Attachment B

California Landfill Methane Control Efficiency Based on Recent Direct Measurement Studies

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Solid Waste Industry for Climate Solutions (SWICS)

Executive Summary

Methane produced by decaying waste in landfills, when not recovered in collection and control systems or oxidized in cover materials, may be released to the atmosphere as fugitive (i.e., uncollectable) emissions through the surface of the landfill. Efficient gas collection and cover systems can significantly minimize methane fugitive emissions. It is important to determine accurately the “control efficiency” of these systems to assess the effectiveness of landfill methane control measures, and to quantify and compare methane reduction benefits associated with solid waste management alternatives.

Direct measurement studies provide superior, science-based estimates of control efficiency as compared to estimates derived using assumed default values in conventional modeling tools. This study made use of site-specific, direct methane measurement studies available for five California landfills. The subject landfills are representative of a substantial number of the State’s facilities that manage a large percentage of the total waste-in-place (WIP) in California that is subject to regulation under the federal New Source Performance Standards (NSPS) for municipal solid waste (MSW) landfills. The five landfills were studied using optical remote sensing (OTM-10) with an Acetylene Tracer Method, and direct measurement of methane oxidation using flux boxes.

This analysis calculated control for the five landfills in California based on direct measurement of flux and oxidation applied to the measured amount of methane collected by the landfill gas collection systems. The results of the direct measurement analyses were then compared with modeling results using the default (i.e., estimated) emission values currently used by the California Air Resource Board (ARB) in its landfill emissions modeling tool.

This study also compared estimated emissions for an additional 113 California landfills using control efficiency determined by the site-specific, direct measurement studies, and comparing these results to those derived by using the ARB emissions modeling tool. Landfill characteristics – other than emissions – used in the analysis were based on information from the California Department of Resources, Recycling, and Recovery (CalRecycle).

Significant findings from the study of the five landfills included:

- Control efficiency (i.e., the ability to lower methane emissions from a landfill through collection and oxidation) was significantly higher (86% overall; range 83-88%) than the ARB’s assumed modeling default of 77.5%. Limited measurement of one closing site under partial final cover resulted in 91% control efficiency when applied to complete closure.

- Methane oxidation (i.e., the ability of the soil to convert methane to biogenic carbon dioxide) was significantly higher (45% overall; range of 27-62%) than the ARB's assumed modeling default of 10%.

- Landfill characteristics such as the physical area covered by the landfill gas collection system and size of the working face, and areas under daily, intermediate, and final cover had negligible impact on control efficiency.

- Overall methane emissions from the direct measurement studies were -44% less than emissions obtained by the ARB modeling tool and -36% less than emissions based on default collection efficiency applied to measured collection.

- When results were compared on a life-cycle basis to other solid waste management options (e.g., composting), the estimates of avoided landfill methane emissions were significantly less (0.056-0.144 $MTCO_2e$/ton) than prior estimates reported by CalRecycle (0.41-0.59 $MTCO_2e$/ton).

- The direct measurement studies of the five California landfills were conducted prior to implementation of the ARB's Landfill Methane Early Action Measure (Landfill Methane Rule (LMR)). Nonetheless, the results of our site-specific analysis are consistent with the ARB's predicted collection efficiency that is expected to be achieved by implementation of the LMR Rule. The ARB used LMR default assumptions and estimated potential collection efficiency at 85%. When methane oxidation by soil cover was included in the analysis, the overall control efficiency increased to 86%. The use of direct, site-specific emissions estimates at the California landfills resulted in a nearly identical control efficiency of 87%. Thus, ARB's predicted collection efficiency was already being achieved at the five landfills subject to and in compliance with the federal NSPS.

Significant findings from the analysis of the 113 landfills included:

- Methane emissions declined much more rapidly after site closure than predicted by the ARB modeling tool. The methane emissions estimates from closed sites were also significantly less than estimated by the ARB and CalRecycle. Estimated emissions were -17% to -37% less for the ARB inventory defaults applied to measured collected methane than for results from the ARB emissions model. Applying 91% control efficiency, based on the direct measurement study, to closed sites resulted in -67% to -75% less emissions than use of the ARB defaults.

- Applying 86% (active) and 91% (closed) control efficiency to the 113 additional landfills resulted in -47% less aggregate emissions than estimated by the modeling tool.

- The landfills analyzed comprise the vast majority (88%) of facilities and WIP in California subject to the LMR.

- The results of this analysis raise significant questions about the validity of predicted estimates of landfill methane emissions to assess the effectiveness of landfill methane controls and to evaluate comparative emissions across alternative solid waste management technologies.

1.0 Introduction

The California Global Warming Solutions Act of 2006 (AB 32) required the California Air Resources Board (ARB) to develop a Scoping Plan, originally adopted in 2008, that describes measures to reduce greenhouse gases (GHG) to 1990 levels by 2020. The ARB is required to update the Scoping Plan every five years. The Department of Resources, Recycling, and Recovery (CalRecycle) and ARB staff are developing a Waste Management Sector Plan as part of the 2013 Scoping Plan Update. This analysis is being submitted to inform and enhance development of the Waste Sector Plan.

Methane is a potent GHG, with a 100-year global warming potential 25 times that of carbon dioxide (Intergovernmental Panel on Climate Change [IPCC], 4th Assessment Report). Methane emissions from landfills in California constitute only about 1.5% of the total net emissions in 2010 as estimated by the ARB (Inventory)[2]. However, minimizing landfill methane emissions through regulatory controls and measures to divert organic waste from landfills to composting, anaerobic digestion, and potentially other transformation facilities has been a priority of the AB 32 Scoping Plan.

