CHAPTER 3

SOLID WASTE DISPOSAL

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3.1 INTRODUCTION

Treatment and disposal of municipal, industrial and other solid waste produces significant amounts of methane (CH_4). In addition to CH_4, solid waste disposal sites (SWDS) also produce biogenic carbon dioxide (CO_2) and non-methane volatile organic compounds (NMVOCs) as well as smaller amounts of nitrous oxide (N_2O), nitrogen oxides (NO_x) and carbon monoxide (CO). CH_4 produced at SWDS contributes approximately 3 to 4 percent to the annual global anthropogenic greenhouse gas emissions (IPCC, 2001). In many industrialised countries, waste management has changed much over the last decade. Waste minimisation and recycling/reuse policies have been introduced to reduce the amount of waste generated, and increasingly, alternative waste management practices to solid waste disposal on land have been implemented to reduce the environmental impacts of waste management. Also, landfill gas recovery has become more common as a measure to reduce CH_4 emissions from SWDS.

Decomposition of organic material derived from biomass sources (e.g., crops, wood) is the primary source of CO_2 released from waste. These CO_2 emissions are not included in national totals, because the carbon is of biogenic origin and net emissions are accounted for under the AFOLU Sector. Methodologies for NMVOCs, NO_x and CO are covered in guidelines under other conventions such as the UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP). Links to these methodologies are provided in Chapter 1 of this volume, and additional information in Chapter 7 of Volume 1. No methodology is provided for N_2O emissions from SWDS because they are not significant.

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*1996 Guidelines*, IPCC, 1997) and the *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (*GPG2000*, IPCC, 2000) described two methods for estimating CH_4 emissions from SWDS: the mass balance method (Tier 1) and the First Order Decay (FOD) method (Tier 2). In this Volume, the use of the mass balance method is strongly discouraged as it produces results that are not comparable with the FOD method which produces more accurate estimates of annual emissions. In place of the mass balance method, this chapter provides a Tier 1 version of the FOD method including a simple spreadsheet model with step-by-step guidance and improved default data. With this guidance, all countries should be able to implement the FOD method.

3.2 METHODOLOGICAL ISSUES

3.2.1 Choice of method

The IPCC methodology for estimating CH_4 emissions from SWDS is based on the First Order Decay (FOD) method. This method assumes that the degradable organic component (degradable organic carbon, DOC) in waste decays slowly throughout a few decades, during which CH_4 and CO_2 are formed. If conditions are constant, the rate of CH_4 production depends solely on the amount of carbon remaining in the waste. As a result emissions of CH_4 from waste deposited in a disposal site are highest in the first few years after deposition, then gradually decline as the degradable carbon in the waste is consumed by the bacteria responsible for the decay.

Transformation of degradable material in the SWDS to CH_4 and CO_2 is by a chain of reactions and parallel reactions. A full model is likely to be very complex and vary with the conditions in the SWDS. However, laboratory and field observations on CH_4 generation data suggest that the overall decomposition process can be approximated by first order kinetics (e.g., Hoeks, 1983), and this has been widely accepted. IPCC has therefore adopted the relatively simple FOD model as basis for the estimation of CH_4 emissions from SWDS.

Half-lives for different types of waste vary from a few years to several decades or longer. The FOD method requires data to be collected or estimated for historical disposals of waste over a time period of 3 to 5 half-lives in order to achieve an acceptably accurate result. It is therefore *good practice* to use disposal data for at least 50 years as this time frame provides an acceptably accurate result for most typical disposal practices and conditions. If a shorter time frame is chosen, the inventory compiler should demonstrate that there will be no significant underestimation of the emissions. These *Guidelines* provide guidance on how to estimate historical waste disposal data (Section 3.2.2, Choice of Activity Data), default values for all the parameters of the FOD model

(Section 3.2.3, Choice of Emission Factors and Parameters), and a simple spreadsheet model to assist countries in using the FOD method.

Three tiers to estimate the CH_4 emissions from SWDS are described:

Tier 1: The estimations of the Tier 1 methods are based on the IPCC FOD method using mainly default activity data and default parameters.

