California Landfill Methane Control Efficiency Based on Recent Direct Measurement Studies

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EXCUTIVE SUMMARY:

Methane produced in landfills not recovered in collection and control systems or oxidized in cover soils is released to the atmosphere as fugitive emissions. The efficiency of collection systems and oxidation in minimizing methane fugitive emissions (Control Efficiency or CE) is an important factor in assessing landfill methane control measures and the relative methane reduction benefits (i.e., avoided landfill methane emissions) of solid waste management alternatives. Direct measurement studies provide superior science-based estimates of Control Efficiency as compared to assumed default values used by conventional modeling tools. Site-specific methane direct measurement studies using Optical Remote Sensing (OTM-10), an Acetylene Tracer Method, and measurement of methane oxidation using flux boxes are available for five California landfills. The subject landfills are representative of a wide range of large facility characteristics and a substantial amount State waste-in-place (WIP) in compliance with U.S. Environmental Protection Agency's (USEPA's) New Source Performance Standards (NSPS). Control Efficiency was estimated for the five landfills based on this site-specific study. Methane emitted was quantified on an annual basis by applying the direct measurements of flux over the entire waste footprint at the time of the measurements. The potential effects of coverage of gas collection system, variation in methane oxidation, leachate generation and recirculation, and relative emissions from the working face and daily and intermediate cover areas were also assessed.

Emissions for the five landfills were further compared with estimates for an additional 113 California landfills using the California Air Resources Board (ARB) landfill emissions modeling tool and measured methane collection. Conclusions are provided relative to ARB's Landfill Methane Rule (LMR), ARB's greenhouse gases (GHG) Inventory, and avoided landfill methane emissions.

Significant findings for the five landfills directly measured are:

1. Control Efficiency is significantly higher 85% (83 to 88%) than ARB's modeling tool default value of 77.5%.

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2. Limited measurement from one site (CA3) of earthen final cover resulted in 35% lower emissions than intermediate cover and 91% Control Efficiency if applied to full closure. Final cover measurements from other States indicate that earthen final cover systems in California may have even lower emissions (by 50 to 75%) than intermediate cover, and emissions at background for geomembrane final cover systems.
3. Methane oxidation is significantly higher 41% (27 to 54%) than ARB's default of 10%.
4. Relative coverage of the landfill gas collection system, variation in methane oxidation, and working face and daily cover areas have negligible impact on Control Efficiency.
5. Four of the five landfills have relatively high leachate generation and/or recirculation rates. Therefore, the estimated Control Efficiency in this document may be conservative (lower) than other landfills with similar size and operation but with more typical dry moisture conditions. CA5 is a very dry site where leachate generation is minimal.
6. Overall methane emissions are 35% less than emissions obtained by the modeling tool and 39% less than emissions based on default values applied to measured collection.
7. Estimated avoided life-cycle landfill methane emissions are 0.05 to 0.15 MTCO2e/ton, significantly less than estimates based on model default values (0.22 MTCO2e/ton).
8. The direct measurement studies were conducted prior to implementation of the LMR. Nonetheless, the results of this site-specific study are consistent with projected GHG reductions to be achieved by the LMR. Thus, ARB's projected reductions were already being achieved at the five landfills subject to the NSPS.

Significant findings for the 113 additional landfills are:

9. Overall emissions calculated using the modeling tool are 7% higher than emissions from measured collection using modeling tool default values. For active landfills the emissions are 17% less and for closed landfills the emissions are 16% higher.
10. Methane emissions decline much more rapidly with time after site closure than the modeling tool predicts. The decrease is 17% to 37% less for modeling tool default values applied to measured collected methane than for results from the modeling tool. Applying 91% Control Efficiency to closed sites results in 66% to 74% less emissions.
11. A distinct category of arid landfills with low effective methane generation and emissions was identified and includes one of the five landfills directly measured (CA5).
12. Applying 85% and 91% (closed) Control Efficiency to 113 additional landfills results in 44% less aggregate emissions than estimated by the modeling tool and at the high end of the LMR goal of 2-4 MMTCO2e reductions (27 to 47% less than 2020 business-as-usual projection of 8.5 MMTCO2e).
13. Although landfills not subject to NSPS comprise only 17% of total State waste-in-place, additional studies are recommended to characterize Control Efficiency and avoided emissions for non-NSPS landfills, landfills implementing the LMR, and closed landfills.