It is essential for policymakers to evaluate the best available science on landfill methane emissions and control efficiency when developing regulations to minimize methane emissions and/or evaluating the costs and benefits of various strategies. Comparing the potential benefits of management alternatives to landfilling requires the use of the most accurate estimates of landfill methane emissions (i.e., avoided methane emissions) that would occur over decades from the time of waste placement in the landfill. Research is rapidly advancing but landfills remain very complex emissions sources.

This study characterizes landfill methane control efficiency and emissions in California based on the most recent and best available data. The study compares the results of this analysis to estimates of potential landfill methane avoided emissions contained in CalRecycle's July 2012 report (CalRecycle July 2012 Report)[3].

2.0 Methodology

The study methodology uses data from direct measurements of fugitive emissions using optical remote sensing (OTM-10) with the acetylene tracer method, and methane oxidation measurements using flux boxes. Five California landfills were studied and are representative of a significant number of facilities and the total State waste-in-place (WIP) subject to regulation under the federal NSPS for MSW Landfills (40 CFR, Part 60, Subpart WWW). Methane emitted (fugitive methane) was quantified by applying the direct measurements of flux to the total waste footprint at the time of measurement (2009). The study assessed the potential effects on fugitive methane relative to the extent of the landfill gas collection system, size of the working face, and area of the landfill under daily, intermediate, and final cover. An additional 113 California landfills (52 closed and 61 active) were analyzed using a modeling tool provided by the ARB to assist in implementing the Landfill Methane Early Action Rule (LMR- Sections 95460-95476, Title 17, CCR), which measured methane collection and facility characteristics compiled by CalRecycle. The LMR modeling tool assumptions are consistent with those used by the ARB for statewide landfill GHG inventory purposes.

The five landfills are representative of the facility characteristics and sub-climates seen across California. They are large, active and private landfills in compliance with existing federal standards, but the measurement studies were conducted prior to implementation of the LMR. Therefore, the results do not reflect the further reductions likely achieved from implementation of the more stringent requirements of the LMR beginning in June of 2010. The five landfills range from 6.1 to 44.1 million tons of waste-in place (WIP), and together total 84 million tons WIP. Approximately 87% of the total active landfill WIP in California (902 million tons) is contained within similarly sized (>5 million tons WIP) landfills.

The LMR applies to landfills that received waste after January 1, 1977 and have more than 450,000 tons WIP. The study's expanded analysis of 118 landfills comprises the vast majority of facilities and WIP subject to the California LMR. The 118 landfills included in this analysis (five field studies from before LMR plus 113 subject to LMR) comprise approximately 88% of WIP and 95% of facilities (1188/124) currently subject to LMR and 90% of the total California 2010 WIP of approximately 1.38 billion tons. Total WIP subject to the LMR is approximately 95% of total 2010 WIP.

The expanded analysis also estimated emissions for the 113 California landfills subject to LMR using control efficiency determined by the direct measurement studies, and compared those results to results derived using the ARB emissions modeling tool and its default values. (CalRecycle 2011)[4]

Modeling was conducted for all 118 landfills using the ARB landfill methane emissions tool (Emission Tool Version 1.3)[5]. The ARB tool assists owners and operators in complying with the LMR and is based on the 2006 (IPCC) Mathematically Exact First-Order Decay (FOD) model. This model assumes that a fixed fraction of the waste available at any time will degrade (anaerobically degradable organic carbon (ANDOC)) at a rate factor (k) that is related to precipitation and moisture content. Input to the ARB tool includes annual tons disposed, k, and either default ANDOC% based on year and statewide waste characterization study, or ANDOC% based on a site-specific waste profile. The model includes a default delay factor (M) of six months before newly disposed waste begins to undergo anaerobic decomposition. The delay factor is consistent with IPCC and USEPA methodology and does not significantly affect the modeling results over the time periods studied. Model output includes annual emissions in metric tonnes (MMT) of carbon dioxide (CO_2) equivalent (CO_2e) for methane and CO_2 with no control and 10% oxidation; and total landfill gas collected with default 75% collection efficiency and collected gas heat content.

For this analysis, annual tons disposed are based on CalRecycle public records for 1990 to 2012. The tons disposed before 1990 were extrapolated based on total WIP and estimated start of non-burn dump disposal. The results are not sensitive to different pre-1990 projection methods, which were based approximately on population growth.

Control efficiency is the ratio of methane collected (recovered) and oxidized in cover soils to methane produced or generated (recovered, oxidized, and emitted). Subsurface methane migration and change in storage are not considered significant factors and are therefore not included in the calculation.

Pertinent definitions relating to control efficiency in this document include:

- Methane Collection Efficiency (%) = (Methane Recovered/Methane Produced) x 100; (Methane Recovered = Methane Collected)
- Methane Produced = Methane Recovered + Methane Emitted + Methane Oxidized
- Methane Control Efficiency (%) = 100 x (Methane Recovered + Methane Oxidized)/Methane Produced
- % Methane Oxidation (or Fraction Methane Oxidized) is the percent of methane delivered to the base of the cover that is oxidized to CO_2 and partitioned to microbial biomass instead of being emitted to the atmosphere as methane.
- Methane Oxidized = (% Methane Oxidation x Methane Emitted)/(1- %Methane Oxidation)

Note that various researchers and agencies use differing definitions and related terminology. Specifically, researchers often ignore methane oxidation, and “collection efficiency” or “abatement efficiency” is calculated as the fraction of methane collected to methane collected plus methane emitted. This document incorporates methane oxidation because it is such an important factor in assessing landfill methane fugitive emissions.

