Critical Analysis of Literature on Landfill Gas Collection Efficiency

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Introduction

The objective of this chapter is to review literature on landfill gas emissions and collection efficiency. The first section of this chapter presents alternative methods for the calculation of the gas collection efficiency. This is followed by a section on the use of temporally-weighted collection efficiencies as opposed to an individual point estimate. The third section of this chapter reviews the literature on emissions measurements and collection efficiency and this chapter concludes with a summary and recommendations.

Calculation of Collection Efficiency

There are at least two alternatives for the calculation of collection efficiency. The conceptual model that is typically used to calculate emissions is given in equation 1. This conceptual model has been used in several life-cycle approaches (e.g., WARM, the EPA-ORD Decision Support Tool).

$$CH_4 \text{ Emissions} = CH_4 \text{ production} * (1 - \text{collection efficiency}) * (1 - CH_4 \text{ oxidation}) \qquad (1)$$

While theoretically correct, equation 1 is only useful if there are data to support separate measurement of the collection efficiency and methane oxidation.

To be consistent with the factors defined in equation 1, the collection efficiency should be calculated based on equation 2.

$$\text{Collection efficiency (\%)} = \frac{CH_4 \text{ collected}}{CH_4 \text{ collected} + CH_4 \text{ emitted} + CH_4 \text{ oxidized}} \qquad (2)$$

The use of equation 2 requires the availability of data on all terms and requires that methane emissions be quantified separately from methane oxidation. Where such data are available, the collection efficiency calculated by equation 2 is consistent with the use of collection efficiency in equation 1. However, in many cases measurements of methane emissions occur after the uncollected gas has been subjected to methane oxidation in the cover soil.

An alternative way to calculation collection efficiency is given in equation 3.

$$\text{Collection efficiency (\%)} = \frac{\text{methane collected}}{\text{methane collected} + \text{emissions}} \qquad (3)$$

In equation 3, a separate value is not available for methane oxidation. As such, the denominator of equation 3 does not reflect 100% of methane generation and the efficiency calculated by equation 3 will be higher than a true efficiency. In the literature review, efficiencies are calculated using equations 2 and 3 where data supporting data are available.

Incorporation of Landfill Gas Collection Efficiency into Life-Cycle Models

A method is required to represent the gas collection efficiency of either the average ton of waste disposed in a landfill or a specific ton placed at a specific time. As most models treat a generic ton of waste in an average landfill, a method has been developed to calculate the efficiency of an average or representative ton. The method described in this section is adopted from a paper by Levis and Barlaz (2011).

Landfill gas collection systems are installed in part based on the age of the landfill cell. As a result, waste buried earlier in the life of a landfill cell will be under gas collection for less time than waste buried later in the life of a landfill cell. It is therefore necessary to temporally average the collection efficiency for each year of cell operation. To illustrate this, a gas collection scenario was based on the following assumptions:

- a cell life of 5 years
- no gas collection in place for the first two years of cell operation (6 mo for bioreactors)
- the collection efficiency prior to cell closure and intermediate cover installation is 50% (i.e., years 3 to 5, or 0.5 to 3 yr for a bioreactor)
- after cell closure at the end of year 5, the collection efficiency is 75%
- 10 years after final waste placement (i.e., 15 years after initial waste placement), a final cover is installed and the gas collection efficiency increases from 75% to 95%

This gas collection system installation schedule was used to calculate a temporally averaged gas collection efficiency which is the volume of gas collected divided by the volume of gas produced over 100 years as it applies to the 5 years of waste buried in a single landfill cell.

The calculated temporally averaged landfill gas collection efficiencies for waste disposed in traditional and bioreactor landfills that collect gas are shown in Table . The results in Table 1 reflect an average mass of waste as opposed to the first mass buried. Thus, even though it was assumed that no gas collection is installed at a traditional landfill for two years, waste disposed in year two comes under some collection within a year of burial; hence the gas collection efficiency for waste buried in year two is non-zero.

Table 1. Temporally averaged landfill gas collection efficiencies[a]

Waste Age (yr)	Collection Efficiency (%) Traditional Landfill	Bioreactor Landfill
1	0	25
2	45	55
3	60	60
4	65	65
5	70	70
6	75	75
7	75	75
8	75	75
9	75	75
10	75	75
11	75	75
12	79	79
13	83	83
14	87	87
15	91	91
≥16	95	95

[a] Value represents the behavior of an average mass of MSW in a landfill with gas collection. The calculation procedure is described in the text. These values are based on an assumed schedule for the installation of a gas collection system, a landfill cell life of 5 years and the installation of final cover 15 years after a cell opens as described in the text.