INTRODUCTION:

The California Global Warming Solutions Act of 2006 (AB 32) required the California Air Resources Board (ARB) to develop a Scoping Plan that describes measures to reduce greenhouse gases (GHG) to achieve the goal of reducing emissions to 1990 levels by 2020. The Scoping Plan was initially adopted 2008 is required to be updated every five years. The first update is in progress. The Department of Resources, Recycling, and Recovery (CalRecycle) and ARB are developing a Waste Management Sector Plan to implement solid waste aspects for the updated Scoping Plan. The draft framework for the Waste Sector Plan was presented in an initial workshop dated June 18, 2013 (ARB, 2013) and the draft Scoping Plan Update released for public comment on February 10, 2014 (ARB, 2014).

Methane is a potent GHG, with a 100-year global warming potential 21-25 times that of carbon dioxide. Methane emissions from landfills are 6.68 MMTCO2e or about 1.5% of the total State GHG emissions for 2010 (ARB Inventory, 2010). Minimizing landfill methane emissions through regulatory controls and measures to divert waste from landfills to composting, anaerobic digestion, and potentially other transformation facilities has been a priority of the AB 32 Scoping Plan. As part of the first Scoping Plan, ARB adopted state regulations to reduce methane emissions from landfills (Landfill Methane Rule or LMR) (ARB Landfill Methane Rule, 2010). LMR regulations became effective in June 2010.

Methane produced in landfills not recovered in collection and control systems or oxidized in cover soils is released to the atmosphere as fugitive emissions. The efficiency of landfill gas collection systems and cover oxidation in minimizing methane fugitive emissions (Control Efficiency or CE) is an important factor in assessing landfill methane control measures and the relative methane reduction benefits of solid waste management alternatives. It is essential for policymakers to evaluate the best available science on landfill methane emissions and CE 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 use of the most accurate estimates of landfill methane emissions (i.e., avoided methane emissions) that would occur over decades from disposal. Research is rapidly advancing but landfills remain very complex emissions sources.

This paper provides a more current and detailed characterization of landfill methane Control Efficiency in California based on the most recent and best available direct measurement studies, landfill methane collection data, agency modeling tools, and facility characteristics. Conclusions are also provided relative to ARB's LMR, ARB's GHG Inventory, and avoided landfill methane emissions.

METHODOLOGY:

This study is based on recent peer-reviewed optical remote sensing (OTM-10), tracer, and methane oxidation direct measurement studies of fugitive methane emissions. Five California landfills were studied and represent a wide range of state-wide facility characteristics in compliance with U.S. Environmental Protection Agency's (USEPA's) New Source Performance Standards (NSPS) under 40 Code of Federal Regulations (CFR), Part 60, Subpart WWW. Methane emitted (fugitive methane) is quantified by applying direct measurement data (flux or emission rate) to the total waste footprint at the time of the study over the year of study (2009). The potential effects on overall flux relative to coverage of the landfill gas collection system, potential variation in oxidation, and relative size and emissions of the working face, daily, intermediate, and final cover areas are assessed. An additional 113 California landfills (52 closed and 61 active) were analyzed using the ARB landfill methane emissions tool (ARB modeling tool) (ARB Emission Tool Version 1.3, 2011). The modeling tool assists owners and operators in complying with the LMR.

The five landfills represent of a range of state-wide facility characteristics and sub-climates in California, if not wetter and higher methane generation sites (except CA5). They represent various state-wide landfill characteristics and facilities implementing and in full compliance with USEPA's NSPS and local air pollution district rules. The direct measurement studies were conducted prior to the June 17, 2010 applicability date of the LMR. Therefore, the more stringent standards of the LMR may result in higher Control Efficiency if subsequent measurements are conducted. The five landfills range from 6.1 to 44.1 million tons waste-in place (WIP) and total 83.4 million tons WIP and 10% of total active 2010 landfill WIP (0.9 billion tons). Approximately 83% of WIP is subject to NSPS (i.e., >2.5 megagrams WIP and operation after effective dates). The total 118 landfills comprise collectively 90% of the total California 2010 WIP of 1.38 billion tons. Landfills within the remaining 10% of total WIP were not included because methane collection from the study period was not available (5%), the site WIP was above the LMR threshold (450,000 tons WIP) but did not have a collection system (3%), or the site WIP was below the LMR threshold (2%). Total statewide WIP above the LMR threshold and within the effective date for receiving waste of January 1, 1977 and therefore subject to the LMR is approximately 95%.