3.0 Direct Measurement Facility Characteristics

Facility characteristics for the five California landfills are summarized in Table 1. Designation of facilities as CA1, CA2, CA3, CA4, and CA5 is based on Goldsmith et al (2012),[6] which also provides OTM-10 measurement results. Additional tracer (acetylene) measurements of CA1 and CA4 were incorporated from Green et al (2010)[7]. Methane oxidation was measured from cover soils at these facilities by Chanton et al (2011)[8]. The OTM-10 and tracer measurements were conducted in 2009 and are summarized in Table 2. Earlier OTM-10 measurements in 2007 and 2008 summarized in Green et al (2009)[9] are similar in flux results from 2009 but are not included because they reflect conditions different than in 2009. Furthermore, OTM-10 measurements from landfills in other states in Goldsmith et al (2012)[6] and ARCADIS U.S., Inc. (January 2012)[10] were not incorporated because they are from primarily more humid climates and not representative of California.

Table 1. Facility Characteristics

Facility and SWIS#:	**CA1** 21-AA-0001	**CA2** 43-AN-0008	**CA3** 01-AA-0008	**CA4** 01-AA-0009	**CA5** 19-AA-0050
Precipitation (inches annual):	25	20	14	14	7
Geomorphic Province:	San Francisco Bay	Coast Ranges	San Francisco Bay	Coast Ranges	Mojave Desert
Average Methane Collected During Study Period (scfm):	1225	685	889	2422	203
Footprint During Study Period (acres):	210	70	115	235	85
Waste-In-Place (MT):	13.5	6.1	13.5	44.1	6.2
% Intermediate Cover	98%	98%	98%	78%	98%
% Daily Cover	2%	2%	2%	2%	2%
% Final Cover	0%	0%	0%	10%	0%
% Coverage by Gas Collection System	98%	98%	98%	98%	98%
Design	Unlined (90%) shallow GW-inward gradient; high % sludge	Composite (75%) Canyon Fill with subdrain GW	Unlined shallow GW-inward gradient	Composite (50%) Canyon Fill with subdrain GW	Composite (10%) negligible leachate
Leachate recirculation?	No	1-5 million gallons per year 2002+	No	1-2.6 million gallons per year	No

GW = groundwater
SWIS = Solid Waste Information System
scfm = standard cubic feet per minute

Table 2. Summary of Direct Measurement Results

Facility	Emission Rate Measurement (grams/m2/day)	Study Date
CA-1 (21-AA-0001)	4.64	2009- June
	19.23	2009- October
	8.5; 7.9; 5.4	2009- October Tracer
	9.13	**Arithmetic Mean**
	5.87	**Standard Deviation**
CA-2 (43-AN-0008)	32.15	2009- June
	9.58	2009- January
	20.87	**Arithmetic Mean**
	15.96	**Standard Deviation**
CA-3 (01-AA-0008)	8.18	2009- June
	10.30	2009- February
	6.04 (Final Cover)	2009- January (Final Cover)
	8.17	**Arithmetic Mean**
	2.13	**Standard Deviation**
CA-4 (01-AA-0009)	9.48	2009- October
	14.45	2009- June
	7.5; 14.3; 13.1	2009- October Tracer
	12.83	**Arithmetic Mean**
	2.32	**Standard Deviation**
CA-5 (19-AA-0050)	0.90	2009- September
	3.96	2009- January
	2.43	**Arithmetic Mean**
	2.16	**Standard Deviation**

The direct measurement results were derived (with one exception for partial final compacted clay cover over CA3) from measurements taken in intermediate cover areas with the landfill gas collection and control systems extending across the entire areas. Because the working face, daily cover, and intermediate cover areas not under control by a landfill collection system are potential areas where methane emissions may be higher, the potential effects of these areas were also considered.

3.1 Working Face

The analysis concluded that the working face is not a significant source of landfill methane emissions. The working face is the maximum daily extent of waste exposed without daily cover. Industry landfill practices for optimizing airspace and 27 CCR regulations effectively limit the working face to an extremely small fraction of the waste footprint. For the facilities studied, the extent of the working face, based on surveys with the landfill operators, comprised approximately 0.1% of the total waste footprint. The survey results were consistent with standard industry calculations for optimizing cell geometry and airspace provided in Bolton

(1995)[11]. Furthermore, some anaerobic decomposition and generation of methane is expected from waste as it arrives at a facility regardless of the management alternative (e.g., composting, anaerobic digestion, or transformation facility); therefore, related reductions will not occur simply by diverting waste from landfills. Finally, surface emissions monitoring data collected during implementation of the AB 32 LMR has not shown significant exceedences of the surface methane standard at the working face. Consideration of these three points supports the conclusion that the working face is not a significant source of landfill methane emissions.

3.2 Daily and Intermediate Cover

Likewise, the analysis concluded that the daily cover area is not a significant source of landfill methane emissions. Daily cover under state and federal requirements is a minimum of six inches of soil or alternative cover materials placed over the working face for up to six months from disposal of the waste. The extent of daily cover is limited by standard industry landfill practices to conserve airspace. Site-specific surveys of the facilities studied indicate the daily cover area is approximately 2% of the total footprint, and is also consistent with standard industry calculations for optimizing cell geometry and airspace provided in Bolton (1995)[11]. Large and efficient landfills, similar to the facilities studied, will likely have a similar relative area of daily cover.

Direct measurement studies have also been conducted on working face and daily cover areas for landfills in other states (see: Goldsmith et al [2012][6]) and corroborate this conclusion. For example, in one arid site (similar to the California sites), the working face and daily cover area fluxes were respectively 14.7 and 1.8 times that of intermediate cover flux. Ignoring the effect on flux of ambient emissions at the working face, the impact based on the arid site flux on control efficiency for the facilities studied was negligible. The average flux increased by 2% and control efficiency decreases by only 0.3% when the total site acreage was considered.

