CHAPTER 3

SOLID WASTE DISPOSAL

[Parts shaded in grey – the unchanged text from the *2006 IPCC Guidelines*]

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3. SOLID WASTE DISPOSAL

3.1 INTRODUCTION

No refinement

3.2 METHODOLOGICAL ISSUES

3.2.1 Choice of method

3.2.1.1 FIRST ORDER DECAY (FOD)

This refinement attempts to guide the inventory complier on estimation of CH_4 emissions from active aeration landfill to the extent of current knowledge and data available. Information on the calculation of methane correction factors (MCFs) for new categories of aerobic SWDS, including active aerobic and semi-aerobic management is presented in Box 3.0A (New).

The *2006 IPCC Guidelines* present the basic concept of FOD as "…..The basis for the calculation is the amount of Decomposable Degradable Organic Carbon (DDOCm) as defined in Equation 3.2. DDOCm is the part of the organic carbon that will degrade under the anaerobic conditions in SWDS. It is used in the equations and spreadsheet models as DDOCm. The index *m* is used for mass. DDOCm equals the product of the waste amount (W), the fraction of degradable organic carbon (DOC) in the waste, the fraction of the degradable organic carbon that decomposes under anaerobic conditions (DOC_f), and the part of the waste that will decompose under aerobic conditions (prior to the conditions becoming anaerobic) in the SWDS, which is interpreted with the methane correction factor (MCF)…..". The parameter that is related to aerobic condition is expressed in terms of MCF. The guidance on the use of MCF in different management conditions of SWDS is updated in Table 3.1 (Updated). Currently many countries use active aeration or aerobic stabilization of managed landfills at large scale as abatement measure (e.g., Germany and some European countries). Decomposition of the organic matter is promoted about 3-4 times (Ishigaki *et al*., 2003, Ritzkowski and Stegmann, 2012). Rapid aerobic decomposition reduces DOC available for anaerobic decomposition.

The IPCC FOD method is adopted as a relatively simple model for estimating CH_4 emissions from SWDS, that express overall decomposition process of a series of chain reactions of anaerobic decay of DOC. Theoretically, it is possible to express aerobic decomposition of DOC by this model. However, the addition of reactions for aerobic decay of DOC to this model makes it complex. Therefore, the MCF is introduced to express the part of waste that is decomposed under aerobic conditions. This idea had also expanded for continuous aerobic management in semi-aerobically managed landfills in the *2006 IPCC Guidelines* although it defines MCF as a part of waste that will decompose under aerobic conditions (prior to the conditions becoming anaerobic) in SWDS. From this context, CH_4 emission from active aeration of managed landfill is also estimated by IPCC FOD method by introducing specific values of MCF.

BOX 3.0A (NEW)

INFORMATION ON CALCULATION OF MCF FOR NEW CATEGORY OF AEROBIC MANAGEMENT OF SWDS (MANAGED POORLY–SEMI-AEROBIC, MANAGED WELL–ACTIVE-AERATION, MANAGED POORLY–ACTIVE-AERATION)

In addition to air injection to SWDS under active aeration, certain design of piping, air volume, pressure, control of temperature and moisture are required (Ritzkowski and Stegmann 2012). These operating differences combined with different climates result in a range of reductions in CH_4 emission. Well-designed operation of aerobic management of SWDS in a laboratory has shown CH_4 emissions reduced by 70% (Ishigaki *et al.*, 2003). However, the field operations have been less effective in reducing emission due to the escape of oxygen and lack of substantial penetration to the waste body. Even if the designed aeration is sufficient for biological oxidation of organics in SWDS, oxygen can escape from the SWDS via void in waste and/or soils. In order to avoid the need to use excess aeration, a low-pressure aeration has been implemented for SWDS(reducing energy use and savingcost of production). These projects have shown the aerobic conversion of carbon decomposition conversion to aerobic condition, estimated by decomposition of carbon or gas emission reduction, from 25% (Raga and Coussu, 2014) to 75% (Hrad *et al.*, 2013), which corresponds to a MCF of 0.75 to 0.25. Cases of lower conversion during aerobic conditions are ascribed to the inhibition of air penetration to the saturated zone and the reduction of moisture by inappropriate control of aeration rate. It is clear that the climate and landfill management conditions influence the aerobic atmosphere in SWDS. Water level and drainage condition must be carefully managed especially in tropical climate. Aeration of fresh waste is less effective than aeration of aged waste is SWDS, especially in the tropical climate or where wet waste is disposed. The best results of aerobic coversion from 50% to 75% was used to develop a default MCF of 0.4 for managed well–active aeration. For active arationsystem that are notwellmanaged a default MCF of 0.7 were derive from the average of available literatures (Raga and Cossu, 2014, Ristkowski et al., 2006, Ritzkowski and Stegmann (2013)).