The expanded study for all 118 landfills using the ARB modeling tool is based on site-specific measured methane collection surveys and site-specific landfill information compiled by CalRecycle (CalRecycle, 2011) and augmented with updated information. The modeling tool is based on the 2006 Intergovernmental Panel on Climate Change (IPCC) Mathematically Exact First-Order Decay (FOD) model. The model assumes a fixed fraction of the waste available at any time will degrade (anaerobically degradable organic carbon (ANDOC)) at a rate factor (k) related to precipitation and moisture content. Input to the modeling tool includes annual tons disposed, k, and either default ANDOC% based on year and waste characterization study, or ANDOC% based on a site-specific waste profile. The modeling tool includes a default delay factor (M) of 6 months before newly disposed waste begins to undergo anaerobic decomposition. Output includes annual emissions in metric tonnes (MT) carbon dioxide (CO_2) equivalent of 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 study, annual tons disposal were based on CalRecycle public records for 1990 to 2012. The tons disposed before 1990 was extrapolated based on total waste-in-place and estimated start of sanitary landfill disposal. The results are not sensitive to different pre-1990 projection methods based approximately on population growth.

Control Efficiency (CE) is the ratio of methane collected and oxidized in cover soils to methane produced. Subsurface methane migration and change in storage are not considered significant factors and therefore not included in the calculation. Pertinent definitions relating to control efficiency in this document include:

- Methane Collection Efficiency (%) = (Methane Recovered/Methane Recovered + Methane Emitted) x 100; (Methane Recovered = Methane Collected)
- Methane Produced = Methane Recovered + Methane Emitted + Methane Oxidized
- Methane Control Efficiency CE (%) = 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 = (% Oxidation x Methane Emitted)/(1- % 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 paper incorporates methane oxidation because it is an important factor in assessing landfill methane fugitive emissions. For example, ARB modeling tool default values of 75% collection efficiency and 10% oxidation result in a CE of 77.5%.

Potential avoided life-cycle landfill methane emissions are approximated based on CE and ARB's default ANDOC% (currently 7.52% from ARB Emission Tool Version 1.3, 2009). Dry landfills where effective ANDOC% and methane yield are lower and wet landfills where effective ANDOC% and methane yield are higher are also considered.

Direct Measurement Facility Characteristics

Facility characteristics of the five California landfills with direct measurement data are summarized in Table 1. Designation of the facilities as CA1, CA2, CA3, CA4, and CA5 is based on (Goldsmith et al., 2012) which also provide the OTM-10 measurement results. Additional tracer (acetylene) measurements of CA1 and CA4 were incorporated from Green et al., 2010). Methane oxidation was measured from cover soils at these facilities using flux boxes and is provided in (Chanton et al., 2011). For this study, % Oxidation was conservatively characterized as the average result from Table 1 of (Chanton et al., 2011) assuming no isotopic fractionation and assuming isotopic fractionation. The OTM-10 and tracer measurements were conducted in 2009 and are summarized in Table 2. The direct measurement results with one exception for partial final cover over CA3 were conducted from intermediate cover areas with coverage of the landfill gas collection and control system. Therefore, the effects on overall flux relative to potential areas not covered by the landfill collection system including the working face, daily cover area, and intermediate cover area are important considerations in estimating CE.

Table 1. Facility Characteristics.

Facility:	**CA1**	**CA2**	**CA3**	**CA4**	**CA5**
Geomorphic Province:	San Francisco Bay	Coast Range	San Francisco Bay	Coast Range	Mojave Desert
Annual Precipitation:	25 inches	20	14	14	7
Waste Footprint:	200 acres	65	115	235	80
Waste-In-Place:	13.5 million tons	6.1	13.5	44.1	6.2
Annual Methane Collected (2009):	1225 scfm	685	939	2422	201
Landfill Gas Collection System	V/H Wells, LCRS, Well Risers	V/H Wells, LCRS, Well Risers	V/H Wells, LCRS, Well Risers	V/H Wells, LCRS, Well Risers	V/H Wells, LCRS, Well Risers
% Daily/ Intermediate/ Final Cover:	98%/2%/0%	98%/2%/0%	65%/2%/33%	78%/2%/10%	98%/2%/0%
% Coverage Gas Collection System:	98+%	98+%	98+%	98+%	98+%
Leachate recirculation:	No	1-5 million gallons/yr	No	1-2.6 million gallons/yr	No
Other Design/ Operation Aspects:	Unlined (90%); Shallow GW-Inward Gradient	Composite lined (75%); Canyon Fill	Unlined; Shallow GW- Inward Gradient	Composite-lined (50%); Canyon Fill	Unlined (90%); Negligible Leachate

Table 2. Measure Flux/Emission Rate (grams/m^2/day).