Intermediate cover that is compliant with state requirements consists of a minimum of 12 inches of soil or alternative cover materials, and is installed where waste will not be placed beyond six months. The largest relative area of an active landfill is typically under intermediate cover and also under control of a landfill gas collection system.

The analysis also concluded that areas of <u>intermediate cover without a landfill gas collection system are not significant sources of landfill methane emissions</u>. NSPS regulations require installation or expansion of the landfill gas collection system in areas within five years of disposal (or within two years if closed, or at final grade) and adjustment and expansion of the system as the landfill is developed to maintain appropriate methane control. A two- or five-year time period before installation or expansion of the gas collection system is rare and normally limited to circumstances when operations expand to newly lined cells. During the life of the landfill, daily cover cells and intermediate cover lifts are chiefly developed over existing fill areas where collection systems (vertical or horizontal) are already in-place. The collection systems are installed and adjusted to allow for working face and daily cover operations while still maintaining control of landfill gas from older waste. These areas are limited in size based on working face size and geometry to optimize airspace. The NSPS requirements for surface monitoring and control limits for methane emissions to less than 500 part per million by volume (ppmv) also effectively limit areas of the landfill potentially not covered by the collection system.

LMR requirements are more stringent than NSPS and further limit the size of these areas. The LMR requires substantially tighter monitoring grids and compliance with 25 ppmv integrated and 500 ppmv instantaneous methane surface concentrations.

3.3 Final Cover

Final cover includes substantial additional layers of soil and low permeability soil or geosynthetic barriers placed to prevent methane emissions. For CA4, about 10% of the waste footprint had final cover (partial closure). Partial closure is a relatively common practice for landfills in California. In CA4, the final cover area was not included in the flux measurements and if included, would be expected to reduce overall flux, thereby increasing control efficiency. For CA3, partial final cover was included in the flux measurements and verified to have -35% less flux than intermediate cover areas.

3.4 Leachate Generation and Recirculation

An additional important consideration is moisture content of the waste. High moisture content of waste enhances methane generation, while dry waste inhibits anaerobic microbial processes that produce methane. The amount of leachate generated and re-circulated in the landfill is indicative of moisture content. Four of the five facilities in the direct measurement study (CA1, CA2, CA3 and CA4) had relatively high levels of leachate generation and recirculation as compared with most other landfills in the state. CA5 is a very dry site where leachate generation is negligible and is representative of desert sites in California.

The four landfills that had relatively high levels of leachate generation and recirculation included CA1 and CA3 that are located in the San Francisco Bay area. These four landfills have fill areas which are predominantly unlined, have shallow ground water partially in contact with waste, and inward gradient systems, which maintain hydraulic control. CA1 also accepts a significantly higher percentage of sewage sludge that adds moisture content to the waste. CA2 and CA4 are canyon fills with predominantly composite lined areas. They collect and recirculate significant quantities of leachate. C1, C2, C3, and C4 represent relatively high potential methane generation and emissions compared with most other landfill sites in California. Therefore, the estimated control efficiencies derived in this study tend to be conservative (less) than for other landfills with similar size and operations.

4.0 Calculated Control Efficiency and Estimated Avoided Emissions

Tables 3 and 4 provide summaries of calculated control efficiency and emissions based on direct measurements of emissions and oxidation, measured collection, and the ARB defaults. Detailed calculations are provided in Attachment 1.

Table 3. Summary of Calculated Control Efficiency Based on Direct Measurement

Facility	CA-1	CA-2	CA-3	CA-4	CA-5	Aggregate
Methane Collected (MG for study period year 2009)	13,049	7,297	9,470	25,800	2,162	57,779
Methane Emissions Based on Measured Flux Applied to Total Waste Footprint	2,833	2,157	1,388	4,454	305	11,139
Methane Emissions Based on ARB Default Factors Applied to Measured Collected Methane	3,915	2,189	2,841	7,740	649	17,334
Measured % Methane Oxidation	51%	62%	27%	28%	34%	***45%***
Control Efficiency Based on Measured Flux, Oxidation, and Collected Methane	85%	83%	88%	86%	88%	***86%***
					One-Standard Deviation:	***80-91%***

MG = Megagrams

Table 4. Emissions Based on Direct Measurement Compared with ARB Emission Tool

Facility	CA-1	CA-2	CA-3	CA-4	CA-5	Aggregate
Methane Collected (MG for study year) Based on ARB Landfill Emissions Tool V. 1.3.	12,900	6,264	8,415	28,187	4,133	59,899
Methane Emissions Based on ARB Landfill Emissions Tool and ARB Defaults.	4,300	2,088	2,805	9,396	1,378	19,966
Methane Emissions Based on Measured Flux Applied to Total Waste Footprint	2,833	2,157	1,388	4,454	305	11,139
% Lower (-) or Higher (+) Emissions Based on Direct Measurement Than ARB Emissions Tool	-34%	3%	-51%	-53%	-78%	***-44%***

Control efficiency for the five landfills in this analysis was determined to be 86% overall, ranging from 83-88% for each facility and an overall one standard deviation range of 80-91%. Methane oxidation was 45% overall and ranged from 27-62%. Control efficiency and methane oxidation were significantly higher than assumptions used in the ARB modeling tool (defaults of 77.5% and 10% respectively). The results were consistent with ARB's estimated 85% collection efficiency (ignoring methane oxidation) expected to be achieved by implementation of the LMR Rule (LMR Appendix D)[12]. Adding 44.5% methane oxidation to the ARB's estimated collection efficiency results in 87% control efficiency ((0.85+((0.15/.55)-0.15))/(0.85+(0.15/.55)).

