kWh for engines. These are consistent with factors used by the LMOP program and are based on engine manufacturer's literature and other information provided to LMOP by manufacturers and distributors. The heat content of CH₄ is 1,012 Btu/dscf (Perry, 1963).

**TABLE 3-9. LANDFILL GAS-FIRED BOILER EMISSIONS DATA
USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS (ALTERNATE
UNIT FACTORS)**

Test Report Reference	Test Method	Boiler Combustion By-Product	Emission Rate (lb/MMBtu) (fuel input)	Emission Rate (lb/MWh)
TR-167	SCAQMD Method 100.1 sampling with a CEMS	NO_X	0.04	0.4
TR-220	SCAQMD Method 100.1 sampling with a CEMS	NO_X	0.03	0.4
TR-268	ARB Method 1-100	NO_X	0.06	0.7
TR-291	SCAQMD Method 100.1 sampling with a CEMS	NO_X	0.04	0.4
TR-292	EPA Method 7E (CEM)	NO_X	0.04	0.4
NO_X Default Emission Factor			**0.04**	**0.4**
1998 NO_X Default Emission Factor[a]			**0.03**	**0.3**
TR-167	SCAQMD Method 100.1 sampling with a CEMS	CO	0.01	0.1
TR-220	SCAQMD Method 100.1 sampling with a CEMS	CO	2.0×10^{-4}	2.1×10^{-3}
TR-268	ARB Method 1-100	CO	0.01	0.1
TR-292	EPA Method 10 (CEM)	CO	0.02	0.2
CO Default Emission Factor			**0.01**	**0.1**
1998 CO Default Emission Factor[a]			**0.01**	**0.1**
TR-167	SCAQMD Method 5.2	PM	3.0×10^{-3}	0.03
TR-188	Environment Canada Report EPS 1/RM/8 "*Reference Method for Source Testing: Measurement of Releases of Particulate from Stationary Sources*"	PM	2.2×10^{-3}	0.02
TR-220	SCAQMD Method 5.1	PM	6.0×10^{-4}	0.01
TR-268	EPA Method 5	PM	4.4×10^{-3}	0.05
PM Default Emission Factor			**2.5×10^{-3}**	**0.03**
1998 PM Default Emission Factor[a]			**8.1×10^{-3}**	**0.09**
TR-220	CARB Method 428	Total dioxin/furan	1.4×10^{-10}	1.5×10^{-9}
TR-268	Modified EPA Method 5 (ASME Semi-VOST)	Total dioxin/furan	8.4×10^{-11}	9.0×10^{-10}
TR-291	CARB Method 428	Total dioxin/furan	8.8×10^{-11}	9.4×10^{-10}
TR-292	EPA Method 23 and EPA Method 8290	Total dioxin/furan	9.4×10^{-10}	1.0×10^{-8}
Total Dioxin/Furan Default Emission Factor			**3.1×10^{-10}**	**3.3×10^{-9}**
1998 Dioxin/Furan Default Emission Factor[a]			**Not available**	**Not available**

[a] − Default emission factor from the November 1998 AP-42 chapter 2.4, but converted to lb/MMBtu and lb/kWh units using 1,012 Btu/dscf CH_4 and 10,700 Btu/kWh, as discussed above.

TABLE 3-10. LANDFILL GAS-FIRED IC ENGINE EMISSIONS DATA USED TO DEVELOP COMBUSTION BY-PRODUCT EMISSION FACTORS (ALTERNATE UNIT FACTORS)

Test Report Reference	Test Method	IC Engine Combustion By-Product	Emission Rate (lb/MMBtu) (fuel input)	Emission Rate (lb/MWh)	Emission Rate (g/bhph)[a]
TR-266	SCAQMD Method 100.1 and EPA Methods 6C and 7E	NO_X	0.5	5.6	2.0
TR-272	EPA Method 7E (CEM)	NO_X	0.4	3.9	1.4
TR-284	EPA Method 7E (CEM)	NO_X	3.7	41	15
BID-64	EPA Method 10 (CEM)	NO_X	0.2	1.7	0.6
BID-67	EPA Method 10 (CEM)	NO_X	0.2	1.7	0.6
BID-68	EPA Method 7E (CEM)	NO_X	0.2	1.7	0.6
BID-98	CARB Method 1-100	NO_X	0.3	3.1	1.1
BID-99	Unspecified	NO_X	0.3	3.2	1.2
BID-101	Phenoldisulfonic Acid (PDSA) method	NO_X	0.8	9.2	3.3
NO_X Default Emission Factor			**0.7**	**8.0**	**2.8**
1998 NO_X Default Emission Factor[b]			**0.2**	**2.7**	**1.0**
TR-266	SCAQMD Method 100.1 and EPA Methods 6C and 7E	CO	0.7	7.6	2.7
TR-272	EPA Method 10 (CEM)	CO	0.7	8.0	2.8
TR-284	EPA Method 10 (CEM)	CO	0.5	5.3	1.9
BID-64	EPA Method 7E (CEM)	CO	0.5	5.6	2.0
BID-67	EPA Method 7E (CEM)	CO	0.6	6.4	2.3
BID-98	CARB Method 1-100	CO	0.4	4.7	1.7
BID-99	Unspecified	CO	0.4	4.4	1.6
BID-101	TCA method	CO	0.4	4.5	1.6
CO Default Emission Factor			**0.5**	**5.8**	**2.1**
1998 CO Default Emission Factor[b]			**0.5**	**5.2**	**1.8**
TR-189	Environment Canada Report EPS 1/RM/8 "*Reference Method for Source Testing: Measurement of Releases of Particulate from Stationary Sources*"	PM	3.5×10^{-3}	3.9×10^{-2}	1.4×10^{-2}
TR-190	Environment Canada Report EPS 1/RM/8 "*Reference Method for Source Testing: Measurement of Releases of Particulate from Stationary Sources*"	PM	3.4×10^{-3}	3.8×10^{-2}	1.3×10^{-2}
TR-194	Environment Canada Report EPS 1/RM/8 "*Reference Method for Source Testing: Measurement of Releases of Particulate from Stationary Sources*"	PM	2.7×10^{-3}	3.0×10^{-2}	1.1×10^{-2}
BID-98	EPA Method 5	PM	4.7×10^{-2}	5.3×10^{-1}	1.9×10^{-1}
PM Default Emission Factor			**1.4×10^{-2}**	**1.6×10^{-1}**	**5.6×10^{-2}**
1998 PM Default Emission Factor[b]			**4.7×10^{-2}**	**5.3×10^{-1}**	**1.9×10^{-1}**

[a] − Per common practice, assumes a 5% energy loss from engine output in converting shaft energy to electricity.

[b] – Default emission factor from the November 1998 AP-42 chapter 2.4, but converted to lb/MMBtu and lb/kWh units using 1,012 Btu/dscf CH_4 and 11,100 Btu/kWh, as discussed above.

3.2.3   Gas Turbine Data Summary

Since the last update of the MSW Landfills section of AP-42 (U.S. EPA, 1998), no additional test data for LFG turbines has been received by EPA. Therefore, these emission factors remain the same as in the previous update. Supporting background information from the 1997 background information document for turbines is included in Appendix F to this document.

References

BID-64. Report of Emission Levels and Fuel Economics for Eight Waukesha 12V-AT25GL Units Located at the Johnston, Rhode Island Central Landfill, Waukesha Pearce Industries, Inc. Houston, TX , July 19, 1991.

BID-67. Final Report for Emissions Compliance Testing of One Waukesha Engine Generator, Browning-Ferris Gas Services, Inc., Chicopee, MA, February 1994.

BID-68. Final Report for Emissions Compliance Testing of Three Waukesha Engine Generators, Browning-Ferris Gas Services, Inc., Richmond, VA, February 1994.

BID-98. Landfill Gas Engine Exhaust Emissions Test Report in Support of Modification to Existing IC Engine Permit at Bakersfield Landfill Unit #1, Pacific Energy Services, December 4, 1990.

BID-99. Addendum to Source Test Report for Superior Engine #1 at Otay Landfill, Pacific Energy Services, April 2, 1991.

BID-101. Source Test Report 88-0096 of Emissions from an Internal Combustion Engine Fueled by Landfill Gas, Toyon Canyon Landfill, Pacific Energy Lighting Systems, South Coast Air Quality Management District, March 8, 1988.

Perry, John H., ed. *Chemical Engineers Handbook*. McGraw-Hill Book Company: NY, 1963, Page 9-9.

TR-163. Compliance Testing for SPADRA Landfill Gas-to-Energy Plant, Ebasco Constructors, Inc., November 1990.

TR-167. 1997 Annual Compliance Source Testing Results for the Coyote Canyon Landfill Gas Recovery Facility Boiler, Laidlaw Gas Recovery Systems, January 1998.

TR-188. Characterization of Emissions from a Power Boiler Fired with Landfill Gas, Environment Canada, Emissions Research and Measurement Division, March 2000.

TR-189. Characterization of Emissions from 925 kWe Reciprocating Engine Fired with Landfill Gas, Environment Canada, Emissions Research and Measurement Division, December 2000.

TR-190. Characterization of Emissions from 812 kWe Reciprocating Engine Fired with Landfill Gas, Environment Canada, Emissions Research and Measurement Division, December 1999.

TR-194. Characterization of Emissions from 1 Mwe Reciprocating Engine Fired with Landfill Gas, Environment Canada, Emissions Research and Measurement Division, January 2002.

TR-220. SCAQMD Performance Tests on the Spadra Energy Recovery from Landfill Gas (SPERG) Facility, County Sanitation Districts of Los Angeles County, April 1992.

TR-266. Compliance Source Test Report – Landfill Gas-Fired Engine, Minnesota Methane, March 3, 1998.

TR-268. Emission Testing at PERG – Maximum Boiler Load, County Sanitation Districts of Los Angeles County, December 1986.

TR-272. Source Testing Final Report – Landfill A, U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division, October 6, 2005.

TR-284. Source Testing Final Report – Landfill C, U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division, October 6, 2005.

TR-291. PCDD/PCDF Emissions Tests on the Palos Verdes Energy Recovery from Landfill Gas (PVERG) Facility, Unit 2, County Sanitation Districts of Los Angeles County, February 1994.

TR-292. Source Testing Final Report – Landfill E, U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division, October 2005.

U.S. Environmental Protection Agency (1997a). Procedures for Preparing Emission Factor Documents ,EPA-454/R-95-015, Office of Air Quality Planning and Standards, Research Triangle Park, NC, November 1997.

U.S. Environmental Protection Agency (1998). Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: Stationary Point and Area Sources, Section 2.4 Municipal Solid Waste Landfills, Research Triangle Park, NC, November 1998.

3.3   CONTROL DEVICE EFFICENCY DATA

NMOC data was compiled for the various control devices and analyzed. This data consists of "A" and "B" data from the prior Municipal Solid Waste (MSW) Landfills section of AP-42 (U.S. EPA, 1998), along with the data available from this update, all of which were rated as "A" quality. The following table (Table 3-11) summarizes the data, which is also found in Table 2.4-3 of the AP-42 section. Appendix F contains the supporting data and calculations used to determine the control device efficiencies.