	Aggregate	**CA1**	**CA2**	**CA3**	**CA4**	**CA5**
OTM-10 (Jan 2009)			9.58 gm/m^2d	6.04 (FC)		3.96
OTM-10 (Feb 2009)				10.3		
OTM-10 (Jun 2009)		4.64	32.15	8.18	14.45	
OTM-10 (Sep 2009)						0.9
OTM-10 (Oct 2009)		19.23			9.48	
Tracer (Oct 2009)		8.5; 7.9; 5.4			7.5; 14.3; 13.1	
Arithmetic Mean	**10.1 gm/m^2d**	9.13	20.87	8.17	12.83	2.43
Standard Deviation:	**4.3**	5.87	15.96	2.13	2.32	2.16

Working Face and Daily Cover Areas

This study concludes that the impacts of relative size and emissions from the working face and daily cover areas on CE for the five landfills are negligible. The working face is the maximum daily extent of waste exposed without daily cover. Industry landfill practices for optimizing airspace and 27 Code of California Regulations (CCR) regulations effectively limit the working face to a very small fraction of the waste footprint. For the facilities studied, the working face size based on operator survey is approximately 0.2% of the waste footprint and consistent with standard industry calculations for optimizing cell geometry and airspace provided in (Bolton, 1995) and illustrated in Figure 2 (working face size range for the five landfills calculated at 0.12 to 0.28% of the total footprint). CalRecycle staff study of 2010 Google Earth™ images for 85 landfills verified working face is a very small area consistent with the industry standards (CalRecycle, 2011). Furthermore, decomposition and generation of methane is expected from waste as it arrives and processed regardless of the waste management alternative, especially for uncovered aerobic (or non-aerated static pile) treatment processes where emission factors for methane are significant (and for nitrous oxide [N_2O], a more potent GHG than methane and not a significant source from landfills).

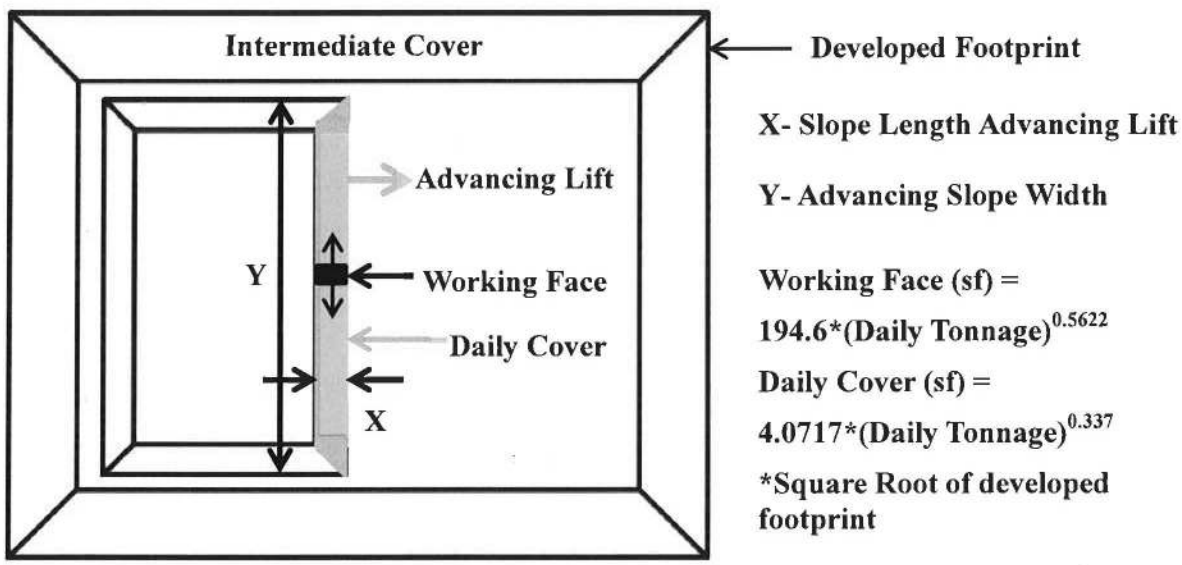
Daily cover under state and federal requirements is a minimum of six inches of soil or alternative cover materials placed over the working face for up to 6 months from disposal of the waste. The extent of daily cover is likewise limited by standard industry landfill practices. Site-specific surveys of the five landfills indicate the daily cover area is approximately 2% of the total footprint (1.5-2.3%) and consistent with standard industry calculations for optimizing cell geometry and airspace provided in (Bolton, 1995) and illustrated in Figure 1.