Partial final cover from one measurement of CA3 resulted in 91% control efficiency if applied to complete closure. Based on the expanded analysis (see next section), closed site emissions are likely less, especially after completion of final closure. Collection efficiency (which ignores methane oxidation) was found to be 93-96% based on air dispersion modeling, surface methane monitoring, and subsequent flux chamber measurements of the Palos Verdes Landfill that closed in 1980 (Huitric and Kong 2006[13]).

Overall methane emissions were -44% less than results from the ARB emissions model and -36% less than from the ARB default collection efficiency applied to measured collected methane.

4.1 Landfill Avoided Emissions

Control efficiency multiplied by the total methane generation potential of the waste (ANDOC%) provides an approximate estimate of the life-cycle landfill methane avoided emissions per ton of waste. In this analysis, the control efficiencies were found to be different for active and closed landfills. The separate control efficiencies were multiplied by the ARB's default ANDOC% of 7.52% (based on CalRecycle's 2008 waste characterization study) to estimate avoided landfill emissions associated with non-landfill management options.

Calculating actual avoided emissions is far more complicated. Waste placed late in the landfill life near to the time of closure will have higher overall control efficiency and less life-cycle avoided emissions than waste placed earlier in the life of the landfill. Thus, avoided emissions for any future diverted waste will be less than what is estimated for current WIP. Decomposition and avoided emissions occur over many decades. Waste varies in decomposable carbon content and is difficult to characterize on a site-specific basis. Effective methane generation potential is less for dry sites where limited moisture inhibits the anaerobic microbial process (see section on Leachate Generation and Recirculation). In this analysis, models of CA5 were calibrated to multiple years of measured methane collection (see section Active Sites, Figures 6-7). The calibrated results provided an effective generation potential 60% of that calculated by using the average ANDOC%. Similar conclusions can be found in other studies (see: GC Environmental 2005[14]).

Subject to the above caveats, this analysis concluded that the avoided landfill methane emissions for an average ton of waste diverted from a landfill were 0.056-0.144 $MTCO_2e$/ton. The estimated life-cycle avoided methane emissions were significantly less (-76% to -86%) than those estimated by CalRecycle (CalRecycle July 2012 Report) of 0.41-0.59 $MTCO_2e$/ton.

5.0 Expanded Analysis of 113 Additional California Landfills

5.1 Closed Sites

Results of modeling using the ARB Landfill Emissions Tool for the additional 52 closed landfills are summarized in Figure 1, and detailed calculations are provided in Attachment 2. Figures 2-5 are detailed plots for sites with multiple years of available collected methane. The most significant finding of this analysis of closed landfills is that collected methane declines much more rapidly with time after site closure than the default models predict. As a result, methane emissions estimates from closed sites are also significantly less than estimated by the ARB and CalRecycle. Estimated emissions in this analysis are -17% to -37% less, where the ARB inventory defaults were applied to measured collected methane, than for the estimates resulting from using the ARB emissions model. Further, applying the 91% control efficiency based on the direct measurement study to closed sites resulted in -67% to -75% less emissions than the ARB defaults.

Figure 1. % Less Aggregate Emissions For Closed Sites From ARB Model (Survey Year 2010)