Please note that the Landfill NSPS requirements are in 40 CFR 60.752(b)(2)(iii) for enclosed combustion devices (e.g., enclosed flares, boilers, engines, turbines) burning untreated LFG require reduction of NMOC by 98 weight % <u>or</u> reduce the outlet NMOC concentration to less than 20 ppmv, dry basis as hexane at 3% oxygen. Therefore, although some of the data show that observed control efficiencies may sometimes be less than 98%, the control device may still meet the regulatory requirements by meeting the 20 ppmv limit of NMOC (dry basis as hexane at 3% oxygen).

Following the same criteria as described for the emission factors, the control device efficiency rankings were assigned as follows: Boiler – "D;" Flare – "A;" Engine – "D;" and Turbine – "E."

TABLE 3-11. NMOC CONTROL EFFICIENCY DATA ANALYSIS SUMMARY

	Number of Data Points	Min (%)	Max (%)	Mean (%)	Standard Deviation (%)	95% Confidence Interval (± %)
Boiler	5	95.9	99.6	98.6	1.6	1.4
Flare	25	85.8	100.0	97.7	3.4	1.3
Engine	3	94.6	99.7	97.2	2.6	2.9
Avg of Boiler, Engine, Flare				97.8		
Turbine	2	91.5	97.3	94.4	4.1	134.8

Historically, controlled emissions have been calculated with Equation 6. In this equation it is assumed that the LFG collection and control system operates 100 percent of the time. Minor durations of system downtime associated with routine maintenance and repair (i.e., 5 to 7 percent) will not appreciably affect emission estimates. The first term in Equation 6 accounts for emissions from uncollected LFG, while the second term accounts for emissions of the pollutant that were collected but not fully combusted in the control or utilization device:

$$CM_P = \left[UM_P \text{ x} \left(1 - \frac{\eta_{col}}{100} \right) \right] + \left[UM_P \text{ x} \frac{\eta_{col}}{100} \text{ x} \left(1 - \frac{\eta_{cnt}}{100} \right) \right] \tag{6}$$

where:

CM_P =   Controlled mass emissions of pollutant P, kg/yr;
UM_P =   Uncontrolled mass emissions of P, kg/yr (from Equation 5);
η_{col} =   Efficiency of the LFG collection system, % (recommended default is 75%); and
η_{cnt} =   Efficiency of the LFG control or utilization device, %.

3.4   CONTROL DEVICE CARBON DIOXIDE, SULFUR DIOXIDE, AND HYDROGEN CHLORIDE EMISSIONS

Controlled emissions of CO_2 and sulfur dioxide (SO_2) are best estimated using site-specific LFG constituent concentrations and mass balance methods (Nesbitt, 1996). If site-specific data are not available, the data in Tables 2-7, 2-8 and 2-9 can be used with the mass balance methods that follow.

Controlled CO_2 emissions include emissions from the CO_2 component of LFG and additional CO_2 formed during the combustion of LFG. The bulk of the CO_2 formed during LFG combustion comes from the combustion of the CH_4 fraction. Small quantities will be formed during the combustion of the NMOC fraction. However, this typically amounts to less than one percent of total CO_2 emissions by weight. This contribution to the overall mass balance picture is also very small and does not have a significant impact on overall CO_2 emissions (Nesbitt, 1996).

The following equation which assumes a 100% combustion efficiency for CH_4 can be used to estimate CO_2 emissions from controlled landfills:

$$CM_{CO_2} = UM_{CO_2} + \left(UM_{CH_4} \text{ x } \frac{\eta_{col}}{100} \text{ x } 2.75 \right) \tag{7}$$

where:

CM_{CO_2} = Controlled mass emissions of CO_2, kg/yr (from Equation 5);
UM_{CO_2} = Uncontrolled mass emissions of CO_2, kg/yr (from Equation 5);
UM_{CH_4} = Uncontrolled mass emissions of CH_4, kg/yr;
η_{col} = Efficiency of the LFG collection system, % (recommended default is 75%); and
2.75 = Ratio of the molecular weight of CO_2 to the molecular weight of CH_4.

To prepare estimates of SO_2 emissions, data on the concentration of reduced sulfur compounds within the LFG are needed. The best way to prepare this estimate is with site-specific information on the total reduced sulfur content of the LFG. Often these data are expressed in ppmv as sulfur (S). Equations 4 and 5 should be used first to determine the uncontrolled mass emission rate of reduced sulfur compounds as sulfur. Then, the following equation can be used to estimate SO_2 emissions:

$$CM_{SO_2} = UM_S \text{ x } \frac{\eta_{col}}{100} \text{ x } 2.0 \tag{8}$$

where:
CM_{SO_2} = Controlled mass emissions of SO_2, kg/yr;
UM_S = Uncontrolled emissions of reduced sulfur compounds as sulfur, kg/yr;
η_{col} = Efficiency of the LFG collection system, %; and
2.0 = Ratio of the molecular weight of SO_2 to the molecular weight of S.

The next best method to estimate SO_2 concentrations, if site-specific data for total reduced sulfur compounds as sulfur are not available, is to use site-specific data for speciated reduced sulfur compound concentrations. These data can be converted to ppmv as S with Equation 9. After the total reduced sulfur as S has been obtained from Equation 9, then Equations 4, 5, and 8 can be used to derive SO_2 emissions.

$$C_S = \sum_{i=1}^{n} C_P \times S_P \tag{9}$$

where:

C_S = Concentration of total reduced sulfur compounds, ppmv as S (for use in Equation 4);

C_P = Concentration of each reduced sulfur compound, ppmv;

S_P = Number of moles of S produced from the combustion of each reduced sulfur compound (i.e., 1 for sulfides, 2 for disulfides); and

n = Number of reduced sulfur compounds available for summation.

If no site-specific data are available, values of 47 and 33 ppmv can be used for C_S in the gas from landfills having a majority of the waste in place before 1992 and from landfills having a majority of the waste in place after 1992, respectively. These values were obtained by using the default concentrations presented in Tables 2-9 and 2-7 for reduced sulfur compounds and Equation 9.

Hydrochloric acid [hydrogen chloride (HCl)] emissions are formed when chlorinated compounds in LFG are combusted in control equipment. The best methods to estimate HCl emissions are mass balance methods that are analogous to those presented above for estimating SO_2 emissions. Hence, the best source of data to estimate HCl emissions is site-specific LFG data on total chloride [expressed in ppmv as the chloride ion (Cl$^-$)]. However, emission estimates may be underestimated, since not every chlorinated compound in the LFG will be represented in the site test report (i.e., only those that the analytical method specifies). If these data are not available, then total chloride can be estimated from data on individual chlorinated species using Equation 10 below.

$$C_{Cl} = \sum_{i=1}^{n} C_P \times Cl_P \tag{10}$$

where:

C_{Cl} = Concentration of total chloride, ppmv as Cl$^-$ (for use in Equation 4);

C_P = Concentration of each chlorinated compound, ppmv;

Cl_P = Number of moles of Cl$^-$ produced from the combustion of each mole of chlorinated compound (i.e., 3 for 1,1,1-trichloroethane); and

n = Number of chlorinated compounds available for summation.

After the total chloride concentration (C_{Cl}) has been estimated, Equations 4 and 5 should be used to determine the total uncontrolled mass emission rate of chlorinated compounds as chloride ion (UM_{Cl}). This value is then used in Equation 11, below, to derive HCl emission estimates:

$$CM_{HCl} = UM_{Cl} \times \frac{\eta_{col}}{100} \times 1.03 \times \frac{\eta_{cnt}}{100} \tag{11}$$

where:

CM_{HCl} = Controlled mass emissions of HCl, kg/yr;

UM_{Cl} = Uncontrolled mass emissions of chlorinated compounds as chloride, kg/yr (from Equations 4 and 5);

η_{col} = Efficiency of the LFG collection system, percent;

1.03 = Ratio of the molecular weight of HCl to the molecular weight of Cl$^-$; and

η_{cnt} = Control efficiency of the LFG control or utilization device, percent.

In estimating HCl emissions, it is assumed that all of the chloride ion from the combustion of chlorinated LFG constituents is converted to HCl. If an estimate of the control efficiency, η_{cnt}, is not available, then the control efficiency for the equipment listed in Table 3-11 should be used. This assumption is recommended to assume that HCl emissions are not under-estimated.

If site-specific data on total chloride or speciated chlorinated compounds are not available, then default values of 42 and 74 ppmv can be used for C_{Cl} in the gas from landfills having a majority of the waste in place before 1992 and from landfills having a majority of the waste in place after 1992, respectively. These values were derived from the default LFG constituent concentrations presented in Tables 2-11 and 2-8. As mentioned above, use of this default may produce underestimates of HCl emissions since it is based only on those compounds for which analyses have been performed. The constituents listed in Table 2-11 and 2-8 are likely not all of the chlorinated compounds present in LFG.

References

Letter and attached documents from C. Nesbitt, Los Angeles County Sanitation Districts, to K. Brust, E.H. Pechan and Associates, Inc., December 6, 1996.

4.0 MERCURY EMISSIONS DATA ANALYSIS

4.1   MERCURY IN RAW LANDFILL GAS

Mercury concentration data for raw LFG were submitted to EPA for a total of 17 landfills. These landfills are represented by nine emissions test reports because one test report (TR-211) contains mercury data for eight landfills in the state of Washington and another (TR-293) contains data for two landfills. This Washington report includes multiple measurements for two of the landfills sampled (TR-211a, TR-211f) because the LFG streams are split between the flare and the energy recovery facility at each landfill. A single average concentration for each of these landfills was calculated to represent each landfill so as not to disproportionately affect the overall average concentration being determined to estimate mercury emissions for an average landfill.

Total mercury, elemental mercury, monomethyl mercury, and dimethyl mercury are the four forms of mercury sampled and analyzed at these 17 landfills. Mercury concentrations are reported in either nanograms per cubic meter (ng/m^3) or milligrams per dry standard cubic foot (mg/dscf). These concentrations were converted to common units of parts per million by volume (ppmv), assuming standard conditions of 20 °C and one atmosphere.

4.1.1 Total Mercury

All nine of the test reports (TR-196, TR-211, TR-212, TR-272, TR-273, TR-284, TR-287, TR-292, TR-293), representing 17 landfills, contain measurement data for total mercury. Concentrations for two landfills were excluded from the total mercury analysis because samples were collected from a leachate well open to the atmosphere for one landfill (TR-211c) and from a passive gas well, with ambient air present, for another landfill (TR-211d).

Total mercury was sampled and analyzed using EPA Method 1631 for 14 of the 17 landfills. The test report for the landfill (TR-196) used CARB Draft Method 436 (adopted as CARB Method 436 in July 1997), Determination of Multiple Metals Emissions from Stationary Sources, to determine total mercury concentration. This test report reveals total mercury concentrations below the method detection limit ($<4.08 \times 10^{-6}$ ppmv) for all three test runs. Based on guidance for detection limits contained in EPA's Procedures for Preparing Emission Factor Documents (U.S. EPA, 1997a), half of the detection limit (2.04×10^{-6} ppmv) was used to represent the average concentration of total mercury for this landfill. This concentration represents the minimum concentration used in the analysis. Another test report (TR-293) used method SW-846 Method 7473, "Mercury in Solids and Solutions by Thermal Decomposition, Mercury Amalgamation, and Atomic Adsorption Spectroscopy" and CFR Part 60 Method 30B, "Determination of Total Vapor Phase Mercury Emissions from Coal-Fired Combustion Sources Using Carbon Sorbent Tubes" to determine total mercury.