Direct measurement studies have also been conducted on working face and daily cover areas for landfills in other states (Goldsmith et al., 2012). In one arid site the working face and daily cover area fluxes were respectively 14.7 and 1.8 times that of intermediate cover flux and ratios for wetter climates are lower. Ignoring the relative effect of waste decomposition during placement in the working face and alternative waste management processes, and that the working face is exposed only during operating hours, the impact on CE is still negligible. The average flux would increase by only 2% and CE decrease by only 0.3%.

Intermediate and Final Cover

Intermediate cover under state requirements is a minimum of 12 inches of soil (and in limited cases alternative cover materials) where waste will not be placed beyond 6 months. Extent of the landfill gas collection system will have the largest potential impact on emissions from intermediate cover (see section below for extent of the gas collection system). Final cover includes substantial additional thickness of soil and low permeability soil or geomembrane barrier layers reducing methane emissions. Partial closure is a relative common practice for landfills in California. CA4 has final cover on 10% of the footprint but measurement of the final cover was not included in the flux measurements. If included, overall flux is expected to be lower thereby increasing CE. For CA3, earthen partial final cover was included in the flux measurements (limited to one measurement event) and determined to have 35% lower flux than intermediate cover areas. More extensive measurements from other states suggest that earthen final covers in California may have flux even lower (50 to 75%) than intermediate cover and that geomembrane final covers may have emission rates at background (Goldsmith et al., 2012).

Figure 1. Relative Area of Working Face and Daily Cover (adapted from Bolton, 1995).



Extent of Coverage of the Landfill Gas Collection System

This study also concludes that areas of intermediate cover without a landfill gas collection system are not a significant source of landfill methane emissions. 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, and gas collection from the leachate collection and removal system) are already in-place. The collection systems are installed and adjusted (which might include vertical risers) 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 LMR methane emissions monitoring and control limits (<25 part per million by volume (ppmv) average integrated and 500 ppmv instantaneous) also effectively limit areas of the landfill potentially not covered by the collection system. For the five landfills studied, the extent of the gas collection system was determined to be >98%, resulting in negligible impact on CE (<1%).

Leachate Generation and Recirculation

Additional important consideration is the amount of leachate generated and recirculated, significant factors that increase methane generation. Four of the five landfills represent relatively high leachate generation and recirculation compared with most landfills in the state. Landfills CA1 and CA3 are in the San Francisco Bay area, are predominantly unlined, have shallow ground water partially in contact with waste, and inward hydraulic gradient systems. CA1 also accepts a high percentage of sewage sludge thereby adding moisture to the fill. CA2 and CA4 are canyon fills with mainly composite lined areas and collect and also recirculate significant quantities of leachate. Sites CA1, CA2, CA3, and CA4 represent relatively high potential methane generation and emissions compared with most other landfill sites in California. Therefore, the estimated CE in this study may be conservative (lower) than other landfills with similar size and operation but more typical dry moisture conditions. CA5 is a very dry site where leachate generation is minimal.

RESULTS AND DISCUSSION

Tables 3 and 4 provide summary of calculated CE and emissions for the five landfills based on measured flux compared with ARB modeling tool default values. Detailed calculations and spreadsheets are available by request to the senior author.

CE for the five landfills in this study is 85% overall, (range 82-88%) with overall one standard deviation range of 80-91%. Methane oxidation is 41% overall and ranges from 27-54%. Methane oxidation is significantly higher than the assumed 10% default of the ARB inventory and modeling tool, but consistent with more recent studies (Chanton, et. al., 2011). However, variation in methane oxidation has a negligible effect on CE. Reduction oxidation from 41% to 10% results in only a 1% increase to the CE of 85%. Lower CE will have a higher effect from variation in methane oxidation. For example, increasing oxidation from 10%-50% for CE of 50% results in an increase of CE from 53% to 67% (not considering change in methane loading rate which may impact oxidation).

Overall methane emissions are 35% less than results from the ARB emissions tool and 39% less than results from the ARB inventory defaults applied to measured collected methane. CE is significantly higher than ARB's inventory and modeling tool defaults (77.5%). The results were consistent with ARB's estimated 85% collection efficiency (ignores methane oxidation) expected to be achieved by implementation of the LMR Rule (ARB Landfill Methane Rule, 2010). Adding 41% methane oxidation to the ARB's estimated collection efficiency results in 86% CE.