Semi-aerobically managed SWDS is another type of aerobic management. The nature of semi-aerobically managed SWDS is natural ventilation driven by the difference of temperature between the inside and outside of SWDS, which is supported by the connection of the network of drainage pipes and certain the number of gas exhausting (ventilation) pipes. Since the exits of leachate drainage pipes must be always open to the atmosphere, they also serve as an entrance for air penetration. In order for ventilation to occur, the water level in the landfills should be kept low in order to avoid the situation of sunk of drainage pipe (Laboratory of Solid Waste Disposal Engineering, 2016). In the tropical climate zone or other high-precipitation region, it is quite hard to manage the water level in SWDS (Tsubaki *et al*., 2009). In the case of drainage sunk, the amount of air penetration is reduced by about 40% of the best result of semi-aerobic management (Yamada *et al*., 2013). Default MCF of 0.7 for the category of poorly managed semi-aerobic landfills is derived from 40% reduction of aerobic decay of DOC from well-managed semi-aerobic landfill (0.5 + (1 - 0.5) x 40%)

In addition to the CH_4 emission from active aerobic landfill, there are some studies on methodology of N_2O emission from active aerobic landfill that are well accepted in CDM methodology AM0083 (2009). The importance of N_2O emission from SWDS is recognized widely whereas accumulation of scientific basis and knowledge is necessary for future methodology development. Information on N_2O emission estimation is provided in Appendix 3A.

3.2.2 Choice of activity data

No refinement

3.2.3 Choice of emission factors and parameters

DEGRADABLE ORGANIC CARBON (DOC)

FRACTION OF DEGRADABLE ORGANIC CARBON WHICH DECOMPOSES (DOC_f)

This refinement elaborates default values of DOC_f for different waste components based on waste components analysed in literature review. The uncertainty values are also updated.

Fraction of degradable organic carbon which decomposes (DOC_f) in SWDS was reported to vary depending on type of organic waste materials being degraded. Highly decomposable waste components were food wastes and grass. Moderately decomposable wastes were paper products including coated paper, old newsprint, old corrugated containers and office paper. Less decomposable wastes were wood components including tree branches and leaves (Eleazer *et al*., 1997) harvested wood products such as sawn and engineered wood materials. Recent literatures have reported different biodegradability of waste components in laboratory experiments and field-scale observations. Structural organization of the organic matter in the waste materials was found as predominant factor affecting their biodegradability which found to be related to the lignin-like residual fraction present in the waste materials (Bayard *et al.,* 2017). The biodegradation yields of the waste components under anaerobic condition were found to largely vary from one component to other, ranging from few percentages for wood to high percentages (60-80%) for food wastes and office paper. Meanwhile, biogenic carbon conversion of paper products were varied largely (21% to 96%) depending on paper products. In general, papers made from mechanical pulps are less degradable than those made from chemical pulps where essentially all lignin was chemically removed. Meanwhile the diaper exhibited limited biodegradability (Wang *et al*., 2015). According to Wang *et al*. (2011), carbon conversion to CH_4 were different for softwoods (0.1-1.4%) and hardwoods (0-7.8%). For the engineered wood products, the DOC_f was low for key product types such as particle board, medium-density fiber board and plywood, ranging from 1.1-1.4%. The carbon loss for wood samples recovered from landfills were found to be low and climate did not influence much on decay of wood in landfills. The observed higher levels of decay for some wood samples were attributed to differences in wood species (Ximenes *et al*., 2015). Average biogenic carbon content stored in the landfills was reported to be 64.6% and 35-95% of the biogenic carbon present in the waste components was recalcitrant and can be expected to go into long term storage. (De la Cruz *et al*., 2013).