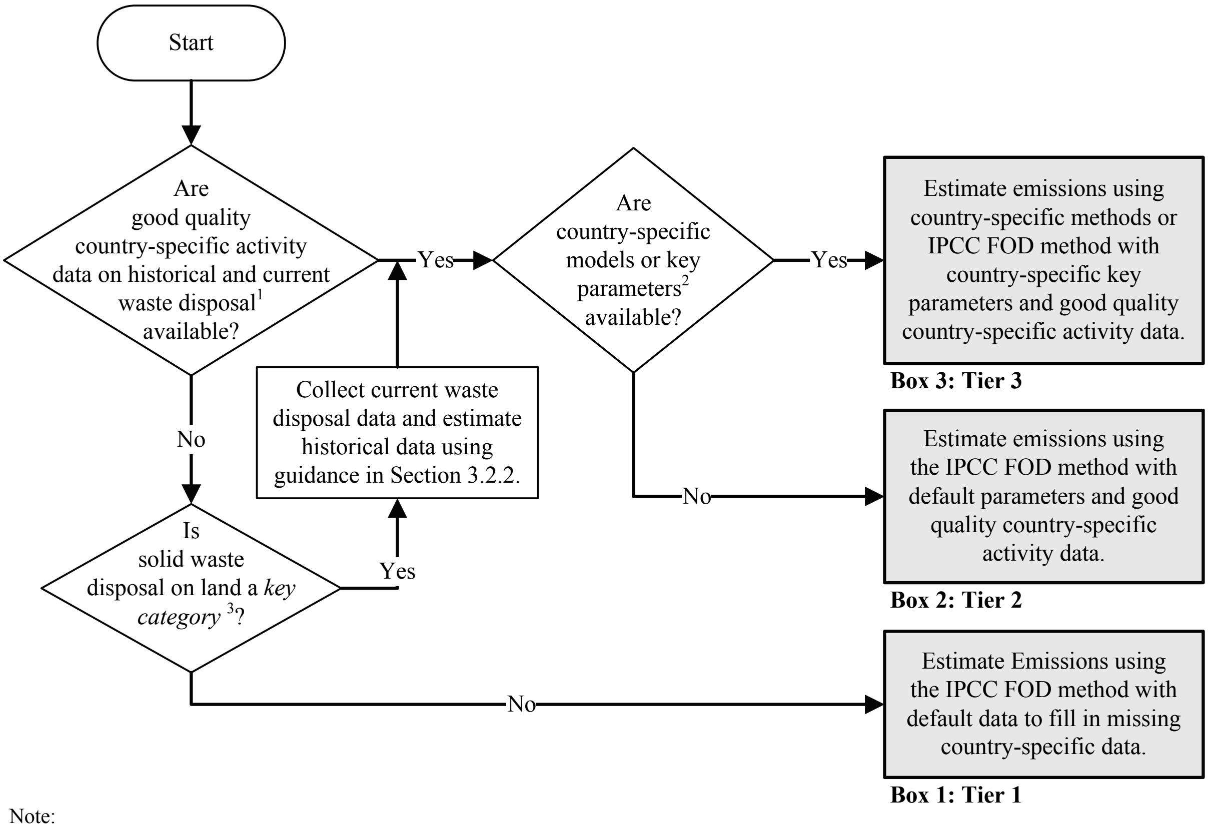
Tier 2: Tier 2 methods use the IPCC FOD method and some default parameters, but require good quality country-specific activity data on current and historical waste disposal at SWDS. Historical waste disposal data for 10 years or more should be based on country-specific statistics, surveys or other similar sources. Data are needed on amounts disposed at the SWDS.

Tier 3: Tier 3 methods are based on the use of good quality country-specific activity data (see Tier 2) and the use of either the FOD method with (1) nationally developed key parameters, or (2) measurement derived country-specific parameters. The inventory compiler may use country-specific methods that are of equal or higher quality to the above defined FOD-based Tier 3 method. Key parameters should include the half-life, and either methane generation potential (L_o) or DOC content in waste and the fraction of DOC which decomposes (DOC_f). These parameters can be based on measurements as described in Box 3.1.

A decision tree for choosing the most appropriate method appears in Figure 3.1. It is *good practice* for all countries to use the FOD method or a validated country-specific method, in order to account for time dependence of the emissions.

The FOD method is briefly described in Section 3.2.1.1 and in more detail in Annex 3A.1. A spreadsheet model has been developed by the IPCC to assist countries in implementing the FOD: *IPCC Spreadsheet for Estimating Methane Emissions from Solid Waste Disposal Sites (IPCC Waste Model)* [1].The *IPCC Waste Model* is described in more detail below and can be modified and used for all tiers.

Figure 3.1 Decision Tree for CH_4 emissions from Solid Waste Disposal Sites



Note:
1. Good quality country-specific activity data mean country-specific data on waste disposed in SWDS for 10 years or more.
2. Key parameters mean DOC/L_o, DOC_f and half-life time.
3. See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.

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[1] See the attached spreadsheets in Excel format. <IPCC_Waste_Model.xls>.

3.2.1.1 FIRST ORDER DECAY (FOD)

METHANE EMISSIONS

The CH_4 emissions from solid waste disposal for a single year can be estimated using Equations 3.1. CH_4 is generated as a result of degradation of organic material under anaerobic conditions. Part of the CH_4 generated is oxidised in the cover of the SWDS, or can be recovered for energy or flaring. The CH_4 actually emitted from the SWDS will hence be smaller than the amount generated.

EQUATION 3.1
CH_4 EMISSION FROM SWDS

$$CH_4\ Emissions = \left[\sum_x CH_4\ generated_{x,T} - R_T \right] \bullet (1 - OX_T)$$

Where:

CH_4 Emissions = CH_4 emitted in year T, Gg

T = inventory year

x = waste category or type/material

R_T = recovered CH_4 in year T, Gg

OX_T = oxidation factor in year T, (fraction)

The CH_4 recovered must be subtracted from the amount CH_4 generated. Only the fraction of CH_4 that is not recovered will be subject to oxidation in the SWDS cover layer.

METHANE GENERATION

The CH_4 generation potential of the waste that is disposed in a certain year will decrease gradually throughout the following decades. In this process, the release of CH_4 from this specific amount of waste decreases gradually. The FOD model is built on an exponential factor that describes the fraction of degradable material which each year is degraded into CH_4 and CO_2.

One key input in the model is the amount of degradable organic matter (DOCm) in waste disposed into SWDS. This is estimated based on information on disposal of different waste categories (municipal solid waste (MSW), sludge, industrial and other waste) and the different waste types/material (food, paper, wood, textiles, etc.) included in these categories, or alternatively as mean DOC in bulk waste disposed. Information is also needed on the types of SWDS in the country and the parameters described in Section 3.2.3. For Tier 1, default regional activity data and default IPCC parameters can be used and these are included in the spreadsheet model. Tiers 2 and 3 require country-specific activity data and/or country-specific parameters.

The equations for estimating the CH_4 generation are given below. As the mathematics are the same for estimating the CH_4 emissions from all waste categories/waste types/materials, no indexing referring to the different categories/waste materials/types is used in the equations below.

The CH_4 potential that is generated throughout the years can be estimated on the basis of the amounts and composition of the waste disposed into SWDS and the waste management practices at the disposal sites. 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 in the waste (DOC), 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).