Review of Studies on Landfill Gas Collection Efficiency

The objective of this section is to summarize published studies on landfill gas collection efficiency. Critical aspects of each study are presented and analyzed to assess what information can be used to inform the selection of model parameters for models in which emissions are estimated. Throughout this review, an effort was made to define the type of landfill cover on which emissions measurements were made so to differentiate the performance of gas collection systems on daily, intermediate and final covers. Studies are reviewed individually in chronological order to support an analysis of appropriate models and parameters to be used to estimate methane emissions.

Mosher et al., 1999

Mosher et al. (1999) reported on methane emissions at nine U.S. landfills using both static chambers (six of the landfills) and a tracer (five of the landfills). Two of the nine landfills did not have any gas collection, two (Rochester and PLF-C) were closed and had a final cover that included a geomembrane plus soil and five had a soil or geomembrane cover on between 18 and 63% of the landfill. Thus with the exception of the closed sites, the measurements encompass more than one type of cover which makes them difficult to use for assignment of collection efficiencies as a function of cover type. In all cases, emissions were reduced by methane oxidation.

Emissions at Rochester were reported to be 1750 liters CH_4/min and collection was reported as 16650 CH_4/min. This would result in a collection efficiency of 90.5% [100*(16650/(1750+16650)] using eqn. 3. However, there is a statement in the manuscript that gas collection was not accurately measured and was therefore estimated based on waste in place and an assumed oxidation value. If this is the case, then there is significant uncertainty in the calculated efficiency, although this site had the lowest emission rate in gm CH_4/m^2/day.

Emissions at PLF-C were reported to be 3900 liters CH_4/min and collection was reported as 15100 liters CH_4/min. This would result in a collection efficiency of 79.4% [100*(15100/(3900 +15100)] using eqn 3. Later in the manuscript, it is noted that here was “measurable off-site migration of gas” at this landfill.

In summary, collection efficiencies of 79.4% and 90.5% were reported for two closed landfills in which the final cover was a geomembrane plus soil. As discussed above, gas collection at Rochester is uncertain which casts some doubt on the precision of the 90.5% value. However, Rochester has the lowest emissions of any of the landfills which is consistent with a high collection efficiency. Given the presence of a geomembrane, it is likely that the measured emissions were not reduced methane oxidation.

Galle et al., 2001

Galle et al. (2001) measured methane emissions on a landfill in Sweden using a time correlation tracer method with tracer and methane concentrations measured by FTIR Absorption Spectroscopy. The landfill had been open since 1960 and in the years leading up to the study, the landfill received about 18,000 tons a year which is low by U.S. standards. Though not explicitly stated, it appears that the landfill was active at the time of testing. Therefore, the landfill was most likely covered with an intermediate cover. Methane emissions were measured to be 38 kg/hr and gas collection was reported as 9 kg/hr. The authors also introduced modeled gas production as well as estimated methane oxidation but these terms were not utilized for this analysis. The author estimates that their emissions estimate was ± 15%. Based on the methane collection and emissions data, a collection efficiency of 19.1% [100*(9/(38+9)] was calculated and actual emissions would have been reduced by methane oxidation.

Given the age of the landfill and the relatively small volume of waste, this landfill does not appear to be representative of a U.S. landfill.

Huitric et al. 2006 and 2007

Huitric et al. (2006 and 2007) presented a series of two papers in the proceedings of the SWANA LFG Symposium that describe work at the LA Sanitation District's Palos Verdes Landfill. In the 2007 paper, the cover is described as 7' of clay (the earlier paper says 5' of clay but this does not affect the conclusions). The landfill was closed in 1980.

This efficiency would include methane oxidation based on the manner in which emissions were measured. LFG emissions were calculated on the premise that the methane concentration is proportional to the emission rate. The concentration was measured by FID surface scan under very strict conditions as specified by local regulations. The concentration at the landfill surface was also calculated based on the assumption that no gas was collected by using the U.S. EPA's Industrial Source Complex (ISC) air dispersion model. The ratio of the measured concentration to the concentration calculated by assuming no gas collection was taken to represent the fraction emitted, so one minus this fraction is the fraction collected and oxidized. Flux chamber measurements were also made and were never significantly greater than zero. However, they were not used for the collection efficiency calculation. (It is recognized that flux chamber measurements will not capture above ground leakage from well boots, header pipes, etc.)

