Attachment 1.1. California Landfill Methane Control Efficiency Based on Recent Direct Measurement
(OTM-10, Tracer, Methane Oxidation, and Measured Methane Collection)

Landfill CalRecycle SWIS Number:	21-AA-0001	43-AN-0008	01-AA-0008	01-AA-0009	19-AA-0050	Aggregate
Study Designation:	**CA-1**	**CA-2**	**CA-3**	**CA-4**	**CA-5**	
CH4 Collected and Combusted (in scfm arithmetic mean for study period year 2009)	1,225	685	889	2,422	203	5,424
CH4 in MG/yr Collected and Combusted	13,049	7,297	9,470	25,800	2,162	57,779
CH4 in scfm Emissions Based on Direct Measurement Applied to Total Landfill Waste Footprint	266	203	130	418	29	1,046
CH4 in MG/yr Emissions Based on Direct Measurement Applied to Total Landfill Waste Footprint	2,833	2,157	1,388	4,454	305	11,139
Measured % Methane Oxidation	50.7%	62.4%	27.4%	28.4%	34.3%	44.5%
Measured Methane Oxidation in scfm	274	336	49	166	15	840
Measured Methane Oxidation in MG/yr	2,914	3,584	524	1,765	159	8,946
Control Efficiency based on Direct Measurement	***85%***	***83%***	***88%***	***86%***	***88%***	***86%***
CH4 in MG/yr Emissions Based on ARB Default Factors Applied to CH4 Collected and Combusted	3,915	2,189	2,841	7,740	649	17,334
CH4 in MG/yr less (-) more (+) for Direct Measurement than for ARB Default Factors Applied to CH4 Collected and Combusted	-1,082	-32	-1,453	-3,286	-344	-6,195
CH4 in % less (-) more (+) for Direct Measurement than for ARB Default Factors Applied to CH4 Collected and Combusted	***-28%***	***-1%***	***-51%***	***-42%***	***-53%***	***-36%***
CH4 Collected (in scfm arithmetic mean for study period). Based on ARB Landfill Emissions Tool Version 1.3 and ARB Default Factors.	1,211	588	790	2,646	388	5,623
CH4 Collected (in MG/yr) Based on ARB Landfill Emissions Tool Version 1.3 and ARB Default Factors.	12,900	6,264	8,415	28,187	4,133	59,899
CH4 Emissions (in scfm arithmetic mean for study period) Based on ARB Landfill Emissions Tool Version 1.3 and ARB Default Factors .	404	196	263	882	129	1,874
CH4 Emissions (in MG/yr) Based on ARB Landfill Emissions Tool Version 1.3 and ARB Default Factors .	4,300	2,088	2,805	9,396	1,378	19,966
CH4 in MG/yr less (-) more (+) for Direct Measurement than for ARB Default Factors Applied to CH4 Collected and Combusted	-1,467	69	-1,417	-4,941	-1,073	-8,828
Difference in Emissions Based on Direct Measurement from ARB Landfill Emissions Tool Version 1.3 and ARB Default Factors.	***-34%***	***3%***	***-51%***	***-53%***	***-78%***	***-44%***
Range for FluxStandard Deviation (SD)						
SD for Flux	1,822	1,650	362	805	272	4,911
Mean + 1SD	4,655	3,808	1,750	5,259	577	16,049
Mean - 1SD	1,011	507	1,027	3,649	33	6,228
Control Efficiency Mean - 1 SD	***93%***	***94%***	***91%***	***88%***	***98%***	***91%***
Control Efficiency Mean + 1 SD	***74%***	***74%***	***85%***	***83%***	***79%***	***80%***

Calculation of Control Efficiency:
Methane Collection Efficiency (%) = (Methane Recovered/Methane Produced) x 100 (Methane Recovered = Methane Collected)
Methane Produced = Methane Recovered + Methane Emitted + Methane Oxidized
Methane Control Efficiency (%) = ((Methane Recovered + Methane Oxidized)/Methane Produced) x 100
% Methane Oxidation (or Fraction Methane Oxidized) is the fraction of methane delivered to the base of the cover that was oxidized to CO2 and partitioned to microbial
Methane Oxidized = (% Methane Oxidation x Methane Emitted)/(1- % Methane Oxidation)