EQUATION 3.2
DECOMPOSABLE DOC FROM WASTE DISPOSAL DATA

$$DDOCm = W \bullet DOC \bullet DOC_f \bullet MCF$$

Where:

DDOCm = mass of decomposable DOC deposited, Gg

W = mass of waste deposited, Gg

DOC = degradable organic carbon in the year of deposition, fraction, Gg C/Gg waste

DOC_f = fraction of DOC that can decompose (fraction)

MCF = CH_4 correction factor for aerobic decomposition in the year of deposition (fraction)

Although CH_4 generation potential (L_o)[2] is not used explicitly in these *Guidelines*, it equals the product of DDOCm, the CH_4 concentration in the gas (F) and the molecular weight ratio of CH_4 and C (16/12).

EQUATION 3.3
TRANSFORMATION FROM DDOCm TO L_O

$$L_o = DDOCm \bullet F \bullet 16/12$$

Where:

L_o = CH_4 generation potential, Gg CH_4

DDOCm = mass of decomposable DOC, Gg

F = fraction of CH_4 in generated landfill gas (volume fraction)

16/12 = molecular weight ratio CH_4/C (ratio)

Using DDOCma (DDOCm accumulated in the SWDS) from the spreadsheets, the above equation can be used to calculate the total CH_4 generation potential of the waste remaining in the SWDS.

FIRST ORDER DECAY BASICS

With a first order reaction, the amount of product is always proportional to the amount of reactive material. This means that the year in which the waste material was deposited in the SWDS is irrelevant to the amount of CH_4 generated each year. It is only the total mass of decomposing material currently in the site that matters.

This also means that when we know the amount of decomposing material in the SWDS at the start of the year, every year can be regarded as year number 1 in the estimation method, and the basic first order calculations can be done by these two simple equations, with the decay reaction beginning on the 1st of January the year after deposition.

EQUATION 3.4
DDOCm ACCUMULATED IN THE SWDS AT THE END OF YEAR T

$$DDOCma_T = DDOCmd_T + \left(DDOCma_{T-1} \bullet\ e^{-k}\right)$$

EQUATION 3.5
DDOCm DECOMPOSED AT THE END OF YEAR T

$$DDOCm\ decomp_T = DDOCma_{T-1} \bullet \left(1 - e^{-k}\right)$$

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[2] In the *2006 Guidelines* L_o (Gg CH_4 generated) is estimated from the amount of decomposable DOC in the SWDS. The equation in *GPG2000* is different as L_o is estimated as Gg CH_4 per Gg waste disposed, and the emissions are obtained by multiplying with the mass disposed.

Where:

T = inventory year

$DDOCma_T$ = DDOCm accumulated in the SWDS at the end of year *T*, Gg

$DDOCma_{T-1}$ = DDOCm accumulated in the SWDS at the end of year (*T*-1), Gg

$DDOCmd_T$ = DDOCm deposited into the SWDS in year *T*, Gg

DDOCm $decomp_T$ = DDOCm decomposed in the SWDS in year *T*, Gg

k = reaction constant, $k = \ln(2)/t_{1/2}$ (y^{-1})

$t_{1/2}$ = half-life time (y)

The method can be adjusted for reaction start dates earlier than 1st of January in the year after deposition. Equations and explanations can be found in Annex 3A.1.

CH_4 generated from decomposable DDOCm

The amount of CH_4 formed from decomposable material is found by multiplying the CH_4 fraction in generated landfill gas and the CH_4 /C molecular weight ratio.

EQUATION 3.6

CH_4 GENERATED FROM DECAYED DDOCm

$$CH_4\ generated_T = DDOCm\ decomp_T \bullet F \bullet 16/12$$

Where:

CH_4 $generated_T$ = amount of CH_4 generated from decomposable material

DDOCm $decomp_T$ = DDOCm decomposed in year *T*, Gg

F = fraction of CH_4, by volume, in generated landfill gas (fraction)

16/12 = molecular weight ratio CH_4/C (ratio)

Further background details on the FOD, and an explanation of differences with the approaches in previous versions of the guidance (IPCC, 1997; IPCC, 2000), are given in Annex 3A.1.

SIMPLE FOD SPREADSHEET MODEL

The simple FOD spreadsheet model (*IPCC Waste Model*) has been developed on the basis of Equations 3.4 and 3.5 shown above. The spreadsheet keeps a running total of the amount of decomposable DOC in the disposal site, taking account of the amount deposited each year and the amount remaining from previous years. This is used to calculate the amount of DOC decomposing to CH_4 and CO_2 each year.

The spreadsheet also allows users to define a time delay between deposition of the waste and the start of CH_4 generation. This represents the time taken for substantial CH_4 to be generated from the disposed waste (see Section 3.2.3 and Annex 3A.1).

The model then calculates the amount of CH_4 generated from the DDOCm, and subtracts the CH_4 recovered and CH_4 oxidised in the cover material (see Annex 3A.1 for equations) to give the amount of CH_4 emitted.

The *IPCC Waste Model* provides two options for the estimation of the emissions from MSW, that can be chosen depending on the available activity data. The first option is a multi-phase model based on **waste composition data**. The amounts of each type of degradable waste material (food, garden and park waste[3], paper and cardboard, wood, textiles, etc.) in MSW are entered separately. The second option is single-phase model based on **bulk waste** (MSW). Emissions from industrial waste and sludge are estimated in a similar way as for bulk MSW. Countries that choose to use the spreadsheet model may use either the waste composition or the bulk waste option, depending on the level of data available. When waste composition is relatively stable, both options give similar results. However when rapid changes in waste composition occur, options might give different

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[3] 'garden waste' may also be called 'yard waste' in US English.

outputs. For example, changes in waste management, such as bans to dispose food waste or degradable organic materials, can result in rapid changes in the composition of waste disposed in SWDS.