Measurements in 2006 showed ~95% collection efficiency while an efficiency of 99% was reported in the 2007 paper. The increase was attributed to improvements in the gas collection and control system (GCCS) design. While the method used to calculate collection efficiency is a little hard to follow and is subject to some uncertainty, the results show high collection efficiencies. All results reflect the combined effects of gas collection and methane oxidation.

The results are of limited applicability given the cover design and the waste age. The results show that for 25 to 30 year old waste in an arid region, a high collection and control efficiency can be achieved with a well operated GCCS.

Spokas et al., 2006

Spokas et al. (2006) presented a study in which they did a carbon balance on three French landfills. They started with the following equation to address all aspects of a landfill methane balance.

$$\text{Methane generated} = \text{emitted} + \text{oxidized} + \text{recovered} + \text{migrated} + \Delta \text{ storage} \tag{4}$$

Methane generation was estimated from a gas production model. Emitted methane was measured by using either static chambers or an atmospheric tracer technique. Methane oxidation was measured by using a stable isotope technique. Recovered methane was based on direct measurements at each landfill and methane migration was based on calculation of methane diffusion through liners. Maximum potential methane storage was calculated from an estimate of waste porosity and changes in the methane concentration of collected gas, and was used as an upper limit of the value required to close a mass balance.

A total of nine cells at the three landfills that were tested, including Montreuil-sur-Barse (MSB), Lapouyade (L), and Grand Landes (GL). The cover characteristics and depth of each landfill are presented in Table 2. MSB and GL are relatively shallow. The higher surface area to volume of these landfills would likely decrease gas collection efficiency relative to a deeper landfill.

To eliminate the need for a gas production model and the storage term, the collection efficiency was calculated as in eqn. 2 and the results are summarized in Table 2. As calculated by eqn. 2, collection efficiencies for final clay covers were uniformly above 90% while the collection efficiency for the temporary cover was slightly above 50% in the summer and over 90% in the winter. One potential explanation for this is that the covers were moist and frozen in the winter, thus decreasing their effective gas conductivity. The GCL at MSB exhibited a collection efficiency of 52% while the efficiency for the geomembrane final cover was 98.7%. Collection efficiencies were also calculated using eqn. 3 for comparison to other literature, which exclude the oxidation and migration terms. The difference between eq. 2 and eq. 2 is minor in consideration of the uncertainty of these types of studies (Table 2).

Interestingly, with reference to Spokas' work, Borjesson et al. (2007) suggests that "… their efficiency rates at over 90% may be overestimates, since the flux measurements with SF6 tracer measurements were done on the edge of the landfill rather than at some distance (Morcet, M., personal communication, 2003)."

The authors suggested the following values for collection efficiency based on their work:
35% for an active cell with a GCCS
65% for a temporary cover with a GCCS
85% for a cell with final clay cover and GCCS
90% for a GM covered cell with a GCCS
These values would appear to be conservative based on the values in Table 2.

Table 2 Landfill Emissions Measurements and Calculated Collection efficiency Based on Data in Spokas et al. (2006).

Site Description	Thickness (m)	Recovery (kg CH_4/day)	Emissions (kg CH_4/day)	Oxdn (kg CH_4/day)	Migration (kg CH_4/day)	Collection (collection + emissions) (eqn. 3)	Collection (collection + emissions + oxidation) (eqn. 2)	Oxidized (oxidized + emitted)
MSB: final clay with LFG recovery	4.3 -4.7	102	8.1	0.3	1.1	92.6	92.4	3.6
MSB: final GCL with LFG recovery	4.3 - 4.7	55.8	49.4	2.1	1.1	53.0	52.0	4.1
L: final clay with LFG recovery, summer	9.9 - 15	3935	298.6	83.5	20	92.9	91.1	21.9
L: final clay with LFG recovery, winter	9.9 - 15	3893	56	9.8	20	98.6	98.3	14.9
L: thin temporary clay cover, summer	9.9 - 15	346	287	6.5	3	54.7	54.1	2.2
L: thin temporary clay cover, winter	9.9 - 15	293.2	15	2.3	4	95.1	94.4	13.3
L: thin temporary clay cover, w/out LFG summer	9.9 - 15	0	5369	7.1	3			
GL: final clay with vertical wells	5.9 -6.9	1101	0.01	4[a]	5.1	100.0	99.6	99.8
GL: final geomembrane with horizontal LFG recovery	5.9 -6.9	799	6.2	4[a]	4.9	99.2	98.7	39.2

MSB = Montreuil-sur-Barse; L = Lapouyade; GL = Grand Landes

a. Methane oxidation was estimated since it could not be calculated in the absence of methane emissions for the clay cover.