Therefore, it is *good practice* to use DOC_f values specific to waste types when waste composition data are available. Table 3.0 (New) shows the recommended default DOC_f values for waste components with different degree of biodegradability. When information on composition of deposited wastes in SWDS is not available, default DOC_f value for bulk wastes can be used. The recommended default DOC_f value of bulk wastes of 0.5 in the *2006 IPCC Guidelines* is still valid based on information derived from updated literatures.

TABLE 3.0 (NEW)
FRACTION OF DEGRADABLE ORGANIC CARBON WHICH DECOMPOSES (DOC_F) FOR DIFFERENT WASTE TYPES

Type of Waste	Recommended Default DOC_f Values	Remark
Less decomposable wastes e.g. wood, branches and leaves	0.1	An average value of 0.088 was derived from DOC_f values for engineered wood products, sawn woods, tree branches reported in 3 references[1-3]
Moderately decomposable wastes e.g. paper, textile, nappies	0.5	An average value of 0.523 was derived from DOC_f values for paper products, textile and nappies reported in 4 references[4-7].
Highly decomposable wastes, e.g. food wastes, grasses	0.7	An average value of 0.706 was derived from DOC_f values for food wastes and grasses reported in 3 references[4-6]
Bulk waste*	0.5	Reported value of 0.46[5] and 0.34[8]

[1] Wang *et al*., (2011); [2]Wang and Balaz (2016); [3] Ximines *et al*., (2018); [4]Eleazer *et al*.,(1997); [5]Bayard *et al.*, (2017); [6]Jeong (2016); [7]Wang *et al.*, (2015); [8] De la Cruz *et al.,* (2013)

* It is used when the fractions of less, moderately and highly decomposable wastes in MSW are not known.

The amount of DOC leached from the SWDS was not considered in the estimation of DOC_f in the *2006 IPCC Guidelines*. However, DOC leached from the SWDS was reported to be significant under extremely wet condition. More accurate estimation of DOC available for biodegradation in SWDS should be considered in higher tier methodology provided that the amount of DOC lost with the leachate could be quantified (see information in Box 3.0B (New)).

BOX 3.0B (NEW)
INFORMATION ON EFFECT OF DOC LEACHING FROM SWDS

Recent literature reported that the operation of anaerobic landfills under wet conditions yielded higher organic carbon release in gas and leachate forms while reducing landfill gas production potential due to carbon washout by leachate (Jiang *et al*., 2007). Average rainfall of 2-12 mm/d influenced total amount of CH_4 generated from food waste because carbon washout increase with rainfall (Karanjekar *et al*., 2015). Drainage of accumulated leachate from municipal solid waste landfills containing waste with high percentage of food waste (~60% wet wt. basis) led to a loss of landfill gas of more than 10% (Zhan *et al*., 2017). Under extremely wet condition such as high leachate level in landfill and when percentage of rapidly biodegradable components in waste is high, it is *good practice* to estimate available DOC for degradation by subtracting DOC lost with the leachate from total DOC stored in SWDS either for one particular year or for multiple years period during which there was an evidence of significant DOC leaching from SWDS such as drainage of leachate from SWDS with high leachate level or high percentage of food waste. The estimation of remaining DOC in SWDS should be performed only when the DOC mass lost through leachate drainage from SWDS could be quantified. The emissions from the remaining DOC stored in SWDS can then be calculated using default DOC_f values.