Both options can be used for estimating the carbon in harvested wood products (HWP) that is long-term stored in SWDS (see Volume 4, Chapter 12, Harvested Wood Products). If no national data are available on bulk waste, it is *good practice* to use the waste composition option in the spreadsheets, using the provided IPCC default data for waste composition.

In the spreadsheet model, separate values for DOC and the decay half-life may be entered for each waste category and in the waste composition option also for each waste type/material. The decay half-life can also be assumed to be the same for all waste categories and/or waste types. The first approach assumes that decomposition of different waste types/materials in a SWDS is completely independent of each other; the second approach assumes that decomposition of all types of waste is completely dependent on each other. At the time of writing these *Guidelines*, no evidence exists that one approach is better than the other (see Section 3.2.3, Half-life).

The spreadsheet calculates the amount of CH_4 generated from each waste component on a different worksheet. The methane correction factor (MCF – see Section 3.2.3) is entered as a weighted average for all disposal sites in the country. MCF may vary by time to take account of changes in waste management practices (such as a move towards more managed SWDS or deeper sites). Finally, the amount of CH_4 generated from each waste category and type/material is summed, and the amounts of CH_4 recovered and oxidised in the cover material are subtracted (if applicable), to give an estimate of total CH_4 emissions. For the bulk waste option, DOC can be a weighted average for MSW.

The spreadsheet model is most useful to Tier 1 methods, but can be adapted for use with all tiers. For Tier 1 the spreadsheets can estimate the activity data from population data and disposal data per capita (for MSW) and GDP (industrial waste), see Section 3.2.2 for additional guidance. When Tier 2 and 3 approaches are used, countries can extend the spreadsheet model to meet their own demands, or create their own models. The spreadsheet model can be extended with more sheets to calculate the CH_4 emissions if needed. MCF, OX and DOC for bulk waste can be made to vary over time. The same can easily be done to other parameters like DOC_f. New half-lives will require new CH_4 calculating sheets. Countries with good data on industrial waste can add new CH_4 calculating sheets and calculate the CH_4 emissions separately for different types of industrial waste. When the spreadsheet model is modified or countries-specific models are used, key assumptions and parameters should be transparently documented. Details on how to use the spreadsheet model can be found in the Instructions spreadsheet.

The model can be copied from the *2006 Guidelines* CDROM or downloaded from the IPCC NGGIP website < http://www.ipcc-nggip.iges.or.jp/ >.

Modelling different geographical or climate regions

It is possible to estimate CH_4 generation in different geographical regions of the country. For example, if the country contains a hot and wet region and a hot and dry region, the decay rates will be different in each region.

Dealing with different waste categories

Some users may find that their national waste statistics do not match the categories used in the model (food, garden and park waste, paper and cardboard, textiles and others as well as industrial waste). Where this is the case, the spreadsheet model will need to be modified to correspond to categorisation used by the country, or country-specific waste types will need to be re-classified into the IPCC categories. For example, clothes, curtain, and rugs are included in textiles, kitchen waste is similar to food waste, and straw and bamboo are similar to wood. The national statistics may contain a category called street sweepings. The user should estimate the composition of this waste. For example, it may be 50 percent inert material, 10 percent food, 30 percent paper and 10 percent garden and park waste. The street sweepings category can then be divided into these IPCC categories and added on to the waste already in these categories. In a similar manner, furniture can be divided into wood, plastic or metal waste, and electronics to metal, plastic and glass waste. This can all be done in a separate worksheet set up by the inventory compiler.

Adjusting waste composition at generation to waste composition at SWDS

The user should establish whether national waste composition statistics refer to the composition of waste generated or waste received at SWDS. The default waste composition statistics presented here are the composition of waste generated, not waste sent to SWDS. The composition should therefore be adjusted if necessary to take account of the impact of recycling or composting activities on the composition of the waste sent to SWDS. This could be best done in a separate spreadsheet set up by the inventory compiler, to estimate the amounts of each waste material generated, then subtract estimates of the amount of each waste material recycled, incinerated or composted, and work out the new composition of the residual waste sent to SWDS.

Open burning of waste at SWDS

Open burning at SWDS is common in many developing countries. The amount of waste (and DDOCm) available for decay at SWDS should be adjusted to the amount burned. Chapter 5 provides methods how to estimate the amount of waste burned. The estimation of emissions from SWDS should be consistent with estimates for open burning of waste at the disposal sites.

3.2.2 Choice of activity data

Activity data consist of the waste generation for bulk waste or by waste component and the fraction of waste disposed to SWDS. Waste generation is the product of the per capita waste generation rate (tonnes/capita/yr) for each component and population (capita). Chapter 2 gives guidance on the collection of data on waste generation and waste composition as well as waste management practices. Regional default values for MSW can be found in Table 2.1 for the generation rate and the fraction disposed in SWDS, and Table 2.3 for the waste composition. For industrial waste default data can be found in Table 2.2. To achieve accurate emission estimates in national inventories it is usually necessary to include data on solid waste disposal (amount, composition) for 3 to 5 half-lives (see Section 3.2.3) of the waste deposited at the SWDS, and specifications of different half-lives for different components of the waste stream or for bulk waste by SWDS type (IPCC, 2000). Changes in waste management practices (e.g., site covering/capping, leachate drainage improvement, compacting, and prohibition of hazardous waste disposal together with MSW) should also be taken into account when compiling historical data.

The FOD methods require data on solid waste disposal (amounts and composition) that are collected by default for 50 years. Countries that do not have historical statistical data, or equivalent data on solid waste disposal that go back for the whole period of 50 years or more will need to estimate these data using surrogates (extrapolation with population, economic or other drivers). The choice of the method will depend on the availability of data in the country.