Lohila et al. 2007

Lohila et al. (2007) measured emission for a landfill in Finland by using eddy covariance. The landfill received about 1000 tpd at the time of the study and the waste depth was 20 m. The gas collection system was drawing gas from an 8 ha area and the authors estimated the area covered by the emissions measurement to be 7 ha. The measurement area included an open area with active waste disposal, and an area covered with 0.2 – 0.5 m (6-15") of compost soil plus 0.5 – 2 m (15-60") diamicton and clay. Diamicton can be defined "as a wide range of non-sorted to poorly sorted terrigenous sediment, i.e. sand or larger size particles that are suspended in a mud matrix" from Wikipedia. The mixture of diamicton and clay appears equivalent to an intermediate cover with an oxidizing layer for a U.S. landfill.

In this study, the effectiveness of the gas collection system was assessed by turning the system off for either 4 or 7 days. In the first test, the system was turned off for 7 days and the mean emission rate increased from 0.37 to 1.79 mg/(m^2/sec). This resulted in a calculated collection efficiency of 79.3% [100*(1.79-0.37)/1.79] using eqn. 3. During the first test, the authors reported that the wind direction was favorable for EC measurements. A second test was conducted over a 4 day period when conditions were not suitable for EC measurements. Thus, during the second test, emissions were measured by using static chambers and high variability was noted with some chambers exhibiting net oxidation. The calculated collection efficiency was 40% but this result does not appear to be reliable. In both cases, emissions were reduced by methane oxidation prior to emissions measurement.

Finally, the authors report an average emission rate over the landfill of 27 m^3/(ha-hr) and gas collection of 60 m^3/(ha-hr) at pump station 2. The authors suggest an overall average collection efficiency of 69% [1-27/(60+27)]*100. If it is assumed that the emissions are attributable to 7 ha and gas collection is attributable to 8 ha, then the emissions could be scaled from 27 to 30.85 27 m^3/(ha-hr) by multiplying by 8/7. This results in a collection efficiency of 66% which is likely not significantly different from 69%. These values all represent emissions from an intermediate cover with some exposed waste that is not under collection. This would suggest a higher efficiency for an intermediate cover with complete GCCS coverage. Of course, these efficiencies also include the influence of methane oxidation.

Borjesson et al., 2007 and Borjesson et al., 2009

Borjesson et al. published two papers (2007 and 2009) describing the results of emissions measurement work that was conducted on three landfills in Sweden between 2001 and 2003. The results are summarized in Table 3. With reference to Table 3, these values were taken directly from the two publications. Where the values differed between the papers, the value in the more recent (2009) paper was used as it is assumed that the value published later represents a refinement of the data.

Emissions measurements were conducted by using a tracer gas release method with a Fourier transform infrared (FTIR) detector. Three types of covers were evaluated including (1) one meter of clay, (2) a mixture of sludge and soil, and (3) a mixture of sludge and wood chips. The 1 m of clay is likely between a long-term intermediate cover and a final cover on a U.S. landfill and will be considered as a final cover although there is no mention of a gas collection layer, a drainage layer or a vegetative layer as would be expected on a final cover at a U.S landfill. Furthermore, many final covers at U.S. landfills include a geomembrane. The sludge-soil mixture is most equivalent to an intermediate cover given that there are no conductivity specifications for intermediate cover for U.S. landfills. As a result, soils types used as intermediate cover vary widely. The sludge and wood chip cover is difficult to relate to any material used even as daily cover in the U.S. and appears unusual as wood chips would increase the porosity and conductivity, thus allowing for increased infiltration and decreased gas collection relative to a soil cover. These materials are not typically used at U.S. landfills.

The Filbrona landfill had some horizontal gas collection piping. Depending on the exact configuration of the GCCS at the time of the testing, the presence of horizontal collectors may have increased collection relative to a vertical system. The 2007 paper points out that Hogbytorp emits as much methane as a much larger landfill even though the larger landfill produces a lot more gas. This means the collection efficiency is considerably lower for Hogbytorp. The gas system was later upgraded and there was an improvement in collection. Nonetheless, the commentary and data suggest that Hogbytorp was not well run.