METHANE CORRECTION FACTOR (MCF)

This refinement elaborates on the MCF default value of active aeration landfills and poorly managed semiaerobic landfills under Tier 1 estimation.

The MCF for shallow and deep unmanaged SWDS considers the degree of reduction of anaerobic microbial activity due to air penetration. But in case of aerobically managed landfills, both semi-aerobic and active aeration, the reduction of anaerobically available DOC due to aerobic degradation cannot be ignored. Further, the drying of waste in a part of active aeration results in reduction of the activity of microbes (both aerobic and anaerobic). Behavior of CH_4 emission from aerobically managed landfills including active aeration and semi-aerobically managed landfills is known to experience high fluctuation (Sutthasil *et al*., 2014) due to difficulty of management to keep aerobic conditions. DOC degraded under aerobic conditions depends on the way of management of SWDS. Therefore, the effects of management that affects DOC decay in aerobically managed landfills is considered in MCF for new categories of aerobic SWDS. Information on calculation of MCF for the new categories is given in Box 3.0A (New).

In addition, performance of landfill aeration highly depends on the age, composition and properties of waste, and capacity and technology of SWDS. It is encouraged to use locally available data which is obtained by the monitoring of each active aeration project of SWDS. This is regarded as higher Tier methodology and provided in detail in Appendix 3B.

TABLE 3.1 (UPDATED)
SWDS CLASSIFICATION AND METHANE CORRECTION FACTORS (MCF)

Type of Site	Methane Correction Factor (MCF) Default Values
Managed – anaerobic [1]	1.0
Managed well – semi-aerobic [2]	0.5
Managed poorly – semi-aerobic [3]	0.7
Managed well – active-aeration [4]	0.4
Managed poorly – active-aeration [5]	0.7
Unmanaged [6] – deep (>5 m waste) and /or high water table	0.8
Unmanaged [7] – shallow (<5 m waste)	0.4
Uncategorised SWDS [8]	0.6

[1] **Anaerobic managed solid waste disposal sites**: These must have controlled placement of waste (i.e., waste directed to specific deposition areas, a degree of control of scavenging and a degree of control of fires) and will include at least one of the following: (i) cover material; (ii) mechanical compacting; or (iii) levelling of the waste.

[2] **Well managed semi-aerobic managed solid waste disposal sites**: These must have controlled placement of waste and will include all of the following structures for introducing air to waste layer: (i) permeable cover material; (ii) leachate drainage system without sunk; (iii) regulating pondage; and (iv) gas ventilation system without cap, (v) connection of leachate drainage system and gas ventilation system.

[3] **Poorly managed semi-aerobically managed solid waste disposal sites:** When semi-aerobic managed SWDS type is managed under one of the following condition, it is regarded as poor management; (i) condition of sunk of leachate drainage system; (ii) closing of valve of drainage or atmosphere-unopening of drainage exit; (iii) capping of gas ventilation exit.

[4] **Well managed active aeration of managed solid waste disposal sites**: Active aeration of managed landfills includes the technology of in-situ low pressure aeration, air spurging, bioventing, passive ventilation with extraction (suction). These must have controlled placement of waste and will include leachate drainage system to avoid the blockage of air penetration, and (i) cover material; (ii) active aeration or gas extraction system without drying of waste.

[5] **Poorly-managed active aeration of managed solid waste disposal sites:** When SWDS, that is equipped as well as active aeration of managed SWDS, is managed under one of the following condition, it is judged as poor management; (i) blockage of aeration system due to failure of drainage; (ii) lack of available moisture for microorganisms due to high- pressure aeration.

[6] **Unmanaged solid waste disposal sites – deep and/or with high water table**: All SWDS not meeting the criteria of managed SWDS and which have depths of greater than or equal to 5 metres and/or high water table at near ground level. Latter situation corresponds to filling inland water, such as pond, river or wetland, by waste.

[7] **Unmanaged shallow solid waste disposal sites**; All SWDS not meeting the criteria of managed SWDS and which have depths of less than 5 metres.