For countries using default data on MSW disposal on land, or for countries whose own data do not cover the past 50 years, the missing historical data can be estimated to be proportional to urban population[4] (or total population when historical data on urban population are not available, or in cases where waste collection covers the whole population). For countries having national data on MSW generation, management practices and composition over a period of years (Tier 2 FOD), analyses on the drivers for solid waste disposal are encouraged. The historical data could be proportional to economic indicators, or combinations of population and economic indicators. Trend extrapolation could also produce good results. Waste management policies to reduce waste generation and to promote alternatives to solid waste disposal should be taken into account in the analyses. Data on industrial production (amount or value of production, preferably by industry type, depending on availability of data) are recommended as surrogate for the estimation of disposal of industrial waste (Tier 2). When production data are not available, historical disposal of industrial waste can be estimated proportional to GDP or other economic indicators. GDP is used as the driver in the Tier 1 method.

Historical data on urban population (or total population), GDP (or other economic indicators) and statistics in industrial production can be obtained from national statistics. International databases can help when national data are not available, for example:

- Population data (1950 onwards with five-year intervals) can be found in UN Statistics (see http://esa.un.org/unpp/).
- GDP data (1970 onwards, annual data at current prices in national currency) can be found in UN Statistics (see http://unstats.un.org/unsd/snaama/selectionbasicFast.asp).

For those years data are not available interpolation or extrapolation can be used.

Alternative methods have been put forward in literature and can be used when they can be shown to give better estimates than the above-mentioned default methods.

The choice of method and surrogate, and the reasoning behind the choice, should be documented transparently in the inventory report. The use of surrogate methods, interpolation and extrapolation as means to derive missing data is described in more detail in Chapter 6, Time Series Consistency, in Volume 1.

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[4] The choice between urban population and total population should be guided by the coverage of waste collection. When data on coverage of waste collection is not available, the recommendation is to use urban population as the driver.

3.2.3 Choice of emission factors and parameters

DEGRADABLE ORGANIC CARBON (DOC)

Degradable organic carbon (DOC) is the organic carbon in waste that is accessible to biochemical decomposition, and should be expressed as Gg C per Gg waste. The DOC in bulk waste is estimated based on the composition of waste and can be calculated from a weighted average of the degradable carbon content of various components (waste types/material) of the waste stream. The following equation estimates DOC using default carbon content values:

EQUATION 3.7
ESTIMATES DOC USING DEFAULT CARBON CONTENT VALUES

$$DOC = \sum_{i} \left(DOC_i \bullet W_i \right)$$

Where:

DOC = fraction of degradable organic carbon in bulk waste, Gg C/Gg waste

DOC_i = fraction of degradable organic carbon in waste type *i*

e.g., the default value for paper is 0.4 (wet weight basis)

W_i = fraction of waste type *i* by waste category

e.g., the default value for paper in MSW in Eastern Asia is 0.188 (wet weight basis)

The default DOC values for these fractions for MSW can be found in Table 2.4 and for industrial waste by industry in Table 2.5 in Chapter 2 of this Volume. A similar approach can be used to estimate the DOC content in total waste disposed in the country. In the spreadsheet model, the estimation of the DOC in MSW is needed only for the *bulk waste option,* and is the average DOC for the MSW disposed in the SWDS, including inert materials.

The inert part of the waste (glass, plastics, metals and other non-degradable waste, see defaults in Table 2.3 in Chapter 2.) is important when estimating the total amount of DOC in MSW. Therefore it is advised not to use IPCC default waste composition data together with country-specific MSW disposal data, without checking that the inert part is close to the inert part in the IPCC default data.

The use of country-specific values is encouraged if data are available. Country-specific values can be obtained by performing waste generation studies, sampling at SWDS combined with analysis of the degradable carbon content within the country. If national values are used, survey data and sampling results should be reported (see also Section 3.2.2 for activity data and Section 3.8 for reporting).

FRACTION OF DEGRADABLE ORGANIC CARBON WHICH DECOMPOSES (DOC_f)

Fraction of degradable organic carbon which decomposes (DOC_f) is an estimate of the fraction of carbon that is ultimately degraded and released from SWDS, and reflects the fact that some degradable organic carbon does not degrade, or degrades very slowly, under anaerobic conditions in the SWDS . The recommended default value for DOC_f is 0.5 (under the assumption that the SWDS environment is anaerobic and the DOC values include lignin, see Table 2.4 in Chapter 2 for default DOC values) (Oonk and Boom, 1995; Bogner and Matthews, 2003). DOC_f value is dependent on many factors like temperature, moisture, pH, composition of waste, etc. National values for DOC_f or values from similar countries can be used for DOC_f, but they should be based on well-documented research.

The amount of DOC leached from the SWDS is not considered in the estimation of DOC_f. Generally the amounts of DOC lost with the leachate are less than 1 percent and can be neglected in the calculations[5].

Higher tier methodologies (Tier 2 or 3) can also use separate DOC_f values defined for specific waste types. There is some literature giving information about anaerobic degradability (DOC_f) for material types (Barlaz,

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[5] In countries with high precipitation rates the amount of DOC lost through leaching may be higher. In Japan, where the precipitation is high, SWDS with high penetration rate, have been found to leach significant amounts of DOC (sometimes more than 10 percent of the carbon in the SWDS) (Matsufuji *et al*., 1996).

2004; Micales & Skog, 1997; US EPA, 2002; Gardner *et al*., 2002). The reported degradabilities especially for wood, vary over a wide range and is yet quite inconclusive. They may also vary with tree species. Separate DOC_f values for specific waste types imply the assumption that degradation of different types of waste is independent of each other. As discussed further, below under Half-Life, scientific knowledge at the moment of writing these *Guidelines* is not yet conclusive on this aspect.