Conversion Methane (CH4) scfm to Mg/yr to kg/d:		
scfm	2,422	scfm
scf year	1,273,003,200	scfmx365x24x60
Liters/Mole@STP	22.414000	
Liters/cf	28.31685	
Grams/Mole	16.04246	
1Mg/1,000,000g	0.000001	0.000001
CH4 combusted (Mg/yr)	25,800	scfmx365x24x60x16.0426x(28.31685/22.414)x0.000001
CH4 combusted (kg/d)	70,686	scfmx60x24x16.0426x(28.31685/22.414)/1000
Conversion Methane (CH4) Mg/yr to scfm:		
CH4 combusted (Mg/yr)	25,800	[CH4 Mg/yr)]
1Mg/1,000,000g	0.000001	0.000001
Liters/Mole@STP	22.414000	
Liters/cf	28.31685	
Grams/Mole	16.04246	
scfm	2,422	[CH4 Mg/yr)]/(60x24x365x16.04246x(28.31685/22.414)x0.000001)

Calculation of Avoided Methane Emissions:			
Methane generation factor (in scf) per ton MSW	2,415		
Molecular Weight CH4	16.04246		
1mol/22.414L@STP x 28.31685L/1cf	1.263		
grams CH4	48,946		
MTCH4	49	86% control	91% control
CO2 Equivalent (T) (21 GWP)	1,028	144	93
Total Emitted in MTCO2e (75% Collection Efficiency + 10% oxidation)	231	0.144	0.093
in MMTCO2e			
Calculation of Avoided Methane Emissions Dry Site (60%):			
Methane generation factor (in scf) per ton MSW	1,449		
Molecular Weight CH4	16.04246		
1mol/22.414L@STP x 28.31685L/1cf	1.263		
grams CH4	29,367		
MTCH4	29	86% control	91% control
CO2 Equivalent (T) (21 GWP)	617	86	56
Total Emitted in MTCO2e (75% Collection Efficiency + 10% oxidation) in MMTCO2e	139	0.086	0.056

Attachment 1.2. Direct Measurement OTM-10/Tracer and Methane Oxidation Studies- California Landfills

References:

[1] Green, Roger, Hater, Gary, Goldsmith, C. Douglas, Chanton, Jeffrey, Swan, Nathan, Abichou, Tarek. (2009). Estimates of Methane Emissions from Three California Landfills using Two Measurement Approaches. Extended Abstract # 89 Journal of the Air & Waste Management Association (A&WMA) First International Greenhouse Gas Measurement Symposium held March 22-25, 2009 in San Francisco, CA.

[2] Goldsmith, C. Douglas, Chanton, Jeffrey, Abichou, Tarek, Swan, Nathan, Green, Roger, and Hater, Gary (2012). Methane emissions from 20 landfill across the United States using vertical radial plume mapping. Journal of the Air & Waste Management Association (A&WMA), 62(2):183-197.

[3] Green, Roger B., Hater, Gary R., Thoma, Eben D., DeWees, Jason, Rella, Chris W., Crosson, Eric R., Goldsmith, C. Douglas, Swan, Nathan (2010). Methane Emissions Measured at Two California Landfills by OTM-10 and an Acetylene Tracer Method. 2010 Global Waste Management Symposium.

[4] Chanton, J., T. Abichou, C. Langford, G. Hater, R. Green, D. Goldsmith and N. Swan. (2011). Landfill Methane Oxidation Across Climate Types in the U.S. Environmental Science Technology. 45 (1): 313-319.

Facility	Emission Rate (gram/m2/day)	Study Date	Methane Collected (kg/d)	Methane Oxidation Direct Measurement	Reference
CA-1 (21-AA-0001)	4.64	2009- June	35,764		(CA 1 Goldsmith et al 2012)[2] Methane collection based on annual average
	19.23	2009- October	35,764		(CA 1 Goldsmith et al 2012)[2] Methane collection based on annual average
	8.5	2009- October	35,764		(Green et al 2010)[3] : Mobile Plume Flux Acetylene Tracer Method
	7.9	2009- October	35,764		(Green et al 2010)[3] : Stationary Plume Flux Acetylene Tracer Method
	5.4	2009- October	35,764		(Green et al 2010)[3] : Stationary Plume Flux Acetylene Tracer Method
Arithmetic Mean	***9.13***				
Standard Deviation	***5.87***				
Median	***7.90***				
Standard Error	***2.63***				
n	***5***				
				50.7%	(Chanton et al 2011a)[4] : Methane Oxidation Direct Measurement (Table 1- % Average Oxidation Chamber Flux mid-point αtrans=1 and αtrans>1).
CA-2 (43-AN-0008)	32.15	2009- June	19,999		(CA 2 Goldsmith et al 2012)[2] Methane collection based on annual average.
	9.58	2009- January	19,999		(CA 2 Goldsmith et al 2012) Methane collection based on annual average
Arithmetic Mean	***20.87***		***19,999***		Not including Green et al 2009[1] preliminary 2008 measurements of 23.13 (January) and 41.53 (June).
Standard Deviation	***15.96***				
Median	***20.87***				
Standard Error	***11.29***				
n	***2***				