Total mercury concentrations for the 15 landfills included in the analysis range from 2.04×10^{-6} to 9.61×10^{-4} ppmv. The maximum concentration of 9.61×10^{-4} ppmv for one landfill (TR-211g) is a suspected outlier when compared to the other concentrations. However, the maximum concentration was included in the analysis because no datum should be rejected solely on the basis of statistical tests since there is a risk of rejecting a concentration that represents actual emissions. The test report containing this suspected outlier (TR-211) is for eight landfills in the state of Washington. This report states that total mercury levels observed at these Washington landfills are in the range of 25 to 8,000 ng/m^3 (3.0×10^{-6} to 9.6×10^{-4} ppmv) which generally agrees with concentrations previously reported by Lindberg et al., 2001.

The arithmetic mean concentration for total mercury for the 13 landfills is 1.2×10^{-4} ppmv. This average concentration was selected as the default to represent total mercury in the AP-42 update. The

previous default concentration in AP-42 (U.S. EPA, 1998) is 2.92×10^{-4} ppmv with a quality rating of "E."

4.1.2 Elemental Mercury

Six test reports (TR-272, TR-273, TR-284, TR-287, TR-292, TR-293), representing seven landfills, include elemental mercury concentrations that were measured by the LUMEX Instrument. Elemental mercury concentrations range from 7.0×10^{-6} to 3.9×10^{-4} ppmv. The arithmetic mean concentration for elemental mercury is 7.7×10^{-5} ppmv, which was selected as the default concentration for the AP-42 update. The previous version of the AP-42 section for MSW landfills (U.S. EPA, 1998) does not include elemental mercury because no data were available to speciate total mercury into the elemental form.

4.1.3 Monomethyl Mercury

Monomethyl mercury concentrations are contained in seven test reports (TR-212, TR-272, TR-273, TR-284, TR-287, TR-292, TR-293) representing eight landfills. Five of these were sampled and analyzed using EPA draft method 1630. One test report (TR-293) used cold-vapor atomic fluorescence spectroscopy (CVAFS). The overall range of concentrations is 4.5×10^{-8} to 2.0×10^{-6} ppmv. The arithmetic mean concentration for monomethyl mercury for the six landfills is 3.8×10^{-7} ppmv. This average concentration was selected as the default to represent total mercury in the AP-42 update. The prior AP-42 section for MSW landfills (U.S. EPA, 1998) does not include monomethyl mercury because no data were available to speciate total mercury into the organic forms.

4.1.4 Dimethyl Mercury

Eight test reports (TR-211, TR-212, TR-272, TR-273, TR-284, TR-287, TR-292, TR-293), representing 16 landfills, contain measurement data for dimethyl mercury. Concentrations for two landfills were excluded from the dimethyl mercury analysis because samples were collected from a leachate well open to the atmosphere for one landfill (TR-211c) and from a passive gas well, with ambient air present, for another landfill (TR-211d). Concentrations thought to be biased low were excluded for two additional landfills (TR-272, TR-273) because spike recoveries are well below normally acceptable levels.

Dimethyl mercury was sampled and analyzed using EPA Method 1630 Appendix A for five test reports. The remaining test report, representing two landfills, used CVAFS.

Dimethyl mercury concentrations range from 2.3×10^{-7} to 5.5×10^{-6} ppmv. The arithmetic mean concentration for dimethyl mercury is 2.5×10^{-6} ppmv, which was selected as the default concentration for the AP-42 update. The prior version of the AP-42 section for MSW landfills (U.S. EPA, 1998) does not include dimethyl mercury because no data were available to speciate total mercury into the organic forms.

4.1.5 Mercury Data Summary

Table 4-1 contains a summary of the mercury data included in the raw LFG analysis for determining default concentrations for the AP-42 update. Appendix E presents statistical data graphs of the mercury data.

A data quality rating of "A" was assigned to each of the individual mercury test data contained in Table 4-1. All of the reports containing these data included adequate detail, the methodology appeared to

be sound, and no problems were reported for the valid test runs. An overall data quality rating of "B" for each of the four default concentrations representing each mercury compound is recommended. This rating exemplifies the fact that the default concentrations were developed from "A"-rated test data from a moderate number of facilities. Although no specific bias is evident, is not clear if the landfills tested represent a random sample of landfills in the U.S. In addition, less than 20 data points were used to determine each default concentration.

TABLE 4-1. RAW LANDFILL GAS MERCURY DATA USED TO DETERMINE AP-42 DEFAULT CONCENTRATIONS

Test Report Reference	Mercury Test Method	Mercury Compound	Concentration (ppmv)
TR-211a	EPA Method 1630 Appendix A	Dimethyl	1.9×10^{-6}
TR-211b	EPA Method 1630 Appendix A	Dimethyl	1.10×10^{-6}
TR-211e	EPA Method 1630 Appendix A	Dimethyl	7.4×10^{-7}
TR-211f	EPA Method 1630 Appendix A	Dimethyl	2.59×10^{-6}
TR-211g	EPA Method 1630 Appendix A	Dimethyl	4.81×10^{-6}
TR-211h	EPA Method 1630 Appendix A	Dimethyl	3.00×10^{-6}
TR-212	EPA Method 1630 Appendix A	Dimethyl	3.97×10^{-6}
TR-284	EPA Method 1630 Appendix A	Dimethyl	1.54×10^{-6}
TR-287	EPA Method 1630 Appendix A	Dimethyl	5.32×10^{-6}
TR-292	EPA Method 1630 Appendix A	Dimethyl	5.48×10^{-6}
TR-293a	CVAFS	Dimethyl	2.3×10^{-7}
TR-293b	CVAFS	Dimethyl	6.8×10^{-7}
Dimethyl Mercury Default Concentration			**2.5×10^{-6}**
TR-272	LUMEX Instrument	Elemental	3.69×10^{-5}
TR-273	LUMEX Instrument	Elemental	7.0×10^{-6}
TR-284	LUMEX Instrument	Elemental	1.2×10^{-5}
TR-287	LUMEX Instrument	Elemental	3.33×10^{-5}
TR-292	LUMEX Instrument	Elemental	5.28×10^{-5}
TR-293a	LUMEX Instrument	Elemental	3.9×10^{-4}
TR-293b	LUMEX Instrument	Elemental	5.6×10^{-6}
Elemental Mercury Default Concentration			**7.7×10^{-5}**
TR-212	EPA Draft Method 1631	Monomethyl	1.446×10^{-7}
TR-272	EPA Draft Method 1630	Monomethyl	4×10^{-8}
TR-273	EPA Draft Method 1630	Monomethyl	1.3×10^{-7}
TR-284	EPA Draft Method 1630	Monomethyl	4.4×10^{-7}
TR-287	EPA Draft Method 1630	Monomethyl	2.76×10^{-7}
TR-292	EPA Draft Method 1630	Monomethyl	6.0×10^{-7}
TR-293a	CVAFS	Monomethyl	1.4×10^{-6}
TR-293b	CVAFS	Monomethyl	2.0×10^{-6}
Monomethyl Mercury Default Concentration			**3.8×10^{-7}**

TABLE 4-1 (CONTINUED). RAW LANDFILL GAS MERCURY DATA USED TO DETERMINE AP-42 DEFAULT CONCENTRATIONS

Test Report Reference	Mercury Test Method	Mercury Compound	Concentration (ppmv)
TR-196	CARB Draft Method 436	Total	2.04×10^{-6}
TR-211a	EPA Method 1631	Total	5.41×10^{-6}
TR-211b	EPA Method 1631	Total	1.4098×10^{-4}
TR-211e	EPA Method 1631	Total	1.13×10^{-5}
TR-211f	EPA Method 1631	Total	2.767×10^{-5}
TR-211g	EPA Method 1631	Total	9.6083×10^{-4}
TR-211h	EPA Method 1631	Total	3.029×10^{-5}
TR-212	EPA Method 1631	Total	4.89×10^{-5}
TR-272	EPA Method 1631	Total	7.58×10^{-5}
TR-273	EPA Method 1631	Total	2.45×10^{-5}
TR-284	EPA Method 1631	Total	5.10×10^{-5}
TR-287	EPA Method 1631	Total	8.87×10^{-5}
TR-292	EPA Method 1631	Total	1.751×10^{-4}
TR-293a	SW-846 Method 7473 / CFR Part 60 Method 30B	Total	6.0×10^{-4}
TR-293b	SW-846 Method 7473 / CFR Part 60 Method 30B	Total	5.2×10^{-6}
Total Mercury Default Concentration			**1.2×10^{-4}**

4.2 POST-COMBUSTION MERCURY EMISSIONS

Burning LFG in combustion devices (control devices), including flares, engines, turbines, and boilers, may change the chemical species of mercury originally in the raw LFG but does not reduce the total quantity of mercury released. The amount of total mercury released from any combustion outlet is directly related to the amount of total mercury contained in the raw LFG. In other words, mercury emissions from landfills will be released to the atmosphere regardless of whether the LFG is combusted. However, combustion of LFG can convert organic forms of mercury, such as dimethyl mercury and monomethyl mercury, to less toxic inorganic forms, such as elemental mercury (Lindberg et al., 2001). The previous version of the AP-42 section for MSW landfills (U.S. EPA, 1998) has the following footnote for Table 2.4-3. Control Efficiencies for LFG Constituents: "For any equipment, the control efficiency for mercury should be assumed to be 0." However, we note that use of activated carbon control technology (e.g., fixed beds) is capable of achieving significant reductions in mercury emission rates. This technology is used for the control of mercury emissions from small municipal waste and hospital incinerator units. It is uncertain whether this particular technology is feasible for LFG combustion applications.

Total mercury concentrations from combustion outlets were provided for five landfills (TR-272, TR-273, TR-284, TR-287, TR-292), representing outlet emissions from two flares, two engines, and one boiler. Total mercury was measured using EPA Method 29 for all five landfills. Concentrations for four of these landfills (TR-272, TR-273, TR-284, TR-287) are below the method detection limit for all three test runs. Based on guidance for detection limits contained in EPA's Procedures for Preparing Emission Factor Documents (U.S. EPA, 1997a), half of the detection limit should be used to represent the average concentration of total mercury for each of these four landfills. However, these halved concentrations are greater than the detect value for the total mercury concentration from the remaining landfill tested (TR-292). Therefore, as directed in the EPA procedures document, these four halved concentrations should not be used in determining a default concentration for post-combustion total mercury emissions. In

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addition, elemental mercury concentrations were provided for post-combustion engine emissions from two landfills (TR-272, TR-284), using the LUMEX Instrument.

Due to the limited post-combustion mercury data provided and the knowledge that mercury in raw LFG is not destroyed through combustion but rather converted from organic to inorganic forms, it is recommended that default concentrations for post-combustion mercury emissions not be developed at this time. If additional data become available, then these factors may be explored further.

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5.0 AP-42 SECTION 2.4

Section 2.4 of AP-42 is presented in the following pages as it would appear in the AP-42 update. Please note that until this is formally released through EPA's Technology Transfer Network (TTN) Clearinghouse for Inventories & Emissions (http://www.epa.gov/ttn/chief/ap42/), the factors and information contained in this section are regarded as draft.