The authors calculated the collection efficiency using the equivalent of eqn. 2 where methane production was calculated as:

$$CH_4 \text{ Production} = \{CH_4 \text{ emissions}/(1\text{-}0.01{*}\%\ CH_4 \text{ oxdn.})\} + CH_4 \text{ Recovery} \qquad (5)$$

In this formulation, the authors recognize that methane oxidation must be considered in the methane production term. The calculated collection efficiency is suitable for use in equation 1. The manuscript indicates that the emissions data have an uncertainty of 18% though it is not clear how to incorporate this in a quantitative manner. The authors also acknowledge considerable uncertainty in the estimate of methane oxidation and recognize that methane oxidation varies over time, an observation that has been made by others as well (e.g., Chanton et al., 2011a, 2011b).

All site data and collection efficiencies are summarized in Table 3. The authors reported a mean collection efficiency of 51% for all of the measurements. However, this mean was calculated by combining data from sites with different cover types and after giving equal weight to two very low measurements, 14 and 21% which were for Hagby when the GCCS had operational problems. A second collection efficiency was calculated using equation 3. As expected, these values are slightly higher because all gas production is not included in the denominator as described above. The difference between the two values ranges between 2 and 21% with two exceptions. Differences of 2 – 21% are likely within the overall uncertainty in the collection efficiency calculation. In the case of Hagby, there are differences of about 50% for the two estimates of collection efficiency. However, these two measurements were made during the time when there were problems with GCCS operations and as such, they are outliers. It is recognized that there may be times when gas collection is either partially or wholly dysfunctional for some period of time. However, this is likely on the order of 1-2% of the time (estimates from owners are required) and could be considered as a separate term as opposed to incorporation of these values into an average collection efficiency in which they are given equal weight with a functioning system. The same issue arises in the EPA report described below.

In summary, for intermediate cover (Hogbytrop, Blaberget), collection efficiencies ranged from 29 – 59% using equations 4 and 5, and using 35 – 63% using equation 3.   Recall that Hogbytrop can be characterized as a landfill that is not well run. For long-term intermediate/final cover (Visby, Hagby, Kristianstad), collection efficiencies ranged from 52 – 67% using equations 4 and 5, and using 63-76% using equation 3.   These ranges exclude the two low values from Hagby given problems with GCCS at the time of operation.

Table 2 Landfill Emissions Measurements and Calculated Collection efficiency Based on Data in Borjesson et al. (2009).

Landfill Site	Cover Description & Comments	Date	Emissions kg/hr	Gas recovery kg/hr	CH4 Oxdn (%)	Prodn kg/hr	Efficiency (recovery/prodn) (eqn. 2)	Efficiency Collect/(Collect + Emit) (eqn. 3)
Filborna[a] (Helsingborg)	wood chips + sludge (not relevant to US)	4-Apr-01	308	852	18	1229	69	73.4
		16-Nov-01	386	832	18	1304	64	68.3
		23-Nov-01	441	820	15	1340	61	65.0
		6-Dec-01	256	987	6.2	1260	78	79.4
		7-Dec-01	361	1006	6.2	1391	72	73.6
		2-Jul-02	346	806	22	1250	64	70.0
		10-Mar-03	403	939	6.2	1369	69	70.0
Hogbytorp[c] (Upplands-Bro)	sewage sludge + soil (int. cover); small landfill (200,000 tons)	6-Jun-01	258	140	25	486	29	35.2
		11-Apr-02	393	202	6	620	33	33.9
		10-Nov-03	382	291	7.7	705	41	43.2
Blaberget (Sundsvall)	sewage sludge + soil (int. cover)	9-Mar-02	33.8	58.3	15	98	59	63.3
Visby	1 m clay	13-Jun-01	28	48	37	92	52	63.2
		4-Jun-02	19.2	39	37	69	57	67.0
		5-Jun-02	18.6	39	37	68	57	67.7
		26-Nov-03	12.8	32.4	38	53	61[b]	71.7

Table 2 Landfill Emissions Measurements and Calculated Collection efficiency Based on Data in Borjesson et al. (2009) (contd.)