Partial final cover from one measurement of CA3 results in 91% CE if applied to complete closure. Based on the expanded study (see next section), closed landfill emissions are likely lower, especially after completion of final closure and with time during postclosure. Other California studies support this conclusion. For example, collection efficiency was found to be 93-96% using air dispersion modeling, surface methane monitoring, and flux chamber measurements by the County of Los Angeles Sanitation Districts for the Palos Verdes Landfill (closed in 1980) (Huitric, et al., 2006).

Landfill Avoided Emissions

A simple conservative estimate of landfill life-cycle avoided methane emissions is CE multiplied by methane generation potential of an average ton of waste converted from ANDOC% (currently 7.52% from ARB Emission Tool Version 1.3, 2009). Actual avoided emissions are more complicated. Waste placed near to time of closure will have higher CE than waste placed earlier in the landfill life. Decomposition and avoided emissions occur over decades to centuries. Waste varies in decomposable carbon content and is difficult to characterize on a site-specific basis. Effective methane generation potential is lower for dry sites. In this study, models of CA5 were calibrated to multiple years of measured methane collection. The calibrated result is an effective generation potential 60% of that calculated by average ANDOC% (Figure 2). Modeling of the 66 landfills in this paper supports a separate category of arid low effective ANDOC% landfills (Figure 3) as do additional studies (e.g., GC Environmental, 2005).

Subject to the above qualifications, the avoided landfill methane for an average ton of waste in his study is 0.05 to 0.15 MTCO2e per ton MSW, significantly lower than estimates based on modeling tool defaults (0.22 MTCO2e/ton) and estimates by CalRecycle in 2012 of 0.4-0.6 MTCO2e/ton (CalRecycle, 2012).

Table 3. Calculated Methane Control Efficiency Based on Direct Measurement.

	Aggregate	**CA1**	**CA2**	**CA3**	**CA4**	**CA5**
Methane Collected (C) (scfm mean for study period year)	5,472	1,225	685	939	2,422	201
C (Megagram MG/year)	55,150	12,346	6,904	9,464	24,410	2,026
Methane measured emissions (E) (MG/yr) applied to total waste footprint	10,677	2,698	1,849	1,388	4,454	287
Measured methane %Oxidation	41%	51%	54%	27%	28%	34%
Oxidation (O) (MG/yr) = (%O x E) ÷ (1-%O)	7,372	2,775	2,071	524	1,765	150
Control Efficiency (CE) = (C+O)/(C+O+E)	**85%**	**85%**	**83%**	**88%**	**85%**	**88%**

Table 4. Methane Emissions Based on Measured Flux Compared with Modeling Tool

	Aggregate	CA1	CA2	CA3	CA4	CA5
Measured emissions (E) Megagram MG/yr applied over footprint:	10,677	2,698	1,849	1,388	4,454	287
Calculated E default values applied to measured collection =C*.225/.75:	16,545	3,704	2,071	2,839	7,323	608
% Difference measured E:	**-35%**	**-27%**	**-11%**	**-51%**	**-39%**	**-53%**
Calculated E from modeling tool using default values:	17,427	3,543	1,809	2,446	8,226	1,200
% Difference measured E:	**-39%**	**-24%**	**+2%**	**-43%**	**-46%**	**-76%**

Figure 2. CA-5 Example of Arid Landfill Category Low Effective ANDOC%.

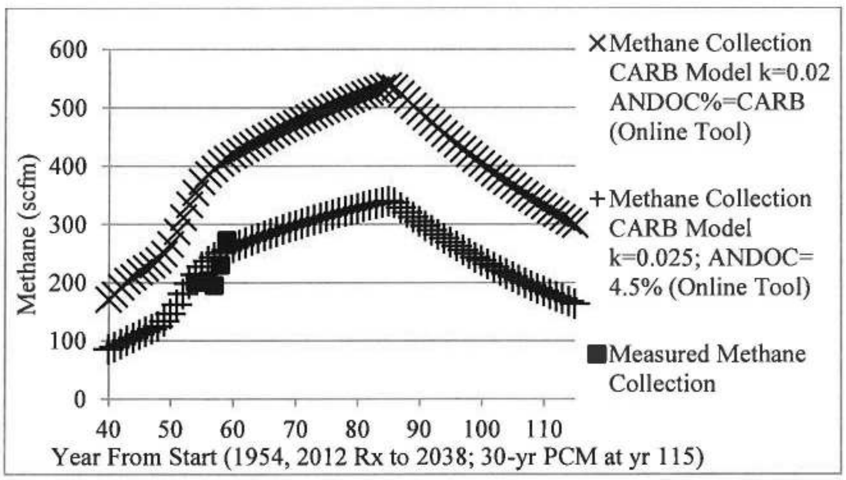


Figure 3. Histogram 66 Landfills Sites: Fraction 2010 Measured Collection to Model.