2.4   MUNICIPAL SOLID WASTE LANDFILLS

2.4.1 General [1-4]

        A municipal solid waste (MSW) landfill unit is a discrete area of land or an excavation that receives household waste, and that is not a land application unit, surface impoundment, injection well, or waste pile. An MSW landfill unit may also receive other types of wastes, such as commercial solid waste, nonhazardous sludge, and industrial solid waste. In addition to household and commercial wastes, the other waste types potentially accepted by MSW landfills include (most landfills accept only a few of the following categories):

   X   Municipal sludge,
   X   Municipal waste combustion ash,
   X   Infectious waste,
   X   Small-quantity generated hazardous waste;
   X   Waste tires,
   X   Industrial non-hazardous waste,
   X   Conditionally exempt small quantity generator (CESQG) hazardous waste,
   X   Construction and demolition waste,
   X   Agricultural wastes,
   X   Oil and gas wastes, and
   X   Mining wastes.

The information presented in this section applies only to landfills which receive primarily MSW. This information is not intended to be used to estimate emissions from landfills which receive large quantities of other waste types such as industrial waste, or construction and demolition wastes. These other wastes exhibit emissions unique to the waste being landfilled.

        In the United States in 2006, approximately 55 percent of solid waste was landfilled, 13 percent was incinerated, and 32 percent was recycled or composted. There were an estimated 1,754 active MSW landfills in the United States in 2006. These landfills were estimated to receive 138 million tons of waste annually, with 55 to 60 percent reported as household waste, and 35 to 45 percent reported as commercial waste.[79]

2.4.2 Process Description [2,5]

        The majority of landfills currently use the "area fill" method which involves placing waste on a landfill liner, spreading it in layers, and compacting it with heavy equipment. A daily soil cover is spread over the compacted waste to prevent wind-blown trash and to protect the trash from scavengers and vectors. The landfill liners are constructed of soil (i.e., recompacted clay) and synthetics (i.e., high density polyethylene) to provide an impermeable barrier to leachate (i.e., water that has passed through the

landfill) and gas migration from the landfill. Once an area of the landfill is completed, it is covered with a "cap" or "final cover" composed of various combinations of clay, synthetics, soil and cover vegetation to control the incursion of precipitation, the erosion of the cover, and the release of gases and odors from the landfill.

2.4.3 Control Technology[2,5,6]

The New Source Performance Standards (NSPS) and Emission Guidelines for air emissions from MSW landfills for certain new and existing landfills were published in the Federal Register on March 1, 1996. Current versions of the NSPS and Emission Guidelines can be found at 40 CFR 60 subparts WWW and Cb, respectively. The regulation requires that Best Demonstrated Technology (BDT) be used to reduce MSW landfill emissions from affected new and existing MSW landfills if (1) the landfill has a design capacity of 2.5 million Mg (2.75 million tons) and 2.5 million cubic meters or more, and (2) the calculated uncontrolled emissions from the landfill are greater than or equal to 50 Mg/yr (55 tons/yr) of nonmethane organic compounds (NMOCs). The MSW landfills that are affected by the NSPS/Emission Guidelines are each new MSW landfill, and each existing MSW landfill that has accepted waste since November 8, 1987 or that has capacity available for future use. Control systems require: (1) a well-designed and well-operated gas collection system, and (2) a control device capable of reducing non-methane organic compounds (NMOCs) in the collected gas by 98 weight-percent (or to 20 ppmv, dry basis as hexane at 3% oxygen for an enclosed combustion device). Other compliance options include use of a flare that meets specified design and operating requirements or treatment of landfill gas (LFG) for use as a fuel. The National Emission Standards for Hazardous Air Pollutants (NESHAP) for MSW landfills was published in the Federal Register on January 16, 2003. It requires control of the same landfills, and the same types of gas collection and control systems as the NSPS. The NESHAP also requires earlier control of bioreactor landfills and contains a few additional reporting requirements for MSW landfills.

Landfill gas collection systems consist of a series of vertical or horizontal perforated pipes that penetrate the waste mass and collect the gases produced by the decaying waste. These collection systems are classified as either active or passive systems. Active collection systems use mechanical blowers or compressors to create a vacuum in the collection piping to optimize the collection of LFG. Passive systems use the natural pressure gradient established between the encapsulated waste and the atmosphere to move the gas through the collection system.

LFG control and treatment options include: (1) combustion of the LFG, and (2) treatment of the LFG for subsequent sale or use. Combustion techniques include techniques that do not recover energy (i.e., flares and thermal incinerators), and techniques that recover energy and generate electricity from the combustion of the LFG (i.e., gas turbines and reciprocating engines). Boilers can also be employed to recover energy from LFG in the form of steam. Flares combust the LFG without the recovery of energy, and are classified by their burner design as being either open or enclosed. Purification techniques are used to process raw LFG to either a medium-BTU gas using dehydration and filtration or as a higher-BTU gas by removal of inert constituents using adsorption, absorption, and membranes.

2.4.4 Emissions[2,7]

Methane (CH_4) and carbon dioxide (CO_2) are the primary constituents of LFG, and are produced by microorganisms within the landfill under anaerobic conditions. Transformations of CH_4 and CO_2 are mediated by microbial populations that are adapted to the cycling of materials in anaerobic environments. Landfill gas generation proceeds through four phases. The first phase is aerobic [i.e., with oxygen (O_2) available from air trapped in the waste] and the primary gas produced is CO_2. The second phase is characterized by O_2 depletion, resulting in an anaerobic environment, where large amounts of CO_2 and some hydrogen (H_2) are produced. In the third phase, CH_4 production begins, with an accompanying

reduction in the amount of CO_2 produced. Nitrogen (N_2) content is initially high in LFG in the first phase, and declines sharply as the landfill proceeds through the second and third phases. In the fourth phase, gas production of CH_4, CO_2, and N_2 becomes fairly steady. The duration of each phase and the total time of gas generation vary with landfill conditions (i.e., waste composition, design management, and anaerobic state).

Typically, LFG also contains NMOC and volatile organic compounds (VOC). NMOC result from either decomposition by-products or volatilization of biodegradable wastes. Although NMOC are considered trace constituents in LFG, the NMOC and VOC emission rates could be "major" with respect to Prevention of Significant Deterioration (PSD) and New Source Review (NSR) requirements. This NMOC fraction often contains various organic hazardous air pollutants (HAP), greenhouse gases (GHG), compounds associated with stratospheric ozone depletion and volatile organic compounds (VOC). However, in MSW landfills where contaminated soils from storage tank cleanups are used as daily cover, much higher levels of NMOC have been observed. As LFG migrates through the contaminated soil, it adsorbs the organics, resulting in the higher concentrations of NMOC and any other contaminant in the soil. In one landfill where contaminated soil was used as daily cover, the NMOC concentration in the LFG was 5,870 ppm as compared to the AP-42 average value of 838 ppm. While there is insufficient data to develop a factor or algorithm for estimating NMOC from contaminated daily cover, the emissions inventory developer should be aware to expect elevated NMOC concentrations from these landfills.

Other emissions associated with MSW landfills include combustion products from LFG control and utilization equipment (i.e., flares, engines, turbines, and boilers). These include carbon monoxide (CO), oxides of nitrogen (NO_X), sulfur dioxide (SO_2), hydrogen chloride (HCl), particulate matter (PM) and other combustion products (including HAPs). PM emissions can also be generated in the form of fugitive dust created by mobile sources (i.e., garbage trucks) traveling along paved and unpaved surfaces. The reader should consult AP-42 Volume I Sections 13.2.1 and 13.2.2 for information on estimating fugitive dust emissions from paved and unpaved roads.

One pollutant that can very greatly between landfills is hydrogen sulfide (H_2S). H_2S is normally present in LFG at levels ranging from 0 to 90 ppm, with an average concentration of 33 ppm. However, a recent trend at some landfills has been the use of construction and demolition waste (C&D) as daily cover. Under certain conditions that are not well understood, some microorganisms will convert the sulfur in the wall-board of C&D waste to H_2S. At these landfills, H_2S concentrations can be significantly higher than at landfills that do not use C&D waste as daily cover. While H_2S measurements are not available for landfills using C&D for daily cover, the State of New Hampshire among others have noted elevated H_2S odor problems at these landfills and have assumed that H_2S concentrations have increased, similarly. In a series of studies at 10 landfills in Florida where a majority of the waste is composed of C&D material, the concentration of H_2S concentration spanned a range from less than the detection limit of the instrument (0.003 ppmv) up to 12,000 ppmv.[8] Another study that was conducted used flux boxes to measure uncontrolled emissions of H_2S at five landfills in Florida. This study reported a range of H_2S emissions between 0.192 and 1.76 mg/(m^2-d).[9] At any MSW landfill where C&D waste was used as daily cover or was comingled with the MSW, it is recommended that direct H_2S measurements be used to develop specific H_2S emissions for the landfill.

The rate of emissions from a landfill is governed by gas production and transport mechanisms. Production mechanisms involve the production of the emission constituent in its vapor phase through vaporization, biological decomposition, or chemical reaction. Transport mechanisms involve the transportation of a volatile constituent in its vapor phase to the surface of the landfill, through the air boundary layer above the landfill, and into the atmosphere. The three major transport mechanisms that enable transport of a volatile constituent in its vapor phase are diffusion, convection, and displacement.

Although relatively uncommon, fires can occur on the surface of the landfill or underground. The smoke from a landfill fire frequently contains many dangerous chemical compounds, including: carbon monoxide, particulate matter and hazardous gases that are the products of incomplete combustion, and very elevated concentrations of the many gaseous constituents normally occurring in LFG. Of particular concern in landfill fires is the emission of dioxins/furans. Accidental fires at landfills and the uncontrolled burning of residential waste are considered the largest sources of dioxin emissions in the United States.[10] The composition of the gases from landfill fires is highly variable and dependent on numerous site specific factors, including: the composition of the material burning, the composition of the surrounding waste, the temperature of the burning waste, and the presence of oxygen. The only reliable method for estimating the emissions from a landfill fire involves testing the emissions directly. More information is available on landfill fires and their emissions from reference 11.

2.4.4.1 Uncontrolled Emissions — Several methods have been developed by EPA to determine the uncontrolled emissions of the various compounds present in LFG. The newest measurement method is optical remote sensing with radial plume mapping (ORS-RPM). This method uses an optical emission detector such as open-path Fourier transform infrared spectroscopy (FTIR), ultraviolet differential absorption spectroscopy (UV-DOAS), or open-path tunable diode laser absorption spectroscopy (OP-TDLAS); coupled with radial plume mapping software that processes path-integrated emission concentration data and meteorological data to yield an estimate of uncontrolled emissions. More information on this newest method is described in *Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology* (EPA/600/R-07/032).[12] Additional research is ongoing to provide additional guidance on the use of optical remote sensing for application at landfills. Evaluating uncontrolled emissions from landfills can be a challenge. This is due to the changing nature of landfills, scale and complexity of the site, topography, and spatial and temporal variability in emissions. Additional guidance is being developed for application of EPA's test method for area sources emissions. This is expected to be released by the spring of 2009. For more information, refer to the Emission Measurement Center of EPA's Technology Transfer Network (http://www.epa.gov/ttn/emc/tmethods.html). Additional information on ORS technology can also be found on EPA's website for Measurement and Monitoring Technologies for 21st Century (21M^2) which provided funding to identify improved technologies for quantifying area source emissions (http://www.clu-in.org/programs/21m2/openpath/).