Landfill Site	Cover Description & Comments	Date	Emissions kg/hr	Gas recovery kg/hr	CH4 Oxdn (%)	Prodn kg/hr	Efficiency (recovery/prodn)	Efficiency Collect/(Collect + Emit)
Hagby (Taby)	1 m clay	18-Apr-01	49	155	37	233	67	76.0
		22-Apr-02	124	32	37	229	14	20.5
		13-Nov-03	141	65.7	43	312	21	31.8
Heljestorp (Vanersborg)	wood chips + sludge (not relevant to US)	29-Mar-01	136	134	6.2	279	48	49.6
		22-May-02	191	262	25	517	51	57.8
Kristianstad	1 m clay	12-Apr-01	43	117	38	187	63	73.1

Notes

a. Filborna had the GCCS turned off on Nov 28, 2001 so no efficiency was calculated.
b. Value reported was 65 in 2007 paper.

Green et al., 2011

Methane emissions were measured at four MSW landfills in California and Colorado using a four corners approach of vertical radial plume mapping with tunable diode lasers to quantify methane concentrations. Field measurements were conducted on two separate occasions at each landfill, with each field campaign lasting several days. Each landfill had intermediate or long-term soil cover. The average result for each field campaign is summarized in Table 4 and collection efficiencies ranged from 72% - 92% based on equation 2.

Table 4 Summary of Collection Efficiencies Reported by Green et al. (2011)

Landfill	Climate	Collection Efficiency (eqn. 2)
DADS	semi-arid	82
		76
Lancaster	arid	92
		81
TriCities	moderate	86
		88
Kirby Canyon	moderate	84
		72

Goldsmith et al. (2012)

Goldsmith et al. (2012) reported methane emissions for 20 landfills across the U.S. based on a vertical plume mapping method in which 2 tunable diode lasers (TDLs) were used to measure methane concentrations upwind and downwind of a source. This method represents an extension of EPA's OTM-10 methodology. The manuscript includes considerable discussion on how to calculate the flux and it is important to recognize that there is some uncertainty in the area contributing to flux. As such, when the flux is normalized to a specific area, there is uncertainty in the emissions estimate. The emissions measurements include the combined effects of gas that is not captured and methane oxidation.

The emissions results were categorized as follows:

- Working face, no cover
- Temporary soil cover which means 15-30 cm of soil
- Intermediate cover which means 600-1200 cm of soil
- Final cover which means 1-2 m of soil

In general, working face emissions in wet warm areas like Mississippi exhibited higher emissions that emissions in cool dry climates such as Colorado. A similar trend was observed for temporary, intermediate and final covers. Results for 10 landfills with final covers were reported. Of the 10, only one had a geosynthetic cap and emissions at this landfill were barely above background on the basis of two field campaigns.

The data were not used to calculate collection efficiencies because the area of gas collection did not match with the area of the emissions measurements. As a result, the data is of limited value for informing an estimate of collection efficiency. It is however noteworthy that emissions at the landfills with final covers that included a geosynthetic cap were barely above background, thus supporting a relatively high collection efficiency. In addition, given the presence of a geomembrane, it is likely that the measured emissions were not impacted methane oxidation. Finally, the manuscript notes that even within climate categories, different regions tend to utilize different types of soil which will impact the extent of collection and emissions. This issue was not addressed quantitatively.

U.S. EPA, 2012

The U.S. EPA reported on emissions measurements at three landfills. Emissions measurements were made using EPA Method OTM-10. The method is similar to that used by Goldsmith et al (2012) except that only one instrument was used and data could not be corrected for upwind methane. Thus, the area contributing to flux may be less certain than the work reported by Goldsmith et al. (2012). Three landfills were tested. Site A includes 32 acres of intermediate cover. Site B has an 86 acre cell with intermediate cover but some parts of the intermediate cover did not have gas extraction and some wells were added in 2008 and 2010. The site stopped accepting waste in 2010 just prior to the measurement campaign. A second 6 acre site had been accepting waste for three months at the time of measurement and no gas wells were installed. Separate measurements were conducted on this area. Site C was closed in 2005 and is 76 acres that was capped with a geosynthetic.

The reported collection efficiencies were as in eqn. 3. As discussed above, the denominator therefore does not represent total production and therefore the calculated efficiencies are elevated. Collection efficiencies were also calculated based on assumptions of methane oxidation between 5 and 20%. However, these calculations add uncertainty to an already uncertain value and were not considered here.

The report presented two estimates of collection efficiency for site A:

- 70% (upper and lower error bounds of 64% and 75%)
- 77% (upper and lower error bounds of 67% and 84%)

The report presented a point estimate collection efficiency of 38% for Site B, with upper and lower error bounds of 31% and 46%. As noted above, Site B included intermediate cover but the gas extraction system was not functional over the entire 86 acres at the time of the tests. As such, while Site B is within the regulations in terms of GCCS installation, it is not representative of the performance on an intermediate cover with a fully functional GCCS.