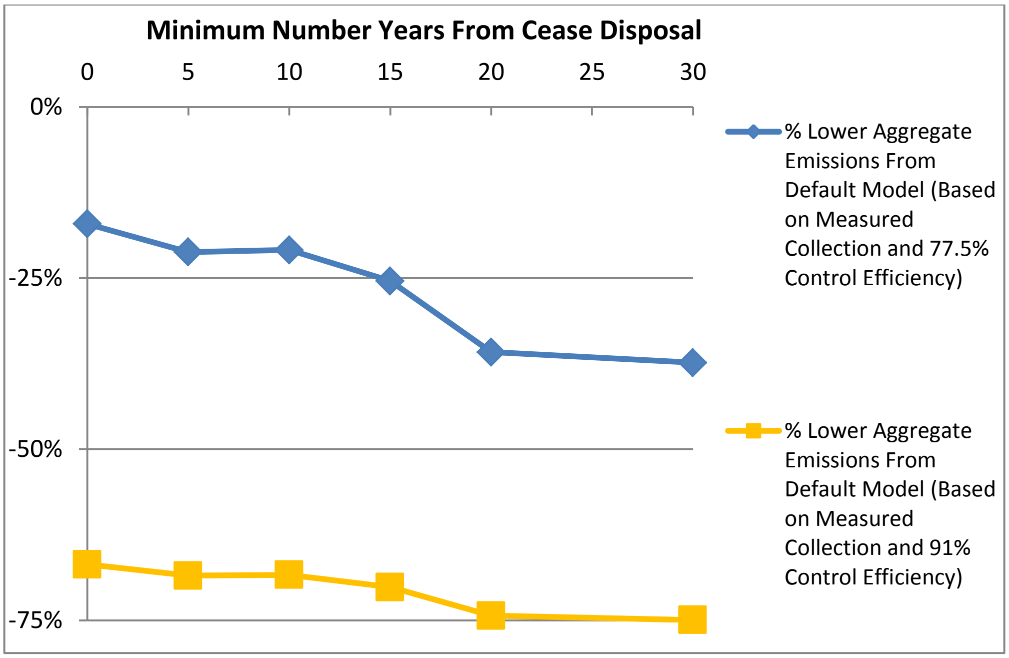


Figure 2. Closed Site 19-AR-0008 Measured Collection Compared With ARB Model

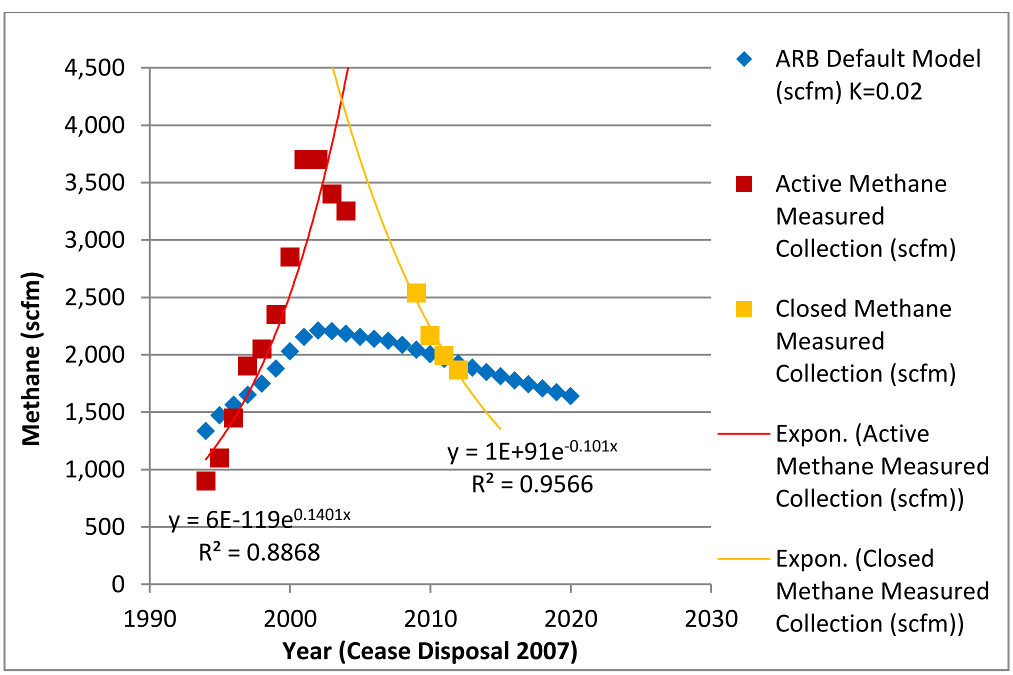


Figure 3. Closed Site 19-AF-0001 Measured Collection Compared With ARB Model

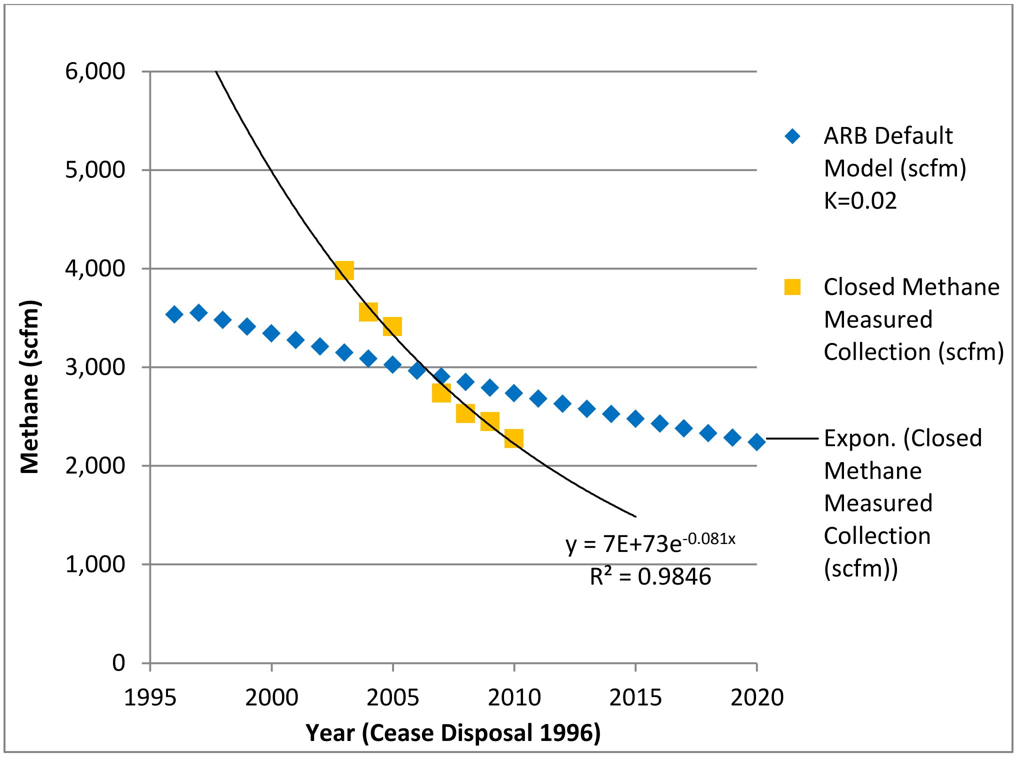


Figure 4. Closed Site 30-AB-0018 Measured Collection Compared With ARB Model

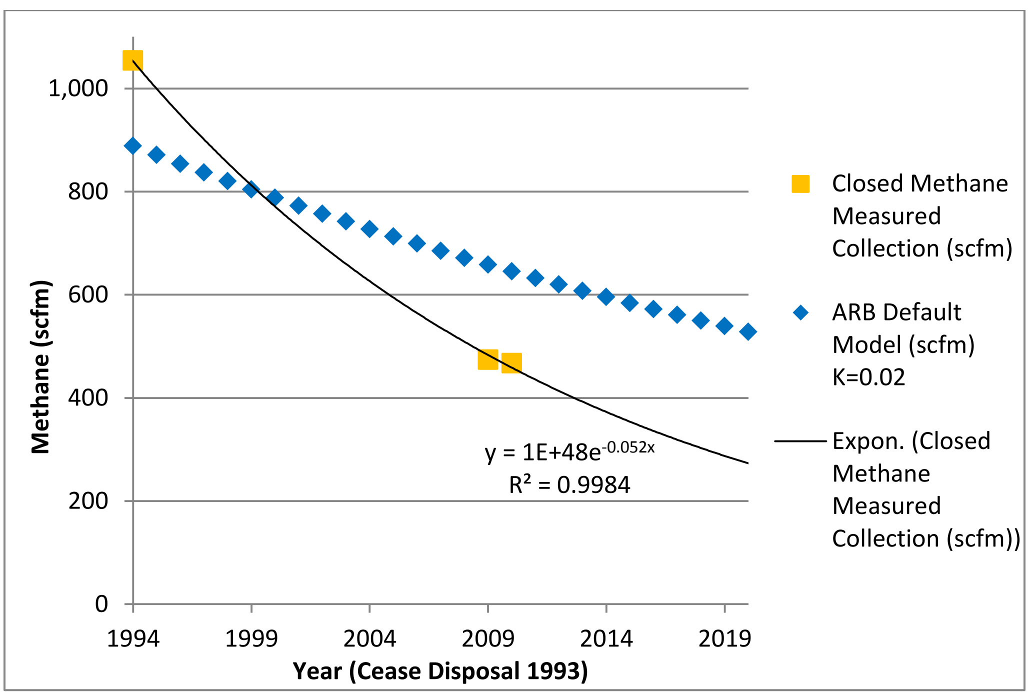
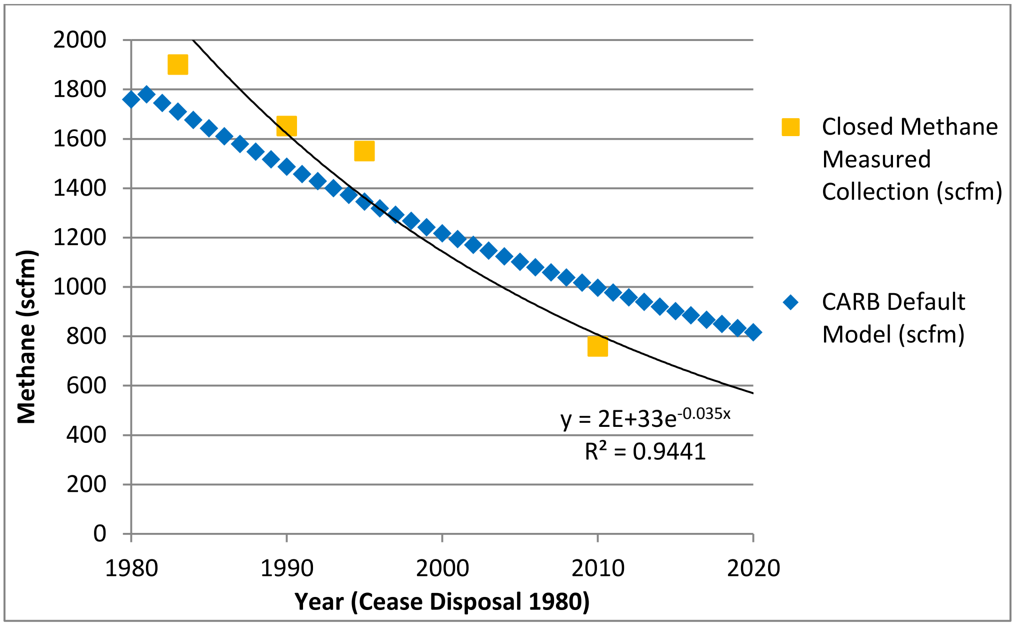


Figure 5. Closed Site 19-AE-0001 Measured Collection Compared With ARB Model



5.2 Active Sites

Results of modeling using the ARB Landfill Emissions Tool Version 1.3 for the additional 66 active landfills are summarized in Table 5 and Figure 6 and detailed calculations provided in Attachment 3.

The higher decay coefficient indicated by closed sites modeling appears to some extent reflected in active sites where generation of methane is higher than predicted by model defaults. In effect, gas generation rates that rise more quickly in an active landfill result in a quicker decrease in gas generation when the landfill closes due to the fact that gas generation potential is constant. Applying 86% control efficiency to the active sites results in methane emissions that are -37% less than the ARB model defaults. The aggregate of all landfills studied in this document results in overall methane emissions that are -44% less than the ARB defaults and modeling tool. Overall, applying the ARB default control efficiency to measured collection results in a similar emission estimate (6% higher) than using the ARB tool.

The histogram in Figure 6 indicates a secondary peak in frequency for active sites where methane emissions based on measured collection is -50% to -70% less than the ARB modeling tool predicts. This secondary peak is consistent with landfill CA5 findings that reflect a subcategory of a dry desert site that exhibits much lower methane generation than other landfills (see section on Landfill Avoided Emissions). Figure 7 provides a plot of methane over time for CA5.