Often flux data are used to evaluate LFG collection efficiency. The concern with the use of this data is that it does not capture emission losses from header pipes or extraction wells. The other concern is that depending upon the design of the study, the emission variability across a landfill surface is not captured. Emission losses can occur from cracks and fissures or difference in landfill cover material. Often, alternative cover material is used to help promote infiltration, particularly for wet landfill operation. This can result in larger loss of fugitive emissions. Another loss of landfill gas is through the leachate collection pumps and wells. For many of these potential losses, a flux box is not considered adequate to capture the total loss of fugitive gas. The use of ORS technology is considered more reliable.

When direct measurement data are not available, the most commonly used EPA method to estimate the uncontrolled emissions associated with LFG is based on a biological decay model. In this method, the generation of CH_4 must first be estimated by using a theoretical first-order kinetic model of CH_4 production developed by the EPA[13]:

$$Q_{CH_4} = 1.3 L_o \ R \, (e^{-kc} - e^{-kt}) \qquad (1)$$

where:

Q_{CH_4} = Methane generation rate at time t, m^3/yr;

L_o = Methane generation potential, m³ CH₄/Mg of "wet" or "as received" refuse;

R = Average annual refuse acceptance rate during active life, Mg of "wet" or "as received" refuse /yr;

e = Base log, unitless;

k = Methane generation rate constant, yr⁻¹;

c = Time since landfill closure, yrs (c = 0 for active landfills); and

t = Time since the initial refuse placement, yrs.

When annual refuse acceptance data is available, the following form of Equation (1) is used. This is the general form of the equation that is used in EPA's Landfill Gas Emissions Model (LandGEM). Due to the complexity of the double summation, Equation (1alt) is normally implemented within a computer model. Equation (1 alt.) is more accurate because it accounts for the varying annual refuse flows and it calculates each year's gas flow in $^1/_{10th}$ year increments.

$$Q_{CH_4} = 1.3 \sum_{i=1}^{n} \sum_{j=0.1}^{1} k\, L_o \frac{R_i}{10}\, e^{-kt_{ij}} \qquad \text{(1 alternate)}$$

where:

Q_{CH_4} = Methane generation rate at time t, m³/yr;

L_o = Methane generation potential, m³ CH₄/Mg of "wet" or "as received" refuse;

R_i = Annual refuse acceptance rate for year i, Mg of "wet" or "as received" refuse /yr;

e = Base log, unitless;

k = Methane generation rate constant, yr⁻¹;

c = Time since landfill closure, yrs (c = 0 for active landfills); and

t = Time since the initial refuse placement, yrs.

i = year in life of the landfill

j = $^1/_{10th}$ year increment in the calculation.

It should be noted that Equation (1) is provided for estimating CH₄ emissions to the atmosphere. Other fates may exist for the gas generated in a landfill, including capture and subsequent microbial degradation within the landfill's surface layer. Currently, there are no data that adequately address this fate. It is generally accepted that the bulk of the CH₄ generated will be emitted through cracks or other openings in the landfill surface and that Equation (1) can be used to approximate CH₄ emissions from an uncontrolled landfill. It should also be noted that Equation (1) is different from the equation used in other models such as LandGEM by the addition of the constant 1.3 at the front of the equation. This constant is included to compensate for L_O which is typically determined by the amount of gas collected by LFG collection systems. The design of these systems will typically result in a gas capture efficiency of only 75%. Therefore, 25% of the gas generated by the landfill is not captured and included in the development of L_O. The ratio of total gas to captured gas is a ratio of 100/75 or equivalent to 1.3.

Site-specific landfill information is generally available for variables R, c, and t. When refuse acceptance rate information is scant or unknown, R can be determined by dividing the refuse in place by the age of the landfill. If a facility has documentation that a certain segment (cell) of a landfill received *only* nondegradable refuse, then the waste from this segment of the landfill can be excluded from the calculation of R. Nondegradable refuse includes concrete, brick, stone, glass, plaster, wallboard, piping, plastics, and metal objects. The average annual acceptance rate should only be estimated by this method when there is inadequate information available on the actual average acceptance rate. The time variable, t, includes the total number of years that the refuse has been in place (including the number of years that the landfill has accepted waste and, if applicable, has been closed).

Values for variables L_o and k are normally estimated. Estimation of the potential CH_4 generation capacity of refuse (L_o) is generally treated as a function of the moisture and organic content of the refuse. Estimation of the CH_4 generation constant (k) is a function of a variety of factors, including moisture, pH, temperature, and other environmental factors, and landfill operating conditions.

Recommended AP-42 defaults for k are:

k Value	Landfill Conditions
0.02	**Areas receiving <25 inches/yr rainfall**
0.04	**Areas receiving >25 inches/yr rainfall**
0.3	**Wet landfills[14]**

For the purpose of the above table, wet landfills are defined as landfills which add large amounts of water to the waste. This added water may be recycled landfill leachates and condensates, or may be other sources of water such as treated wastewater.

The CH_4 generation potential, L_o, has been observed to vary from 6 to 270 m^3/Mg (200 to 8670 ft3/ton), depending on the organic content of the waste material. A higher organic content results in a higher L_o. Food, textiles, paper, wood, and horticultural waste have the highest L_o value on a dry basis, while inert materials such as glass, metal and plastic have no L_o value.[2] Since moisture does not contribute to the value of L_o, a high moisture content waste, such as food or organic sludge, will have a lower L_o on an "as received" basis. When using Equation 1 to estimate emissions for typical MSW landfills in the U.S., a mean L_o value of 100 m^3/Mg refuse (3,530 ft^3 /ton, "as received" basis) is recommended.

There is a significant level of uncertainty in Equation 2 and its recommended defaults values for k and L_o. The recommended defaults k and L_o for conventional landfills, based upon the best fit to 40 different landfills, yielded predicted CH_4 emissions that ranged from ~30 to 400% of measured values and had a relative standard deviation of 0.73 (Table 2-2). The default values for wet landfills were based on a more limited set of data and are expected to contain even greater uncertainty.

When gas generation reaches steady state conditions, LFG consists of approximately equal volumes of CO_2 and CH_4. LFG also typically contains as much as five percent N_2 and other gases, and trace amounts of NMOCs. Since the flow of CO_2 is approximately equal to the flow of CH_4, the estimate derived for CH_4 generation using Equation (1) can also be used to estimate CO_2 generation. Addition of the CH_4 and CO_2 emissions will yield an estimate of total LFG emissions. If site-specific information is available on the actual CH_4 and CO_2 contents of the LFG, then the site-specific information should be used.

Most of the NMOC emissions from landfills result from the volatilization of organic compounds contained in the landfilled waste. Small amounts may also be created by biological processes and chemical reactions within the landfill. Available data show that the range of values for total NMOC in LFG is from 31 ppmv to over 5,387 ppmv, and averages 838 ppmv. The proposed regulatory default of 4,000 ppmv for NMOC concentration was developed for regulatory compliance purposes and is considered more conservative. For emissions inventory purposes, site-specific information should be taken into account when determining the total NMOC concentration, whenever available. Measured pollutant concentrations (i.e., as measured by EPA Reference Method 25C), must be corrected for air infiltration which can occur by two different mechanisms: LFG sample dilution and air intrusion into the landfill. These corrections require site-specific data for the LFG CH_4, CO_2, N_2, and O_2 content. If the ratio of N_2 to O_2 is less than or equal to 4.0 (as found in ambient air), then the total pollutant concentration

is adjusted for sample dilution by assuming that CO_2 and CH_2 are the primary constituents of LFG (assumed to account for 100% of the LGF), and the following equation is used:

$$C_P \text{ (corrected for air infiltration)} = \frac{C_P \times (1 \times 10^6)}{C_{CO_2} + C_{CH_4}}$$

(2)

where:

C_P	=	Concentration of pollutant P in LFG (i.e., NMOC as hexane), ppmv;
C_{CO2}	=	CO_2 concentration in LFG, ppmv;
Q_{CH4}	=	CH_4 Concentration in LFG, ppmv; and
1×10^6	=	Constant used to correct concentration of P to units of ppmv.

If the ratio of N_2 to O_2 concentrations (i.e., C_{N2}, C_{O2}) is greater than 4.0, then the total pollutant concentration should be adjusted for air intrusion into the landfill by using Equation (2) and adding the concentration of N_2 (i.e., C_{N2}) to the denominator. Values for C_{CO2}, C_{CH4}, C_{N2}, C_{O2}, can usually be found in the source test report for the particular landfill along with the total pollutant concentration data.

To estimate uncontrolled emissions of NMOC or other LFG constituents, the following equation should be used:

$$Q_P = \frac{Q_{CH4} \times C_P}{C_{CH_4} \times (1 \times 10^6)}$$

(3)

where:

Q_P	=	Emission rate of pollutant P (i.e., NMOC), m^3/yr;
Q_{CH4}	=	CH_4 generation rate, m^3/yr (from Equation 1);
C_P	=	Concentration of pollutant P in LFG, ppmv; and
C_{CH4}	=	Concentration of CH_4 in the LFG (assumed to be 50% expressed as 0.5)

Uncontrolled mass emissions per year of total NMOC (as hexane) and speciated organic and inorganic compounds can be estimated by the following equation:

$$UM_P = Q_P \times \frac{MW_P \times 1 \text{ atm}}{(8.205 \times 10^{-5} \, m^3 - atm/gmol - {}^\circ K) \times (1000 g/kg) \times (273 + T)}$$

(4)

where:

UM_P	=	Uncontrolled mass emissions of pollutant P (i.e., NMOC), kg/yr;
MW_P	=	Molecular weight of P, g/gmol (i.e., 86.18 for NMOC as hexane);
Q_P	=	Emission rate of pollutant P, m^3/yr; and
T	=	Temperature of LFG, $^\circ$C.

This equation assumes that the operating pressure of the system is approximately 1 atmosphere. If the temperature of the LFG is not known, a temperature of 25 $^\circ$C (77 $^\circ$F) is recommended.

Uncontrolled default concentrations of VOC, NMOC and speciated compounds are presented in Table 2.4-1 for landfills having a majority of the waste in place on or after 1992 and in Table 2.4-2 for landfills having a majority of the waste in place before 1992. These default concentrations have already been corrected for air infiltration and can be used as input parameters to Equation (3) for estimating

emissions from landfills when site-specific data are not available. An analysis of the data, based on the co-disposal history (with non-residential wastes) of the individual landfills from which the concentration data were derived, indicates that for benzene, NMOC, and toluene, there is a difference in the uncontrolled concentrations.

It is important to note that the compounds listed in Tables 2.4-1 and 2.4-2 are not the only compounds likely to be present in LFG. The listed compounds are those that were identified through a review of the available landfill test reports. The reader should be aware that additional compounds are likely present, such as those associated with consumer or industrial products. Given this information, extreme caution should be exercised in the use of the default emission concentrations given in Tables 2.4-1 and 2.4-2. Available data have shown that there is a range of over two orders of magnitude in many of the pollutant concentrations among gases from various MSW landfills.