Facility	Emission Rate (gram/m2/day)	Study Date	Methane Collected (kg/d)	Methane Oxidation Direct Measurement	Reference
				62.4%	(Chanton et al 2011a)[4] : Methane Oxidation Direct Measurement (Table 2- % Average Oxidation Surface Methane, mid-point αtrans=1 and αtrans>1).
				62.4%	*Arithmetic Mean*
CA-3 (01-AA-0008)	8.18	2009- June	25,955		(CA 3 Goldsmith et al 2012)[2] Methane collection based on annual average
	10.30	2009- February	25,955		(CA 3 Goldsmith et al 2012)[2] Methane collection based on annual average
	6.04	*2009- January*	*25,955*		*CA 3 Goldsmith et al 2012)[2] Note- measurement of final cover as being constructed over part of the site. Construction completion to occur in 2013. Methane collection based on annual average.*
Arithmetic Mean	***8.17***		***25,955***		Not including Green et al 2009[1] preliminary 2008 measurements of 10.73 (February) and 7.81 (June).
Standard Deviation	***2.13***				
Median	***8.18***				
Standard Error	***1.23***				
n	***3***				
				26.6%	(Chanton et al 2011a)[4] : Methane Oxidation (Table 1- % Average Oxidation Chamber Flux mid-point αtrans=1 and αtrans>1).
				28.3%	(Chanton et al 2011a)[4] : Methane Oxidation (Table 2- % Average Oxidation Surface Methane, mid-point αtrans=1 and αtrans>1).
				27.4%	*Arithmetic Mean*
CA-4 (01-AA-0009)	9.48	2009- October	70,711		(CA 4 Goldsmith et al 2012)[2] Methane collection based on annual average
	14.45	2009- June	70,711		(CA 4 Goldsmith et al 2012)[2] Methane collection based on annual average
	14.3	2009- October	70,711		(Green et al 2010)[3] : Mobile Plume Flux Acetylene Tracer Method
	13.1	2009- October	70,711		(Green et al 2010)[3] : Stationary Plume Flux Acetylene Tracer Method
Arithmetic Mean	***12.83***				
Standard Deviation	***2.32***				
Median	***13.70***				
Standard Error	***1.16***				
n	***4***				

Facility	Emission Rate (gram/m2/day)	Study Date	Methane Collected (kg/d)	Methane Oxidation Direct Measurement	Reference
				26.6%	(Chanton et al 2011a)[4] : Methane Oxidation (Table 1- % Average Oxidation Chamber Flux mid-point αtrans=1 and αtrans>1).
				30.2%	(Chanton et al 2011a)[4] : Methane Oxidation (Table 2- % Average Oxidation Surface Methane, mid-point αtrans=1 and αtrans>1).
				28.4%	*Arithmetic Mean*
CA-5 (19-AA-0050)	0.90	2009- September	5,927		(CA 5 Goldsmith et al 2012)[2] Methane collection based on annual average
	3.96	2009- January	5,927		(CA 5 Goldsmith et al 2012) Methane collection based on annual average
Arithmetic Mean	***2.43***		***5,927***		Not including Green et al 2009[1] preliminary measurements of 1.08 (2007 September) and 4.70 (January).
Standard Deviation	***2.16***				
Median	***2.43***				
Standard Error	***1.53***				
n	***2***				
				34.3%	(Chanton et al 2011a)[4] : Methane Oxidation (Table 2- % Average Oxidation Surface Methane, mid-point αtrans=1 and αtrans>1).