Table 5. % Above (+) or Below (-) 2010 Measured Collection from ARB Model

	% Higher (+) or Lower (-) Aggregate Emissions From Default Model (Based on Measured Collection and 77.5% Control Efficiency)	% Lower Aggregate From Default Model Emissions (Based on Measured Collection and 86% (Active) and 91% (Closed) Control Efficiency
Active	15%	-37%
Closed	-17%	-73%
All	6%	-47%

Figure 6. Histogram Active Sites Fraction Above (+) Below (-) 2010 Measured Collection from ARB Model

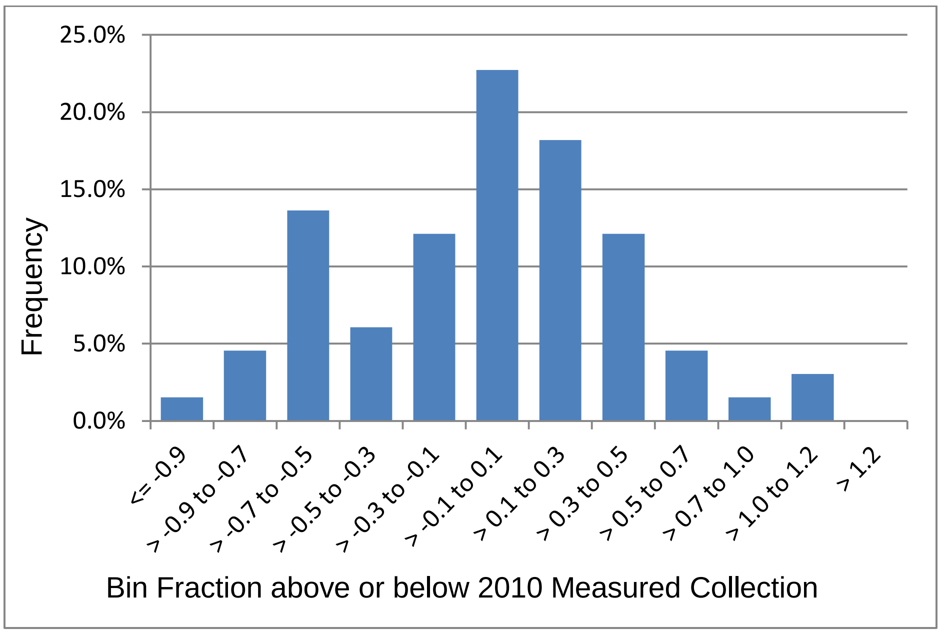
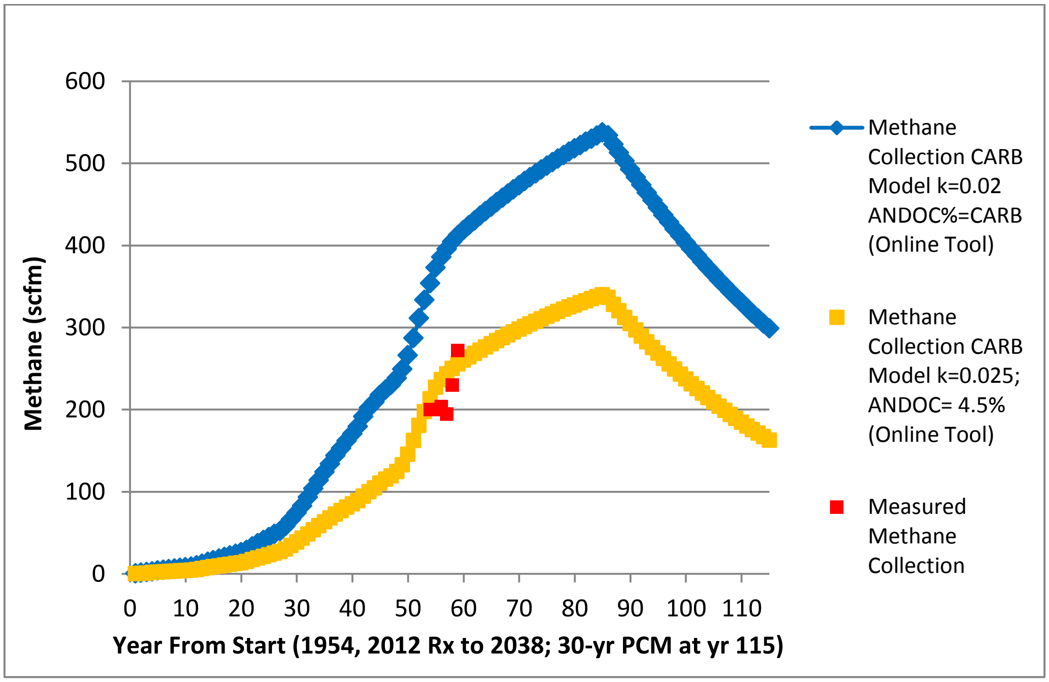


Figure 7. CA5 Landfill Methane Model



Attachments:

Detailed Calculations for Five Landfills with Direct Measurement Studies:

1.1. California Landfill Methane Control Efficiency Based on Recent Direct Measurement
1.2. Direct Measurement OTM-10/Tracer and Methane Oxidation Studies- California Landfills
1.3. Direct Measurement Flux Applied Over Landfill Footprint
1.4. Calculation of Optimum Working Face and Daily Cover Areas
1.5. Site Information
1.6. Input to ARB Landfill Emissions Tool Version 1.3
1.7. Output from ARB Landfill Emissions Tool Version 1.3
1.8. CA5 Methane Measured Collection and ARB Model

Detailed Calculations for 66 Active and 52 Closed Landfills- ARB Tool Compared with Measured Collection and Direct Measurement Studies:

2.1. Summary of 66 Active and 52 Closed Landfills- ARB Tool Compared with Measured Collection and Direct Measurement Studies
2.2. Histogram: Active Sites Fraction Above (+) or Below (-) 2010 Measured Collection from ARB Default Model
2.3 Closed Site Plots of Methane Collection Compared With ARB Default Model
2.4. Active Sites Input to ARB Landfill Emissions Tool Version 1.3
2.5. Active Sites Output From ARB Landfill Emissions Tool Version 1.3
2.6. Closed Sites Input to ARB Landfill Emissions Tool Version 1.3
2.7. Closed Sites Output From ARB Landfill Emissions Tool Version 1.3
2.8. Active Sites Facility Information
2.9. Closed Sites Facility Information
2.10. Active Sites Disposal Information
2.11. Closed Sites Disposal Information

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