Hence the use of waste type specific values for DOC_f can introduce additional uncertainty to the estimates in cases where the data on waste composition are based on default values, modelling or estimates based on expert judgement. Therefore, it is *good practice* to use DOC_f values specific to waste types only when waste composition data are based on representative sampling and analyses.

METHANE CORRECTION FACTOR (MCF)[6]

Waste disposal practices vary in the control, placement of waste and management of the site. The CH_4 correction factor (MCF) accounts for the fact that unmanaged SWDS produce less CH_4 from a given amount of waste than anaerobic managed SWDS. In unmanaged SWDS, a larger fraction of waste decomposes aerobically in the top layer. In unmanaged SWDS with deep disposal and/or with high water table, the fraction of waste that degrades aerobically should be smaller than in shallow SWDS. Semi-aerobic managed SWDS are managed passively to introduce air to the waste layer to create a semi-aerobic environment within the SWDS. The MCF in relation to solid waste management is specific to that area and should be interpreted as the waste management correction factor that reflects the management aspect it encompasses.

An MCF is assigned to each of four categories, as shown in Table 3.1. A default value is provided for countries where the quantity of waste disposed to each SWDS is not known. A country's classification of its waste sites into managed or unmanaged may change over a number of years as national waste management policies are implemented.

The Fraction of Solid Waste Disposed to Solid Waste Disposal Sites (SW_F) and MCF reflect the way waste is managed and the effect of site structure and management practices on CH_4 generation. The methodology requires countries to provide data or estimates of the quantity of waste that is disposed of to each of four categories of solid waste disposal sites (Table 3.1). Only if countries cannot categorise their SWDS into four categories of managed and unmanaged SWDS, the MCF for 'uncategorised SWDS' can be used.

TABLE 3.1
SWDS CLASSIFICATION AND METHANE CORRECTION FACTORS (MCF)

Type of Site	Methane Correction Factor (MCF) Default Values
Managed – anaerobic [1]	1.0
Managed – semi-aerobic [2]	0.5
Unmanaged [3] – deep (>5 m waste) and /or high water table	0.8
Unmanaged [4] – shallow (<5 m waste)	0.4
Uncategorised SWDS [5]	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] **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; (iii) regulating pondage; and (iv) gas ventilation system.

[3] **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.

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

[5] **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)

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[6] The term methane correction factor (MCF) in this context should not be confused with the methane conversion factor (MCF) referred to in the Agriculture, Forestry, and Other Land Use Sector for livestock manure management emissions.

FRACTION OF CH_4 IN GENERATED LANDFILL GAS (F)

Most waste in SWDS generates a gas with approximately 50 percent CH_4. Only material including substantial amounts of fat or oil can generate gas with substantially more than 50 percent CH_4. The use of the IPCC default value for the fraction of CH_4 in landfill gas (0.5) is therefore encouraged.

The fraction of CH_4 in generated landfill gas should not be confused with measured CH_4 in gas emitted from the SWDS. In the SWDS, CO_2 is absorbed in seepage water, and the neutral condition of the SWDS transforms much of the absorbed CO_2 to bicarbonate. Therefore, it is *good practice* to adjust for the CO_2 absorption in seepage water, if the fraction of CH_4 in landfill gas is based on measurements of CH_4 concentrations measured in landfill gas emitted from the SWDS (Bergman, 1995; Kämpfer and Weissenfels, 2001; IPCC, 1997).

OXIDATION FACTOR (OX)

The oxidation factor (OX) reflects the amount of CH_4 from SWDS that is oxidised in the soil or other material covering the waste.

CH_4 oxidation is by methanotrophic micro-organisms in cover soils and can range from negligible to 100 percent of internally produced CH_4. The thickness, physical properties and moisture content of cover soils directly affect CH_4 oxidation (Bogner and Matthews, 2003).

Studies show that sanitary, well-managed SWDS tend to have higher oxidation rates than unmanaged dump sites. The oxidation factor at sites covered with thick and well-aerated material may differ significantly from sites with no cover or where large amounts of CH_4 can escape through cracks/fissures in the cover.

Field and laboratory CH_4 and CO_2 emission concentrations and flux measurements that determine CH_4 oxidation from uniform and homogeneous soil layers should not be used directly to determine the oxidation factor, since in reality, only a fraction of the CH_4 generated will diffuse through such a homogeneous layer. Another fraction will escape through cracks/fissures or via lateral diffusion without being oxidised. Therefore, unless the spatial extent of measurements is wide enough and cracks/fissures are explicitly included, results from field and laboratory studies may lead to over-estimation of oxidation in SWDS cover soils.

The default value for oxidation factor is zero. See Table 3.2. The use of the oxidation value of 0.1 is justified for covered, well-managed SWDS to estimate both diffusion through the cap and escape by cracks/fissures. The use of an oxidation value higher than 0.1, should be clearly documented, referenced, and supported by data relevant to national circumstances. It is important to remember that any CH_4 that is recovered must be subtracted from the amount generated before applying an oxidation factor.

TABLE 3.2
OXIDATION FACTOR (OX) FOR SWDS

Type of Site	Oxidation Factor (OX) Default Values
Managed [1], unmanaged and uncategorised SWDS	0
Managed covered with CH_4 oxidising material [2]	0.1

[1] Managed but not covered with aerated material

[2] Examples: soil, compost

HALF-LIFE

The half-life value, $t_{1/2}$ is the time taken for the DOCm in waste to decay to half its initial mass. In the FOD model and in the equations in this Volume, the reaction constant k is used. The relationship between k and $t_{1/2}$ is: $k = \ln(2)/t_{1/2}$. The half-life is affected by a wide variety of factors related with the composition of the waste, climatic conditions at the site where the SWDS is located, characteristics of the SWDS, waste disposal practices and others (Pelt *et al.*, 1998; Environment Canada, 2003).