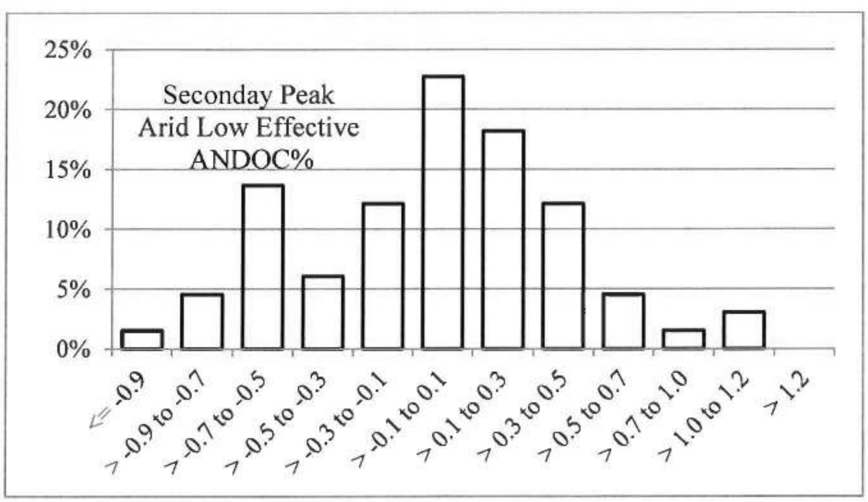


Table 5. Methane Emissions 118 Landfills Based on Measured Collection And Modeling Tool.

	Aggregate	Closed Landfills	Active Landfills
Calculated methane emissions (E) MG Year 2010 default 77.5% CE to measured collection (C) (= C*.225/.75):	245,430	53,668	191,761
Calculated E from modeling tool using default values:	229,589	64,714	164,875
% Difference C to modeling tool:	**7%**	**-17%**	**16%**
Emissions Based on Measured Collection and 85% (Active) and 91% (Closed) CE	129,187	17,688	111,499
% Difference C 85%/91% CE to modeling tool:	**-44%**	**-73%**	**-32%**

Expanded Study Using the ARB Emissions Modeling Tool and Measured Collection

Overall emissions calculated using the ARB landfill emissions modeling tool are 7% higher than emissions from measured collection using modeling default values (Table 5). For active landfills the emissions were 17% less and for closed landfills the emissions were 16% higher. The aggregate of all landfills studied in this document applying 85% (active) and 91% (closed) CE results in overall 44% less aggregate emissions than estimated by the modeling tool and at the high end of ARB's LMR goal of 2-4 MMTCO2e reductions (27 to 47% less than 2020 business-as-usual projection of 8.5 MMTCO2e).

Results of modeling tool analyses for the additional fifty-two (52) closed landfills are summarized in Figure 4. A significant finding is that emissions from closed landfills are significantly lower than estimates using the modeling tool and measured collection, and declines much more rapidly with time after site closure than the default values predict. Estimated emissions are 17- 37% lower over 30 years since closure for modeling tool default values applied to measured collected methane than estimates from the modeling tool. Applying 91% control efficiency based on the direct measurement study to closed sites results in 67-75% lower emissions from the modeling tool. Results of modeling using the modeling tool for the additional sixty six (66) active landfills are summarized in Figure 3. Higher decay coefficient (k) indicated by closed landfill modeling appears to some extent reflected in active sites where generation of methane is higher than predicted by default values (Figure 5). Applying the 85% CE found in this study to active landfills results in 32% lower emissions than default values.

Although landfills not subject to NSPS comprise only 17% of total State waste-in-place, additional direct measurement studies are recommended to characterize CE and avoided emissions for non-NSPS landfills, landfills implementing the LMR, and closed sites.

Figure 4. Difference Measured Collection to Model With Time Since Closure.