2.4.4.2 Controlled Emissions — Emissions from landfills are typically controlled by installing a gas collection system, and either combusting the collected gas through the use of internal combustion engines, flares, or turbines, or by purifying the gas for direct use in place of a fuel such as natural gas. Gas collection systems are not 100% efficient in collecting LFG, so emissions of CH_4 and NMOC at a landfill with a gas recovery system still occur. To estimate controlled emissions of CH_4, NMOC, and other constituents in LFG, the collection efficiency of the system must first be estimated. Reported collection efficiencies typically range from 50 to 95%, with a default efficiency of 75% recommended by EPA for inventory purposes. The lower collection efficiencies are experienced at landfills with a large number of open cells, no liners, shallow soil covers, poor collection system and cap maintenance programs and/or a large number of cells without gas collection. The higher collection efficiencies may be achieved at closed sites employing good liners, extensive geomembrane-clay composite caps in conjunction with well engineered gas collection systems, and aggressive operation and maintenance of the cap and collection system. If documented site-specific collection efficiencies are available (i.e., through a comprehensive surface sampling program), then they may be used instead of the 75% average. An analysis showing a range in the gas collection system taking into account delays from gas collection from initial waste placement is provided in Section 2.0.

Estimates of controlled emissions may also need to account for the control efficiency of the control device. Control efficiencies for NMOC and VOC based on test data for the combustion of LFG with differing control devices are presented in Table 2.4-3. As noted in the table, these control efficiencies may also be applied to other LFG constituents. Emissions from the control devices need to be added to the uncollected emissions to estimate total controlled emissions.

Controlled CH_4, NMOC, VOC, and speciated emissions can be determined by either of two methods developed by EPA. The newest method is the optical remote sensing with radial plume mapping (ORS-RPM). This method uses an optical emission detector such as open-path Fourier transform infrared spectroscopy (FTIR), ultraviolet differential absorption spectroscopy (UV-DOAS), or open-path tunable diode laser absorption spectroscopy (OP-TDLAS); coupled with radial plume mapping software that processes path-integrated emission concentration data and meteorological data to yield an estimate of uncontrolled emissions. More information on this newest method is described in *Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology* (EPA/600/R-07/032).[12]

Historically, controlled emissions have been calculated with Equation 5. In this equation it is assumed that the LFG collection and control system operates 100 percent of the time. Minor durations of system downtime associated with routine maintenance and repair (i.e., 5 to 7 percent) will not appreciably effect emission estimates. The first term in Equation 5 accounts for emissions from uncollected LFG, while the second term accounts for emissions of the pollutant that were collected but not fully combusted in the control or utilization device:

$$CM_P = \left[UM_P \text{ x } \left(1 - \frac{\eta_{col}}{100} \right) \right] + \left[UM_P \text{ x } \frac{\eta_{col}}{100} \text{ x } \left(1 - \frac{\eta_{cnt}}{100} \right) \right] \qquad (5)$$

where:

CM_P = Controlled mass emissions of pollutant P, kg/yr;
UM_P = Uncontrolled mass emissions of P, kg/yr (from Equation 4);
η_{col} = Efficiency of the LFG collection system, % (recommended default is 75%); and
η_{cnt} = Efficiency of the LFG control or utilization device, %.

Emission factors for the secondary compounds, CO, PM, NO_x and dioxins/furans exiting the control device are presented in Table 2.4-4. These emission factors should be used when equipment vendor emission guarantees are not available.

Controlled emissions of CO_2 and sulfur dioxide (SO_2) are best estimated using site-specific LFG constituent concentrations and mass balance methods.[15] If site-specific data are not available, the data in Tables 2.4-1 and 2.4-2 can be used with the mass balance methods that follow.

Controlled CO_2 emissions include emissions from the CO_2 component of LFG and additional CO_2 formed during the combustion of LFG. The bulk of the CO_2 formed during LFG combustion comes from the combustion of the CH_4 fraction. Small quantities will be formed during the combustion of the NMOC fraction. However, this typically amounts to less than 1 percent of total CO_2 emissions by weight. Also, the formation of CO through incomplete combustion of LFG will result in small quantities of CO_2 not being formed. This contribution to the overall mass balance picture is also very small and does not have a significant impact on overall CO_2 emissions.[15]

The following equation which assumes a 100% combustion efficiency for CH_4 can be used to estimate CO_2 emissions from controlled landfills:

$$CM_{CO_2} = UM_{CO_2} + \left(UM_{CH_4} \text{ x } \frac{\eta_{col}}{100} \text{ x } 2.75 \right) \qquad (6)$$

where:

CM_{CO_2} = Controlled mass emissions of CO_2, kg/yr;
UM_{CO_2} = Uncontrolled mass emissions of CO_2, kg/yr (from Equation 4);
UM_{CH_4} = Uncontrolled mass emissions of CH_4, kg/yr (from Equation 4);
η_{col} = Efficiency of the LFG collection system, % (recommended default is 75%); and
2.75 = Ratio of the molecular weight of CO_2 to the molecular weight of CH_4.

To prepare estimates of SO_2 emissions, data on the concentration of reduced sulfur compounds within the LFG are needed. The best way to prepare this estimate is with site-specific information on the total reduced sulfur content of the LFG. Often these data are expressed in ppmv as sulfur (S). Equations 3 and 4 should be used first to determine the uncontrolled mass emission rate of reduced sulfur compounds as sulfur. Then, the following equation can be used to estimate SO_2 emissions:

$$CM_{SO_2} = UM_S \text{ x } \frac{\eta_{col}}{100} \text{ x } 2.0 \qquad (7)$$

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where:

CM_{SO_2} = Controlled mass emissions of SO_2, kg/yr;

UM_S = Uncontrolled emissions of reduced sulfur compounds as sulfur, kg/yr (from Equations 3 and 4);

η_{col} = Efficiency of the LFG collection system, %; and

2.0 = Ratio of the molecular weight of SO_2 to the molecular weight of S.

The next best method to estimate SO_2 concentrations, if site-specific data for total reduced sulfur compounds as sulfur are not available, is to use site-specific data for speciated reduced sulfur compound concentrations. These data can be converted to ppmv as S with Equation 8. After the total reduced sulfur as S has been obtained from Equation 8, then Equations 3, 4, and 7 can be used to derive SO_2 emissions.

$$C_S = \sum_{i=1}^{n} C_P \times S_P \tag{8}$$

where:

C_S = Concentration of total reduced sulfur compounds, ppmv as S (for use in Equation 3);

C_P = Concentration of each reduced sulfur compound, ppmv;

S_P = Number of moles of S produced from the combustion of each reduced sulfur compound (i.e., 1 for sulfides, 2 for disulfides); and

n = Number of reduced sulfur compounds available for summation.

If no site-specific data are available, values of 47 and 33 ppmv can be used for C_S in the gas from landfills having a majority of the waste in place before 1992 and from landfills having a majority of the waste in place after 1992, respectively. These values were obtained by using the default concentrations presented in Tables 2.4-1 and 2.4-2 for reduced sulfur compounds and Equation 8.

Hydrochloric acid [Hydrogen Chloride (HCl)] emissions are formed when chlorinated compounds in LFG are combusted in control equipment. The best methods to estimate HCl emissions are mass balance methods that are analogous to those presented above for estimating SO_2 emissions. Hence, the best source of data to estimate HCl emissions is site-specific LFG data on total chloride [expressed in ppmv as the chloride ion (Cl^-)]. However, emission estimates may be underestimated, since not every chlorinated compound in the LFG will be represented in the site test report (i.e., only those that the analytical method specifies). If these data are not available, then total chloride can be estimated from data on individual chlorinated species using Equation 9 below.

$$C_{Cl} = \sum_{i=1}^{n} C_P \times Cl_P \tag{9}$$

where:

C_{Cl} = Concentration of total chloride, ppmv as Cl^- (for use in Equation 3);

C_P = Concentration of each chlorinated compound, ppmv;

Cl_P = Number of moles of Cl^- produced from the combustion of each mole of chlorinated compound (i.e., 3 for 1,1,1-trichloroethane); and

n = Number of chlorinated compounds available for summation.

After the total chloride concentration (C_{Cl}) has been estimated, Equations 3 and 4 should be used to determine the total uncontrolled mass emission rate of chlorinated compounds as chloride ion (UM_{Cl}). This value is then used in Equation 10, below, to derive HCl emission estimates:

$$CM_{HCl} = UM_{Cl} \text{ x } \frac{\eta_{col}}{100} \text{ x } 1.03 \text{ x } \frac{\eta_{cnt}}{100} \tag{10}$$

where:

CM_{HCl} = Controlled mass emissions of HCl, kg/yr;

UM_{Cl} = Uncontrolled mass emissions of chlorinated compounds as chloride, kg/yr (from Equations 3 and 4);

η_{col} = Efficiency of the LFG collection system, percent;

1.03 = Ratio of the molecular weight of HCl to the molecular weight of Cl^-; and

η_{cnt} = Control efficiency of the LFG control or utilization device, percent.

In estimating HCl emissions, it is assumed that all of the chloride ion from the combustion of chlorinated LFG constituents is converted to HCl. If an estimate of the control efficiency, η_{cnt}, is not available, then the control efficiency for the equipment listed in Table 2.4-3 should be used. This assumption is recommended to assume that HCl emissions are not under-estimated.

If site-specific data on total chloride or speciated chlorinated compounds are not available, then default values of 42 and 74 ppmv can be used for C_{Cl} in the gas from landfills having a majority of the waste in place before 1992 and from landfills having a majority of the waste in place after 1992, respectively. These values were derived from the default LFG constituent concentrations presented in Tables 2.4-1 and 2.4-2. As mentioned above, use of this default may produce underestimates of HCl emissions since it is based only on those compounds for which analyses have been performed. The constituents listed in Table 2.4-1 and 2.4-2 are likely not all of the chlorinated compounds present in LFG.

The reader is referred to AP-42 Volume I, Sections 13.2.1 and 13.2.2 for information on estimating fugitive dust emissions from paved and unpaved roads, and to Section 13.2.3 for information on estimating fugitive dust emissions from heavy construction operations; and to AP-42 Volume II Section II-7 for estimating exhaust emissions from construction equipment.

2.4.5 Updates Since the Fifth Edition

The Fifth Edition was released in January 1995. The November 1998 revision includes major revisions of the text and recommended emission factors contained in the section. The most significant revisions to this section since publication in the Fifth Edition are summarized below.

X The equations to calculate the CH_4, CO_2 and other constituents were simplified.

X The default L_0 and k were revised based upon an expanded base of gas generation data.

X The default ratio of CO_2 to CH_4 was revised based upon averages observed in available source test reports.

X The default concentrations of LFG constituents were revised based upon additional data. References 16-148 are the emission test reports from which data were obtained for this section.

X Additional control efficiencies were included and existing efficiencies were revised based upon additional emission test data.

X Revised and expanded the recommended emission factors for secondary compounds emitted from typical control devices.

The current (i.e., 2008) update includes text revisions and additional discussion, as well as revised recommended emission factors contained within the section. The more significant revisions are summarized below:

X Default concentrations of LFG constituents were developed for landfills with the majority of their waste in place on or after 1992 (proposal of RCRA Subtitle D). The LFG constituent list from the last update reflects data from landfills with waste in place prior to 1992, so Table 2.4-2 was renamed to reflect this.

X Control efficiencies were updated to incorporate additional emission test data and the table was revised to show the NMOC and VOC control efficiencies.

X Revised and expanded the recommended emission factors for secondary compounds emitted from typical control devices.

X The description of modern landfills and statistics about waste disposition in the U.S. were updated with 2006 information.