The half-life value applicable to any single SWDS is determined by a large number of factors associated with the composition of the waste and the conditions at the site. Recent studies have provided more data on half-lives (experimental or by means of models), but the results obtained are based on the characteristics of developed countries under temperate conditions. Few available results reflect the characteristics of developing countries and tropical conditions. Measurements from SWDS in Argentina, New Zealand, the United States, the United Kingdom and the Netherlands support values for $t_{1/2}$ in the range of approximately 3 to 35 years (Oonk and Boom, 1995; USEPA, 2005; Scharff *et al.*, 2003; Canada, 2004; and Argentina, 2004).

The most rapid rates ($k = 0.2$, or a half-life of about 3 years) are associated with high moisture conditions and rapidly degradable material such as food waste. The slower decay rates ($k = 0.02$, or a half-life of about 35 years) are associated with dry site conditions and slowly degradable waste such as wood or paper. A much longer half-life of 70 years or above could be justified for shallow dry SWDS in a temperate climate or for wood waste in a dry, temperate climate. A half-life of less than 3 years may be appropriate for managed SWDS in a wet, temperate climate or rapidly degrading waste in a wet, tropical climate. The inventory compiler is encouraged to establish country specific half-life values. Current knowledge and data limitations constrain the development of a default methodology for estimating half-lives from field-data at SWDS.

There are two alternative approaches to select the half-life (or k value) for the calculation: (a) calculate a weighted average for $t_{1/2}$ for mixed MSW (Jensen and Pipatti, 2002) or (b) divide the waste stream into categories of waste according to their degradation speed (Brown *et al.*, 1999). The first approach assumes degradation of different types of waste to be completely dependent on each other. So the decay of wood is enhanced due to the present of food waste, and the decay of food waste is slowed down due to the wood. The second approach assumes degradation of different types of waste is independent of each other. Wood degrades as wood, irrespective whether it is in an almost inert SWDS or in a SWDS that contains large amounts of more rapidly degrading wastes. In reality the truth will probably be somewhere in the middle. However there has been little research performed to identify the better one of both approaches (Oonk and Boom, 1995; Scharff *et al.*, 2003) and this research was not conclusive. Two options of the IPCC spreadsheet model apply either of above approaches to select the half-life as follows:

Bulk waste option**:** The bulk waste option requires alternative (a) above, and is suitable for countries without data or with limited data on waste composition, but with good information on bulk waste disposed at SWDS. Default values are estimated as a function of the climate zone.

Waste composition option**:** The waste composition option requires alternative (b) and is applicable for countries having data on waste composition. Specification of the half-life ($t_{1/2}$) of each component of the waste stream (IPCC, 2000) is required to achieve acceptably accurate results.

For both options default half-life values are estimated as a function of the climate zone. The main assumptions and considerations made are:

- Waste composition (especially the organic component) is one of the main factors influencing both the amount and the timing of CH_4 production.
- Moisture content of a SWDS is an essential element for anaerobic decomposition and CH_4 generation. A simplified method assumes that the moisture content of a SWDS is proportional to the mean annual precipitation (MAP) in the location of the SWDS (Pelt *et al.*, 1998; U.S. EPA, 1998; Environment Canada, 2003) or to the ratio of MAP and potential evapotranspiration (PET).
- The extent to which ambient air temperatures influence the temperature of the SWDS and gas generation rates depends mainly on the degree of waste management and the depth of SWDS.
- Wastes in shallow open dumps generally decompose aerobically and produce little $CH_{4,}$ and the emissions decline in shorter time than the anaerobic conditions. Managed (and also deep unmanaged) SWDS creates anaerobic conditions.

Countries may develop specific half-life values (or k values) more appropriate for their circumstances and characteristics. It is *good practice* that countries which develop their own half-life values document the experimental procedures used to derive to them.

Default *k* values and the corresponding half-lives are provided below in Table 3.3 and in Table 3.4.

TABLE 3.3
RECOMMENDED DEFAULT METHANE GENERATION RATE (*k*) VALUES UNDER TIER 1

(Derived from *k* values obtained in experimental measurements, calculated by models, or used in greenhouse gas inventories and other studies)

Type of Waste		**Climate Zone***							
		Boreal and Temperate (MAT ≤ 20°C)				**Tropical[1] (MAT > 20°C)**			
		Dry (MAP/PET < 1)		**Wet (MAP/PET > 1)**		**Dry (MAP < 1000 mm)**		**Moist and Wet (MAP ≥ 1000 mm)**	
		Default	**Range[2]**	**Default**	**Range[2]**	**Default**	**Range[2]**	**Default**	**Range[2]**
Slowly degrading waste	**Paper/textiles waste**	0.04	0.03[3,5] – 0.05[3,4]	0.06	0.05 – 0.07[3,5]	0.045	0.04 – 0.06	0.07	0.06 – 0.085
	Wood/ straw waste	0.02	0.01[3,4] – 0.03[6,7]	0.03	0.02 – 0.04	0.025	0.02 – 0.04	0.035	0.03 – 0.05
Moderately degrading waste	**Other (non – food) organic putrescible/ Garden and park waste**	0.05	0.04 – 0.06	0.1	0.06 – 0.1[8]	0.065	0.05 – 0.08	0.17	0.15 – 0.2
Rapidly degrading waste	**Food waste/Sewage sludge**	0.06	0.05 – 0.08	0.185[4]	0.1[3,4] – 0.2[9]	0.085	0.07 – 0.1	0.4	0.17 – 0.7[10]
Bulk Waste		0.05	0.04 – 0.06	0.09	0.08[8] – 0.1	0.065	0.05 – 0.08	0.17	0.15[11] – 0.2

[1] The available information on the determination of k and half-lives in tropical conditions is quite limited. The values included in the table, for those conditions, are indicative and mostly have been derived from the assumptions described in the text and values obtained for temperate conditions.