[8] **Uncategorised solid waste disposal sites**: Only if countries cannot categorise their SWDS into above four categories of managed and unmanaged SWDS, the MCF for this category can be used.

Sources: IPCC (2000); Matsufuji *et al*. (1996), , Hrad *et al*., 2013, Ishigaki *et al*., 2003, Raga and Cossu 2014, Ritzkowski *et al*., 2016, Ritzkowski and Stegmann 2013 Van Vossen W. and Heyer, 2009, Yamada *et al*., 2013

3.3 USE OF MEASUREMENT IN THE ESTIMATION OF CH_4 EMISSIONS FROM SWDS

No refinement

3.4 CARBON STORED IN SWDS

No refinement

3.5 COMPLETENESS

No refinement

3.6 DEVELOPING A CONSISTENT TIME SERIES

No refinement

3.7 UNCERTAINTY ASSESSMENT

No refinement

3.7.1 Uncertainty attributable to the method

No refinement

3.7.2 Uncertainty attributable to data

Please see Section 3.7.2.2

3.7.2.1 UNCERTAINTIES ASSOCIATED WITH ACTIVITY DATA

No refinement

3.7.2.2 UNCERTAINTIES ASSOCIATED WITH PARAMETERS

Methane correction factor (MCF), Fraction of degradable organic carbon (DOC) in waste and Fraction of degradable organic carbon which decomposes (DOC_f)

This section provides updates on uncertainty of default DOC_f value as shown in Table 3.5 (Updated). The estimates are based on DOC_f derived from information reported in the literatures and expert judgement. Reported biodegradability of waste components were varied in a wide range depending on the composition of materials in bulk wastes as well as environmental factors in which the wastes are undergone biodegradation. It is recognized that laboratory experiments where some of reported DOC_f values are derived from would be quite different from the real condition of SWDS but there was also some good agreement between the reported biodegradable fractions of waste components derived from laboratory experiments and observed data from field investigations. In the *2006 IPCC Guidelines*, the uncertainty range of proposed default DOC_f value of bulk wastes is ±20% which is in agreement with recent updated information on DOC percentages of ±18% found in SWDS (De la Cruz et al., 2013). Moreover, the proposed default DOC_f values for different waste component are derived based on the information reported in the literatures.

TABLE 3.5 (UPDATED)
ESTIMATES OF UNCERTAINTIES ASSOCIATED WITH THE DEFAULT ACTIVITY DATA AND PARAMETERS IN THE FOD METHOD FOR CH_4 EMISSIONS FROM SWDS

Activity data and emission factors	Uncertainty Range
Total Municipal Solid Waste (MSW_T)	**Country-specific:** 30% is a typical value for countries which collect waste generation data on regular basis. ±10% for countries with high quality data (e.g., weighing at all SWDS and other treatment facilities). For countries with poor quality data: more than a factor of two.
Fraction of MSW_T sent to SWDS (MSW_F)	±10% for countries with high quality data (e.g., weighing at all SWDS). ±30% for countries collecting data on disposal at SWDS. For countries with poor quality data: more than a factor of two.
Total uncertainty of Waste composition	±10% for countries with high quality data (e.g., regular sampling at representative SWDS). ±30% for countries with country-specific data based on studies including periodic sampling. For countries with poor quality data: more than a factor of two.
Degradable Organic Carbon (DOC)[1]	**For IPCC default values** : ±20% **For country-specific values**: Based on representative sampling and analyses: ±10%
Fraction of Degradable Organic Carbon Decomposed (DOC_f)	**For IPCC default value (0.5)**: ± 20% **For IPCC default value for each waste type**

[1] The uncertainty range given applies to the DOC content in bulk waste. The ranges for DOC for different waste components in MSW given in Table 2.4 can be used to estimate the uncertainties for these components.