X EPA's newest measurement method for determining landfill emissions, Optical Remote Sensing with Radial Plume Mapping (ORS-RPM), was added to the discussion of available options for measuring landfill emissions.

X A factor of 1.3 was added to Equation (1) to account for the fact that L_0 is typically determined by the amount of CH_4 collected at landfills using equipment that typically has a capture efficiency of only 75%.

X A k value of 0.3 was added to the list of recommended k values for use in Equation (1) to more accurately model landfill gas emissions from wet landfills.

Table 2.4-1. DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS FOR LANDFILLS WITH WASTE IN PLACE ON OR AFTER 1992				
Compound	CAS Number	Molecular Weight	Default Concentration (ppmv)	Recommended Emission Factor Rating
NMOC (as hexane)[a]		86.18	8.38E+02	A
VOC[b]		NA	8.35E+02	A
1,1,1-Trichloroethane[c]	71556	133.40	2.43E-01	A
1,1,2,2-Tetrachloroethane[c]	79345	167.85	5.35E-01	E
1,1,2,3,4,4-Hexachloro-1,3-butadiene (Hexachlorobutadiene)[c]	87683	260.76	3.49E-03	D
1,1,2-Trichloro-1,2,2-Trifluoroethane (Freon 113)	76131	187.37	6.72E-02	C
1,1,2-Trichloroethane[c]	79005	133.40	1.58E-01	D
1,1-Dichloroethane[c]	75343	98.96	2.08E+00	A
1,1-Dichloroethene (1,1-Dichloroethylene)[c]	75354	96.94	1.60E-01	A
1,2,3-Trimethylbenzene	526738	120.19	3.59E-01	D
1,2,4-Trichlorobenzene[c]	120821	181.45	5.51E-03	C

1,2,4-Trimethylbenzene	95636	120.19	1.37E+00	B
1,2-Dibromoethane (Ethylene dibromide)[c]	106934	187.86	4.80E-03	B
1,2-Dichloro-1,1,2,2-tetrafluoroethane (Freon 114)	76142	170.92	1.06E-01	B
1,2-Dichloroethane (Ethylene dichloride)[c]	107062	98.96	1.59E-01	A
1,2-Dichloroethene	540590	96.94	1.14E+01	E
1,2-Dichloropropane[c]	78875	112.99	5.20E-02	D
1,2-Diethylbenzene	135013	134.22	1.99E-02	D
1,3,5-Trimethylbenzene	108678	120.19	6.23E-01	C
1,3-Butadiene (Vinyl ethylene)[c]	106990	54.09	1.66E-01	C
1,3-Diethylbenzene	141935	134.22	6.55E-02	D
1,4-Diethylbenzene	105055	134.22	2.62E-01	D
1,4-Dioxane (1,4-Diethylene dioxide)[c]	123911	88.11	8.29E-03	D
1-Butene / 2-Methylbutene	106989 / 513359	56.11 / 70.13	1.22E+00	D
1-Butene / 2-Methylpropene	106989 / 115117	56.11	1.10E+00	E
1-Ethyl-4-methylbenzene (4-Ethyl toluene)	622968	120.19	9.89E-01	C
1-Ethyl-4-methylbenzene (4-Ethyl toluene) + 1,3,5-Trimethylbenzene	622968 / 108678	120.19	5.79E-01	D
1-Heptene	592767	98.19	6.25E-01	E
1-Hexene / 2-Methyl-1-pentene	592416 / 763291	84.16	8.88E-02	D
1-Methylcyclohexene	591491	96.17	2.27E-02	D
1-Methylcyclopentene	693890	82.14	2.52E-02	D
1-Pentene	109671	70.13	2.20E-01	D
1-Propanethiol (n-Propyl mercaptan)	107039	76.16	1.25E-01	A
2,2,3-Trimethylbutane	464062	100.20	9.19E-03	D
2,2,4-Trimethylpentane[c]	540841	114.23	6.14E-01	D
2,2,5-Trimethylhexane	3522949	128.26	1.56E-01	D
2,2-Dimethylbutane	75832	86.18	1.56E-01	D
2,2-Dimethylpentane	590352	100.20	6.08E-02	D
2,2-Dimethylpropane	463821	72.15	2.74E-02	E
2,3,4-Trimethylpentane	565753	114.23	3.12E-01	D
2,3-Dimethylbutane	79298	86.18	1.67E-01	D
2,3-Dimethylpentane	565593	100.20	3.10E-01	D
2,4-Dimethylhexane	589435	114.23	2.22E-01	D
2,4-Dimethylpentane	108087	100.20	1.00E-01	D
2,5-Dimethylhexane	592132	114.23	1.66E-01	D
2,5-Dimethylthiophene	638028	112.19	6.44E-02	E
2-Butanone (Methyl ethyl ketone)[c]	78933	72.11	4.01E+00	C
2-Ethyl-1-butene	760214	84.16	1.77E-02	D
2-Ethylthiophene	872559	112.19	6.29E-02	E
2-Ethyltoluene	611143	120.19	3.23E-01	D
2-Hexanone (Methyl butyl ketone)	591786	100.16	6.13E-01	E
2-Methyl-1-butene	563462	70.13	1.79E-01	D
2-Methyl-1-propanethiol (Isobutyl mercaptan)	513440	90.19	1.70E-01	E
2-Methyl-2-butene	513359	70.13	3.03E-01	D

Table 2.4-1(CONTINUED). DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS FOR LANDFILLS WITH WASTE IN PLACE ON OR AFTER 1992

Compound	CAS Number	Molecular Weight	Default Concentration (ppmv)	Recommended Emission Factor Rating
2-Methyl-2-propanethiol (tert-Butylmercaptan)	75661	90.19	3.25E-01	E
2-Methylbutane	78784	72.15	2.26E+00	D
2-Methylheptane	592278	114.23	7.16E-01	D
2-Methylhexane	591764	100.20	8.16E-01	D
2-Methylpentane	107835	86.18	6.88E-01	D
2-Propanol (Isopropyl alcohol)	67630	60.10	1.80E+00	C
3,6-Dimethyloctane	15869940	142.28	7.85E-01	D
3-Ethyltoluene	620144	120.19	7.80E-01	D
3-Methyl-1-pentene	760203	84.16	6.99E-03	D
3-Methylheptane	589811	114.23	7.63E-01	D
3-Methylhexane	589344	100.20	1.13E+00	D
3-Methylpentane	96140	86.18	7.40E-01	D
3-Methylthiophene	616444	98.17	9.25E-02	E
4-Methyl-1-pentene	691372	84.16	2.33E-02	E
4-Methyl-2-pentanone (MIBK)[c]	108101	100.16	8.83E-01	C
4-Methylheptane	589537	114.23	2.49E-01	D
Acetaldehyde[c]	75070	44.05	7.74E-02	D
Acetone	67641	58.08	6.70E+00	C
Acetonitrile[c]	75058	41.05	5.56E-01	A
Acrylonitrile[c,d]	107131	53.06	BDL	
Benzene[c]	71432	78.11	2.40E+00	A
Benzyl chloride[c]	100447	126.58	1.81E-02	A
Bromodichloromethane	75274	163.83	8.78E-03	E
Bromomethane (Methyl bromide)[c]	74839	94.94	2.10E-02	C
Butane	106978	58.12	6.22E+00	C
Carbon disulfide[c]	75150	76.14	1.47E-01	A
Carbon monoxide	630080	28.01	2.44E+01	C
Carbon tetrachloride[c]	56235	153.82	7.98E-03	A
Carbon tetrafluoride (Freon 14)	75730	88.00	1.51E-01	E
Carbonyl sulfide (Carbon oxysulfide)[c]	463581	60.08	1.22E-01	A
Chlorobenzene	108907	112.56	4.84E-01	A
Chlorodifluoromethane (Freon 22)[c]	75456	86.47	7.96E-01	D
Chloroethane (Ethyl chloride)[c]	75003	64.51	3.95E+00	B
Chloromethane (Methyl chloride)[c]	74873	50.49	2.44E-01	B
cis-1,2-Dichloroethene	156592	96.94	1.24E+00	B
cis-1,2-Dimethylcyclohexane	2207014	112.21	8.10E-02	D
cis-1,3-Dichloropropene	10061015	110.97	3.03E-03	D
cis-1,3-Dimethylcyclohexane	638040	112.21	5.01E-01	D
cis-1,4-Dimethylcyclohexane / trans-1,3-Dimethylcyclohexane	624293 / 2207036	112.21	2.48E-01	D
cis-2-Butene	590181	56.11	1.05E-01	D
cis-2-Heptene	6443921	98.19	2.45E-02	E
cis-2-Hexene	7688213	84.16	1.72E-02	D
cis-2-Octene	7642048	112.21	2.20E-01	D
cis-2-Pentene	627203	70.13	4.79E-02	D
cis-3-Methyl-2-pentene	922623	84.16	1.79E-02	D
Cyclohexane	110827	84.16	1.01E+00	B
Cyclohexene	110838	82.14	1.84E-02	D

Table 2.4-1(CONTINUED). DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS FOR LANDFILLS WITH WASTE IN PLACE ON OR AFTER 1992				
Compound	CAS Number	Molecular Weight	Default Concentration (ppmv)	Recommended Emission Factor Rating
Cyclopentane	287923	70.13	2.21E-02	D
Cyclopentene	142290	68.12	1.21E-02	D
Decane	124185	142.28	3.80E+00	D
Dibromochloromethane	124481	208.28	1.51E-02	D
Dibromomethane (Methylene dibromide)	74953	173.84	8.35E-04	E
Dichlorobenzene[c,e]	106467	147.00	9.40E-01	A
Dichlorodifluoromethane (Freon 12)	75718	120.91	1.18E+00	B
Dichloromethane (Methylene chloride)[c]	75092	84.93	6.15E+00	A
Diethyl sulfide	352932	90.19	8.62E-02	E
Dimethyl disulfide	624920	94.20	1.37E-01	A
Dimethyl sulfide	75183	62.14	5.66E+00	A
Dodecane (n-Dodecane)	112403	170.33	2.21E-01	D
Ethane	74840	30.07	9.05E+00	D
Ethanol	64175	46.07	2.30E-01	D
Ethyl acetate	141786	88.11	1.88E+00	C
Ethyl mercaptan (Ethanediol)	75081	62.14	1.98E-01	A
Ethyl methyl sulfide	624895	76.16	3.67E-02	E
Ethylbenzene[c]	100414	106.17	4.86E+00	B
Formaldehyde[c]	50000	30.03	1.17E-02	D
Heptane	142825	100.20	1.34E+00	B
Hexane[c]	110543	86.18	3.10E+00	B
Hydrogen sulfide	7783064	34.08	3.20E+01	A
Indane (2,3-Dihydroindene)	496117	34.08	6.66E-02	D
Isobutane (2-Methylpropane)	75285	58.12	8.16E+00	D
Isobutylbenzene	538932	134.22	4.07E-02	D
Isoprene (2-Methyl-1,3-butadiene)	78795	68.12	1.65E-02	D
Isopropyl mercaptan	75332	76.16	1.75E-01	A
Isopropylbenzene (Cumene)[c]	98828	120.19	4.30E-01	D
Mercury (total)[c]	7439976	200.59	1.22E-04	B
Mercury (elemental)[c]	7439976	200.59	7.70E-05	C
Mercury (monomethyl)[c]	51176126	216.63	3.84E-07	C
Mercury (dimethyl)[c]	627441	258.71	2.53E-06	B
Methanethiol (Methyl mercaptan)	74931	48.11	1.37E+00	A
Methyl tert-butyl ether (MTBE)[c]	1634044	88.15	1.18E-01	D
Methylcyclohexane	108872	98.19	1.29E+00	D
Methylcyclopentane	96377	84.16	6.50E-01	D
Naphthalene[c]	91203	128.17	1.07E-01	D
n-Butylbenzene	104518	134.22	6.80E-02	D
Nonane	111842	128.26	2.37E+00	D
n-Propylbenzene (Propylbenzene)	103651	120.19	4.13E-01	D
Octane	111659	114.23	1.08E+00	D
p-Cymene (1-Methyl-4-lsopropylbenzene)	99876	134.22	3.58E+00	D
Pentane	109660	72.15	4.46E+00	C
Propane	74986	44.10	1.55E+01	C
Propene	115071	42.08	3.32E+00	D
Propyne	74997	40.06	3.80E-02	E
sec-Butylbenzene	135988	134.22	6.75E-02	D