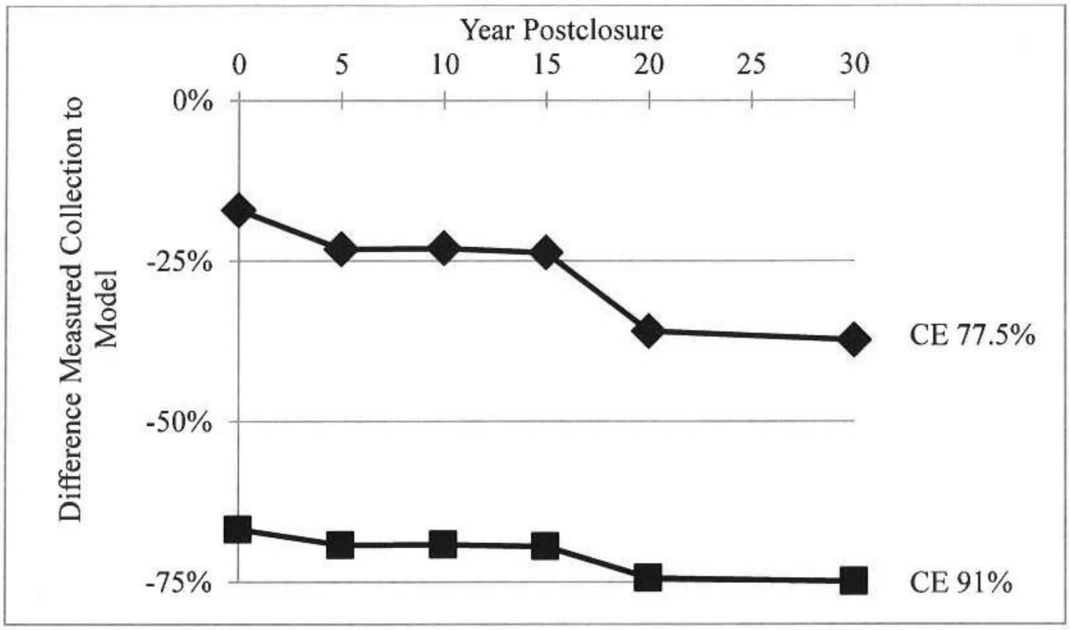
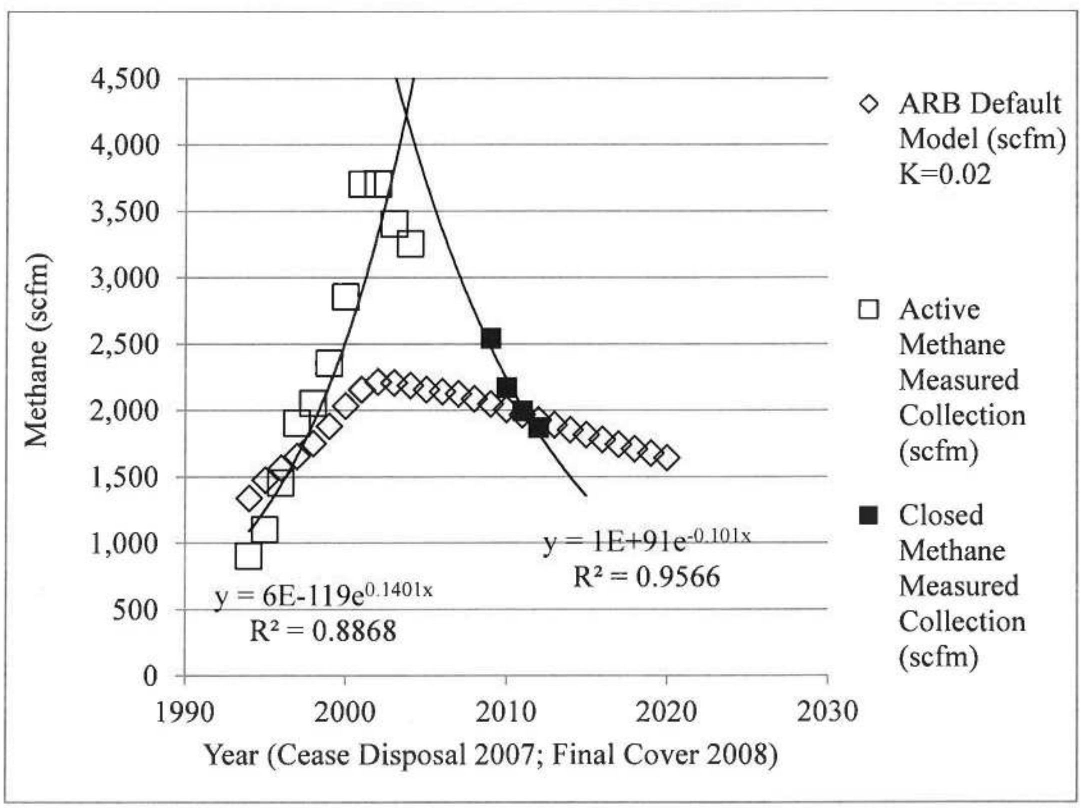


Figure 5. Closed Landfill 19-AF-0001 Difference Measured Collection to Model.



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