= 0.1 = 0.5 = 0.7	±90% ±70% ±30% **For country-specific value** ± 10% for countries based on the experimental data over longer time periods.
Methane Correction Factor (MCF) = 1.0 = 0.8 = 0.7 = 0.5 = 0.4 = 0.4[1] = 0.6	**For IPCC default value:** –10%, +0% ±20% ±30% ±20% ±30% ±60% –50%, +60%
Fraction of CH_4 in generated Landfill Gas (F) = 0.5	**For IPCC default value**: ±5%
Methane Recovery (R)	The uncertainty range will depend on how the amounts of CH_4 recovered and flared or utilised are estimated: ± 10% if metering is in place. ± 50% if metering is not in place.
Oxidation Factor (OX)	Include OX in the uncertainty analysis if a value other than zero has been used for OX itself. In this case the justification for a non-zero value should include consideration of uncertainties.
half-life ($t_{1/2}$)	Ranges for the IPCC default values are provided in Table 3.4. Country-specific values should include consideration of uncertainties.

Source: Expert judgement by Lead Authors of the Chapter.

1: MCF for Managed well – active aeration

3.8 QA/QC, Reporting and Documentation

No refinement

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Second-order Draft

Appendix 3A Information on Nitrous Oxide Emission from Solid Waste Disposal Site

Significant generation of N_2O from SWDS was indicated by the IPCC Fourth Assessment Report (2007). However, the *2006 IPCC Guidelines* do not present a methodlogy or parameters by which N_2O emissions can be estimated.

Approved CDM methodology, AM0083 (UNFCCC CDM Executive Board 2009), is applicable to project activities where landfilled waste is treated aerobically on-site by means of air venting (overdrawing) or low pressure aeration with the objective of avoiding anaerobic degradation processes and achieving aerobic degradation. The AM0083 provides two alternative methodologies for estimating N_2O emissions. One is estimation based on measured N_2O on the site, and the other is using emission factor. Aerobic pathway of N_2O generation in SWDS is well known (Borjesson and Svensson 1997; He et al., 2011; Harborth et al. 2013), and the emission factor given in AM0083 is based on waste composting (0.2-1.6 g N_2O/kg waste treated on a dry weight base or 0.06-0.6 g N_2O/kg waste treated on a wet weight base), which is regarded as an analogue process to low pressure aeration. While the properties of waste in SWDS or aeration rate adopted in the active aeration are far from the condition of composting, it is recommeded to obtain the local monitoring data to be used for estimation of N_2O emission from SWDS.

Not only active aeration of managed landfills, but cover soils and woking faces in all SWDS are potential emission sources of N_2O because these zones are allowed to penetrate atmospheric oxygen duffusively. Emission of N_2O has not been reported in semi-aerobically managed landfills while not so many information is available. If the specific project on active aeration of SWDS in each country is adopted for emission estimation, and if it also reported N_2O emission as well in accordance with AM0083, that can also be taken into consideration for inventory reports.

Anaerobic generation of N_2O is also common and has been observed in SWDS (Rinne et al., 2005; Matthew et al., 2005; Ishigaki et al., 2016). Anaerobic pathway of N_2O generation is combined with denitrification process and is correlated to anaerobic decay of DOC. There are two uncertainties on the degree of conversion of nitrogen componds to N_2O and the degree of carbon consumption by nitrogen conversion for the emission estimation. Apparent correlation of N_2O and CH_4 emissions was obtained about 20% by equivalent to CO_2 in anaerobically managed landfills (Ishigaki et al., 2016), wheareas it requires to validate for country specific condition in order to obtain reliable emission estimate.

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Appendix 3B Information on Estimation of CH_4 Emission from Solid Waste Disposal Site Managed by Active Aeration Using Locally Available Measured Data

Estimation of MCF for Active Aeration Using Measured Data

The practice of implementation of active aeration of solid waste disposal site (SWDS) is very limited. Therefore, improvement of the default values of MCF for active aeration shown in Table 3.1 (Updated) is necessary. Locally available measured data on landfill gas emission in SWDS managed by active aeration, which are normally collected as operational data, can be applied for estimating MCF. Stable operational conditions of aeration of SWDS is still under development, therefore monitoring data tends to fluctuate even in the same country. Assessment of uncertainty of local monitoring data is indispensable before estimating the emission in this category.