Table 2.4-1(CONTINUED). DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS FOR LANDFILLS WITH WASTE IN PLACE ON OR AFTER 1992

Compound	CAS Number	Molecular Weight	Default Concentration (ppmv)	Recommended Emission Factor Rating
Styrene (Vinylbenzene)[c]	100425	104.15	4.11E-01	B
Tetrachloroethylene (Perchloroethylene)[c]	127184	165.83	2.03E+00	A
Tetrahydrofuran (Diethylene oxide)	109999	72.11	9.69E-01	C
Thiophene	110021	84.14	3.49E-01	E
Toluene (Methyl benzene)[c]	108883	92.14	2.95E+01	A
trans-1,2-Dichloroethene	156605	96.94	2.87E-02	C
trans-1,2-Dimethylcyclohexane	6876239	112.21	4.04E-01	D
trans-1,3-Dichloropropene	10061026	110.97	9.43E-03	D
trans-1,4-Dimethylcyclohexane	2207047	112.21	2.05E-01	D
trans-2-Butene	624646	56.11	1.04E-01	D
trans-2-Heptene	14686136	98.19	2.50E-03	E
trans-2-Hexene	4050457	84.16	2.06E-02	D
trans-2-Octene	13389429	112.21	2.41E-01	D
trans-2-Pentene	646048	70.13	3.47E-02	D
trans-3-Methyl-2-pentene	616126	84.16	1.55E-02	D
Tribromomethane (Bromoform)[c]	75252	252.73	1.24E-02	D
Trichloroethylene (Trichloroethene)[c]	79016	131.39	8.28E-01	A
Trichlorofluoromethane (Freon 11)	91315616	137.37	2.48E-01	B
Trichloromethane (Chloroform)[c]	8013545	119.38	7.08E-02	A
Undecane	1120214	156.31	1.67E+00	D
Vinyl acetate[c]	85306269	86.09	2.48E-01	C
Vinyl chloride (Chloroethene)[c]	75014	62.50	1.42E+00	A
Xylenes (o-, m-, p-, mixtures)	8026093	106.17	9.23E+00	A

NOTE: This is not an all-inclusive list of potential LFG constituents, only those for which test data were available at multiple sites. References 83-148.

[a] For NSPS/Emission Guideline compliance purposes, the default concentration for NMOC as specified in the final rule must be used.

[b] Calculated as 99.7% of NMOC, based on speciated emission test data.

[c] Hazardous Air Pollutant listed in Title III of the 1990 Clean Air Act Amendments.

[d] All tests below detection limit. Method detection limits are available for three tests, and are as follows: MDL = 2.00E-04, 4.00E-03, and 2.00E-02 ppm

[e] Many source tests did not indicate whether this compound was the ortho-, meta-, or para- isomer. The para isomer is a Title III listed HAP.

Table 2.4-2. DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS FOR LANDFILLS WITH WASTE IN PLACE PRIOR TO 1992 (SCC 50100402, 50300603)

Compound	Molecular Weight	Default Concentration (ppmv)	Emission Factor Rating
NMOC (as hexane)[e]	86.18		
Co-disposal (SCC 50300603)		2,420	D
No or Unknown co-disposal (SCC 50100402)		595	B
1,1,1-Trichloroethane (methyl chloroform)[a]	133.42	0.48	B
1,1,2,2-Tetrachloroethane[a]	167.85	1.11	C
1,1-Dichloroethane (ethylidene dichloride)[a]	98.95	2.35	B
1,1-Dichloroethene (vinylidene chloride)[a]	96.94	0.20	B

Compound	Molecular Weight	Default Concentration (ppmv)	Emission Factor Rating
Table 2.4-2 (CONTINUED). DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS FOR LANDFILLS WITH WASTE IN PLACE PRIOR TO 1992 (SCC 50100402, 50300603)			
1,2-Dichloroethane (ethylene dichloride)[a]	98.96	0.41	B
1,2-Dichloropropane (propylene dichloride)[a]	112.98	0.18	D
2-Propanol (isopropyl alcohol)	60.11	50.1	E
Acetone	58.08	7.01	B
Acrylonitrile[a]	53.06	6.33	D
Benzene[a]	78.11		
Co-disposal (SCC 50300603)		11.1	D
No or Unknown co-disposal (SCC 50100402)		1.91	B
Bromodichloromethane	163.83	3.13	C
Butane	58.12	5.03	C
Carbon disulfide[a]	76.13	0.58	C
Carbon monoxide[b]	28.01	141	E
Carbon tetrachloride[a]	153.84	0.004	B
Carbonyl sulfide[a]	60.07	0.49	D
Chlorobenzene[a]	112.56	0.25	C
Chlorodifluoromethane	86.47	1.30	C
Chloroethane (ethyl chloride)[a]	64.52	1.25	B
Chloroform[a]	119.39	0.03	B
Chloromethane	50.49	1.21	B
Dichlorobenzene[c]	147	0.21	E
Dichlorodifluoromethane	120.91	15.7	A
Dichlorofluoromethane	102.92	2.62	D
Dichloromethane (methylene chloride)[a]	84.94	14.3	A
Dimethyl sulfide (methyl sulfide)	62.13	7.82	C
Ethane	30.07	889	C
Ethanol	46.08	27.2	E
Ethyl mercaptan (ethanethiol)	62.13	2.28	D
Ethylbenzene[a]	106.16	4.61	B
Ethylene dibromide	187.88	0.001	E
Fluorotrichloromethane	137.38	0.76	B
Hexane[a]	86.18	6.57	B
Hydrogen sulfide	34.08	35.5	B
Mercury (total)[a,d]	200.61	2.92×10^{-4}	E
Methyl ethyl ketone[a]	72.11	7.09	A
Methyl isobutyl ketone[a]	100.16	1.87	B
Methyl mercaptan	48.11	2.49	C

Table 2.4-2 (CONTINUED). DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS FOR LANDFILLS WITH WASTE IN PLACE PRIOR TO 1992 (SCC 50100402, 50300603)			
Compound	Molecular Weight	Default Concentration (ppmv)	Emission Factor Rating
Pentane	72.15	3.29	C
Perchloroethylene (tetrachloroethylene)[a]	165.83	3.73	B
Propane	44.09	11.1	B
t-1,2-dichloroethene	96.94	2.84	B
Toluene[a]	92.13		
Co-disposal (SCC 50300603)		165	D
No or Unknown co-disposal (SCC 50100402)		39.3	A
Trichloroethylene (trichloroethene)[a]	131.38	2.82	B
Vinyl chloride[a]	62.50	7.34	B
Xylenes[a]	106.16	12.1	B

NOTE: This is not an all-inclusive list of potential LFG constituents, only those for which test data were available at multiple sites. References 16-82. Source Classification Codes in parentheses.

[a] Hazardous Air Pollutants listed in Title III of the 1990 Clean Air Act Amendments.

[b] Carbon monoxide is not a typical constituent of LFG, but does exist in instances involving landfill (underground) combustion. Therefore, this default value should be used with caution. Of 18 sites where CO was measured, only 2 showed detectable levels of CO.

[c] Source tests did not indicate whether this compound was the para- or ortho- isomer. The para isomer is a Title III-listed HAP.

[d] No data were available to speciate total Hg into the elemental and organic forms.

[e] For NSPS/Emission Guideline compliance purposes, the default concentration for NMOC as specified in the final rule must be used. For purposes not associated with NSPS/Emission Guideline compliance, the default VOC content at co-disposal sites can be estimated by 85 percent by weight (2,060 ppmv as hexane); at No or Unknown sites can be estimated by 39 percent by weight 235 ppmv as hexane).

Table 2.4-3. CONTROL EFFICIENCIES FOR LFG NMOC and VOC[a]

Control Device	Control Efficiency (%)[b]		
	Typical	Range	Rating
Boiler/Steam Turbine (50100423)	98.6	96-99+	D
Flare[c] (50100410) (50300601)	97.7	86-99+	A
Gas Turbine (50100420)	94.4	92-97	E
IC Engine (50100421)	97.2	95-99+	D

[a] References 16-148. Source Classification Codes in parentheses.

[b] Control efficiency may also be applied to LFG constituents in Tables 2-4.1 and 2.4-2, except for mercury. For any combustion equipment, the control efficiency for Hg should be assumed to be 0.

[c] Where information on equipment was given in the reference, test data were taken from enclosed flares. Control efficiencies are assumed to be equally representative of open flares.

Table 2.4-4. EMISSION FACTORS FOR SECONDARY COMPOUNDS
EXITING CONTROL DEVICES[a]

Control Device	Pollutant[b]	Typical Rate, kg/10^6 dscm CH$_4$	Typical Rate, lb/10^6 dscf CH$_4$	Emission Factor Rating
Flare[c] (50100410) (50300601)	Nitrogen dioxide	631	39	A
	Carbon monoxide	737	46	A
	Particulate matter	238	15	A
	Dioxin/Furan	6.7×10^{-6}	4.2×10^{-7}	E
IC Engine (50100421)	Nitrogen dioxide	11,620	725	C
	Carbon monoxide	8,462	528	C
	Particulate matter	232	15	D
Boiler/Steam Turbine[d] (50100423)	Nitrogen dioxide	677	42	D
	Carbon monoxide	116	7	D
	Particulate matter	41	3	D
	Dioxin/Furan	5.1×10^{-6}	3.2×10^{-7}	D
Gas Turbine (50100420)	Nitrogen dioxide	1,400	87	D
	Carbon monoxide	3,600	230	E
	Particulate matter	350	22	E

[a] Source Classification Codes in parentheses.
[b] No data on PM size distributions were available, however for other gas-fired combustion sources, most of the particulate matter is less than 2.5 microns in diameter. Hence, this emission factor can be used to provide estimates of PM-10 or PM-2.5 emissions. See section 2.4.4.2 for methods to estimate CO_2, SO_2, and HCl.
[c] Where information on equipment was given in the reference, test data were taken from enclosed flares. Control efficiencies are assumed to be equally representative of open flares.
[d] All source tests were conducted on boilers, however emission factors should also be representative of steam turbines. Emission factors are representative of boilers equipped with low-NO$_x$ burners and flue gas recirculation. No data were available for uncontrolled NO$_x$ emissions.

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