The report presented two estimates of collection efficiency for site C:

- 73% (error bounds of 51 – 88%)
- 88% (error bounds of 72 – 95%)

The 73% is surprisingly low but there is no analysis of this value in the report.

The report concludes that "the data collected does not support the use of collection efficiency values of 90% of greater as has been published in other studies." Unfortunately, there is not a citation for this statement so the "other studies" cannot be identified. While the values measured for Site C help to inform the appropriate range of collection efficiencies, they are probably best applied to landfills with geosynthetic covers.

Summary and Recommendations

A summary of all reported measurements is presented in Table 5 and the associated statistics are summarized in Table 6. Entries are sorted by cover type to facilitate comparison across studies. The use of equation 2 or 3 to calculate the collection efficiency is noted in Table 5. Given the relatively small differences between equations 2 and 3 as reviewed for each study, all values are considered together. The values calculated using equation 3 are slightly higher than values calculated by using equation 2 but the difference is likely less than the associated uncertainty.

Before reviewing the summary, some discussion of cover classifications is appropriate. Many soils are used for intermediate cover and given the absence of a requirement for the conductivity of an intermediate cover, considerably variability can be expected, even without consideration of variation in the quality of the GCCS. Initially, cover types were divided into intermediate and final covers. However, this may be overly simplistic as many landfills use what is referred to as a long-term interim cover. This long-term interim cover may be in use for years to decades before additional waste is placed. In this context, a formal Subtitle D final cover may not be placed for years to decades but the long-term interim cover that is used would be expected to restrict gas emissions in a manner that is close to a Subtitle D final cover. Given the ambiguity, summary statistics are calculated with the 1m clay covers described in Borjesson classified as both intermediate and final covers (Table 5). As presented in Table 6, the final cover summary statistics in which the Borjesson data are classified as intermediate cover then include only data where the cover was specifically specified to be final.

With respect to the intermediate covers, several outliers were identified (14, 21, 19, 29, 33) and summary statistics were calculated with and without these values. Outliers were associated with landfills that were either not well run or with measurements made when the gas collection system was not fully functional over the areas of the emissions measurements. The calculated average ranges from 60.2 – 72.6% (medians 62 - 77%) and a value of 75% still appears reasonable though standard deviations are on the order of 20% (Table 6).

In the case of final covers, it is important to recognize that there are many configurations including clay only, geosynthetic clays and geomembrane plus clay. The average for final covers is 77.5% when the Borjesson data are included and 87.3% when these data are excluded. The overall range for final covers was 14 – 99.6% across all cover types (median = 73, mean = 71.2, std. dev. =25.4). This range includes the high values reported by Huitric for an unusually thick clay cover on an older landfill as well as the lowest values of Borjesson which appear to be outliers.

Based on this analysis, the limited data set and the uncertainty in all of the values, the following is suggested:

- Interim cover: 75% collection efficiency with lower values (~50%) used for waste under a daily rather than an interim cover

- Long-term interim cover which is used prior to Subtitle D final cover installation: 82.5% which is the average of 75% and 90%

- Final cover: 90%

It is recognized that uncertainty remains in all of the values.

As explained in this chapter, some collection efficiencies do not consider the oxidation of methane as part of the gas production term. As a result, efficiencies calculated in this manner are biased high. For the most part, the difference between the efficiency calculated using equations 2 and 3 is small and likely within the uncertainty of the values. While, measurements of emissions include emissions plus methane oxidation, measurements of collection accurately reflect collected gas. As such, it remains appropriate to apply a methane oxidation factor to the uncollected methane.

Finally, it is apparent that even the best operated GCCS can have days of weak performance. For life-cycle modeling, it may be appropriate to add an additional factor which is the fraction of the time that the system is operational and the fraction of the time when the GCCS is either not-operational (i.e., collection efficiency of zero) or operating at a reduced level (i.e., collection efficiency of perhaps 50% of the default value). Such an approach would take into account the fact that the GCCS may not be fully operational 100% of the time. In cases where the energy recovery system is not operational but the gas is diverted to a flare, this too could be considered as methane would be used beneficially for the time of diversion from a beneficial use to a flare.