MCF for SWDS managed by active aeration is determined by measured data of CH_4 and CO_2 in landfill gas.

EQUATION 3B.1 (NEW)
MCF FOR MANAGED SWDS (ACTIVE AERATION)

$$MCF = 1 - \left(\frac{(P - P') + (Q - Q')}{2} \right) \cdot \left(\frac{1}{P} \right)$$

Where:

P = fraction of CH_4 measured in landfill gas at cell managed anaerobically or before active aeration (fraction)

P' = fraction of CH_4 measured in landfill gas during active aeration (fraction), $P' \leq P$

Q = fraction of CO_2 measured in landfill gas at cell managed anaerobically or before active aeration (fraction)

Q' = fraction of CO_2 measured in landfill gas during active aeration (fraction), $Q' \geq Q$

This method is suitable if fraction of CH_4 and CO_2 are measured at systems of forced extraction or suction of landfill gas. In other case variance of measured data is high and careful assessment of validity of data is essential. Uncertainty and consistency of MCF and estimated emission is also evaluated.

Default value for fraction of CH_4 in generated landfill gas (0.5) is given in the *2006 IPCC Guidelines* (Chapter 3.2.3, Volume 5). As stated there, fraction of CH_4 in generated landfill gas must not be confused with measured CH_4 in landfill gas emitted, because CO_2 generated is absorbed in seepage water. Even if the fractions of CH_4 and CO_2 measured in landfill gas at a cell managed anaerobically or before active aeration (P and Q) are not available, using default value for fraction of CH_4 in generated landfill gas (F) is not recommended, and adjustment of CO_2 absorption in seepage water is required. Consideration of CH_4 oxidation is also necessary when it is enhanced by active aeration.

Estimation of Emissions Using Measurements of Flow Rates and CH_4 Concentrations

While consistent measured data of fractions of CH_4 and CO_2 in landfill gas is not available or its validity is poor, direct estimation of CH_4 emission by using measured data in individual SWDS is encouraged.

To monitor actual CH_4 emissions from the aerated landfill, both surface and vented emissions from the surface have to be measured. As shown in the *2006 IPCC Guidelines* (Chapter 3.3, Volume 5), measurement of gases in collection system and fugitive emission through the surface are covered.

CH_4 emission from gas collection system is obtained as the product of content of CH_4 (Gg/m^3) and flow rate of the landfill gas from the pipe (m^3/yr). Flow rate of landfill gas is estimated by multiplying the velocity of gas in certain depth by the area of the pipe. When forced extraction is implemented, CH_4 emission from gas collection system dominate and reliable and representative data is obtained. Even though, it is necessary to take into consideration the variance of emissions in each well for accurate estimation. At least quarterly measurements should be done within each venting well in order to account for the seasonal variation of emissions.

CH_4 emission from surface of SWDS is obtained by several methods shown in Box 3.2 in the *2006 IPCC Guidelines*. Representativeness and coverage of surface emission should be carefully considered. Since results obtained by flux chamber method fluctuate to a great extent from one zone to other within the same SWDS, a number of measurement points is required to express the surface distribution of emissions. Geostatistical analysis methods should be applied in order to obtain representative data of emissions from fluctuated fluxes in different zones of the SWDS. The SWDS can be subdivided into different zones with distinctive characteristics with regard to expected surface emissions. A flux density of the landfill gas ($mg/m^2 \cdot s$) can be calculated for each measurement. Then, average surface emissions rate can be calculated for each zone by multiplying the average flux density with the corresponding area of the zone. Due to the high uncertainty of surface measurements, a conservativeness factor should be used to account for such uncertainties. For example, a conservativeness factor of 1.37 is multiplied by CH_4 emission from surface emissions is proposed by UNFCCC CDM Executive Board (2009).

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