Table 5 Summary of Published Studies on Landfill Gas Collection Efficiency

Study	Cover Type	Estimated efficiency using equation 2 unless noted	Comments
		Intermediate Covers	
Galle et al., 2001	Not clear, presumably intermediate cover	19.1[a]	Given the age of the landfill and the relatively small volume of waste, this landfill does not appear to be representative of a U.S. landfill. Because eqn. 3 was used, these values are biased high.
Spokas et al., 2006	Intermediate clay	54.1, 94.4	
Lohila et al., 2007	compost soil plus diamicton and clay	79.3[a,b], 40[a,b]	Assume comparable to an intermediate cover. The lower value is likely inaccurate because static chambers were used for the emissions measurement and high variability was reported. The authors also reported an efficiency of 66 – 69% for an intermediate cover with some exposed waste.
Borjesson et al., 2007; Borjesson et al., 2009	sewage sludge + soil	29, 33, 41	Assume comparable to an intermediate cover; small landfill (200,000 tons), landfill not well operated
Borjesson et al., 2007; Borjesson et al., 2009	sewage sludge + soil	59	Assume comparable to an intermediate cover
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	52, 57, 57, 61	Assume comparable to an intermediate cover (see discussion and Table 6)
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	67, 14, 21	Assume comparable to an intermediate cover; the low values (14, 21) were attributed to GCCS operational problems (see discussion and Table 6)
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	63	Assume comparable to an intermediate cover (see discussion and Table 6)

Study	Cover Type	Estimated efficiency using equation 2 unless noted	Comments
Green et al. 2011	intermediate	82, 76	
	intermediate	92, 81	
	intermediate	86, 88	
	intermediate	84, 72	
U.S. EPA (2012)	Intermediate	70[a],77[a]	Because eqn. 3 was used, these values are biased high.
U.S. EPA (2012)	Intermediate	38[a]	Gas extraction system was not functional over the entire test area at the time of the tests. Because eqn. 3 was used, these values are biased high.
Final Covers			
Mosher et al., 1999	Final cover with geomembrane (Rochester)	90.5	Value is uncertain as gas collection was not accurately measured and was therefore estimated based on waste in place and an assumed oxidation value. Given presence of geomembrane, emissions were likely not impacted by oxidation so attribute value to eqn. 2
Mosher et al., 1999	Final cover with geomembrane (Rochester)	79.4	Given presence of geomembrane, emissions were likely not impacted by oxidation so attribute value to eqn. 2.
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	52, 57, 57, 61	Assume comparable to a final cover (see discussion and Table 6)
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	67, 14, 21	Assume comparable to a final cover (see discussion and Table 6); the low values (14, 21) were attributed to GCCS operational problems
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	63	Assume comparable to a final cover (see discussion and Table 6)

Study	Cover Type	Estimated efficiency using equation 2 unless noted	Comments
Huitric et al., (2006, 2007)	7 ft (2.3 m) clay	95-99[a]	Landfill closed in 1980 so low production likely low. Unusually thick clay cover. Value entered as 97.
Spokas et al., 2006	Final clay cover	99.6	
Spokas et al., 2006	Final clay	92.4, 98.3	
Spokas et al., 2006	Final clay cover	91.1	
Spokas et al., 2006	Final geomembrane	98.7	
Spokas et al., 2006	Final geosynthetic clay	52	
Goldsmith et al. (2012)	geomembranes		Not quantified but emissions barely above background
U.S. EPA (2012)	Geosynthetic cap	73[a], 88[a]	Because eqn. 3 was used, these values are biased high.
Not Applicable			
Borjesson et al., 2007; Borjesson et al., 2009	wood chips + sludge	69, 64, 61, 78, 72, 64, 69	Cover not relevant to U.S. landfills
Borjesson et al., 2007; Borjesson et al., 2009	wood chips + sludge	48, 51	Cover not relevant to U.S. landfills

a. Based on equation 3.
b. The methane collection efficiency was calculated from measurements of emissions with and without operation of the GCCS.
c. The methane collection efficiency was estimated by comparing measured methane concentrations at the landfill surface to modeled concentrations assuming no methane collection.

Table 6 Summary Statistics for Cover Data

	Intermediate Cover with Borjesson data	Intermediate Cover without Borjesson data	Final cover with Borjesson data	Final cover without Borjesson data
All Data Included				
Median	62.0	74.0	73	91.1
Mean	60.2	64.7	71.2	87.3
Standard deviation	23.4	23.5	25.4	14.4
Outliers Excluded				
Median	74.0	77.0	79.4	No outliers excluded
Mean	72.6	71.4	77.5	
Standard deviation	13.3	18.4	18.0	

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