[2] The range refers to the minimum and maximum data reported in literature or estimated by the authors of the chapter. It is included, basically, to describe the uncertainty associated with the default value.

[3] Oonk and Boom (1995).

[4] IPCC (2000).

[5] Brown *et a*l. (1999). A near value (16 yr) was used, for slow degradability, in the GasSim model verification (Attenborough *et al*., 2002).

[6] Environment Canada (2003).

[7] In this range are reported longer half-lives values (up to 231 years) that were not included in the table since are derived from extremely low *k* values used in sites with mean daily temperature < 0ºC (Levelton, 1991).

[8] Estimated from RIVM (2004).

[9] Value used for rapid degradability, in the GasSim model verification (Attenborough *et al*., 2002);

[10] Estimated from Jensen and Pipatti (2003).

[11] Considering t1/2 = 4 - 7 yr as characteristic values for most developing countries in a tropical climate. High moisture conditions and higly degradable waste.

*Adapted from: Chapter 3 in *GPG-LULUCF* (IPCC, 2003).

MAT – Mean annual temperature; MAP – Mean annual precipitation; PET – Potential evapotranspiration.

MAP/PET is the ratio of MAP to PET. The average annual MAT, MAP and PET during the time series should be selected to estimate emissions and indicated by the nearest representative meteorological station.

TABLE 3.4
RECOMMENDED DEFAULT HALF-LIFE ($t_{1/2}$) VALUES (YR) UNDER TIER 1

(Derived from *k* values obtained in experimental measurements, calculated by models, or used in greenhouse gas inventories and other studies)

Type of Waste		**Climate Zone***							
		Boreal and Temperate (MAT ≤ 20°C)				**Tropical[1] (MAT > 20°C)**			
		Dry (MAP/PET < 1)		**Wet (MAP/PET > 1)**		**Dry (MAP < 1000 mm)**		**Moist and Wet (MAP ≥ 1000 mm)**	
		Default	**Range[2]**	**Default**	**Range[2]**	**Default**	**Range[2]**	**Default**	**Range[2]**
Slowly degrading waste	**Paper/textiles waste**	17	14[3,5] – 23[3,4]	12	10 – 14[3,5]	15	12 – 17	10	8 – 12
	Wood/ straw waste	35	23[3,4] – 69[6,7]	23	17 – 35	28	17 – 35	20	14 – 23
Moderately degrading waste	**Other (non – food) organic putrescible/ Garden and park waste**	14	12 – 17	7	6 – 9[8]	11	9 – 14	4	3 – 5
Rapidly degrading waste	**Food waste/Sewage sludge**	12	9 – 14	4[4]	3[3,4] – 6[9]	8	6 – 10	2	1[10] – 4
Bulk Waste		14	12 – 17	7	6 – 9[8]	11	9 – 14	4	3 – 5[11]

[1] The available information on the determination of k and half-lives in tropical conditions is quite limited. The values included in the table, for those conditions, are indicative and mostly have been derived from the assumptions described in the text and values obtained for temperate conditions.

[2] The range refers to the minimum and maximum data reported in literature or estimated by the authors of the chapter. It is included, basically, to describe the uncertainty associated with the default value.

[3] Oonk and Boom (1995).

[4] IPCC (2000).

[5] Brown *et al*. (1999). A near value (16 yr) was used, for slow degradability, in the GasSim model verification (Attenborough *et al*., 2002).

[6] Environment Canada (2003).

[7] In this range are reported longer half-lives values (up to 231 years) that were not included in the table since are derived from extremely low *k* values used in sites with mean daily temperature < 0ºC (Levelton,1991).

[8] Estimated from RIVM (2004).

[9] Value used for rapid degradability, in the GasSim model verification (Attenborough *et al*., 2002).

[10] Estimated from Jensen and Pipatti (2003).

[11] Considering t1/2 = 4 - 7 yr as characteristic values for most developing countries in a tropical climate. High moisture conditions and higly degradable waste.

*Adapted from: Chapter 3 –*GPG-LULUCF* (IPCC, 2003).

MAT – Mean annual temperature; MAP – Mean annual precipitation; PET – Potential evapotranspiration.

MAP/PET is the ratio of MAP to PET. The average annual MAT, MAP and PET during the time series should be selected to estimate emissions and indicated by the nearest representative meteorological station.

METHANE RECOVERY (R)

CH_4 generated at SWDS can be recovered and combusted in a flare or energy device. The amount of CH_4 which is recovered is expressed as R in Equation 3.1. If the recovered gas is used for energy, then the resulting greenhouse gas emissions should be reported under the Energy Sector. Emissions from flaring are however not significant, as the CO_2 emissions are of biogenic origin and the CH_4 and N_2O emissions are very small, so *good practice* in the waste sector does not require their estimation. However, if it is wished to do so these emissions should be reported under the waste sector. A discussion of emissions from flares and more detailed information are given in Volume 2, Energy, Chapter 4.2. Emissions from flaring are not treated at Tier 1.

The default value for CH_4 recovery is zero. CH_4 recovery should be reported only when references documenting the amount of CH_4 recovery are available. Reporting based on metering of all gas recovered for energy and flaring, or reporting of gas recovery based on the monitoring of produced amount of electricity from the gas (considering the availability of load factors, heating value and corresponding heat rate, and other factors impacting the amount of gas used to produce the monitored amount of electricity) is consistent with *good practice*.

Estimating the amount of CH_4 recovered using more indirect methods should be done with great care, using substantiated assumptions. Indirect methods might be based on the number of SWDS in a country with CH_4 collection or the total capacity of utilisation equipment or flaring capacity sold.

When CH_4 recovery is estimated on the basis of the number of SWDS with landfill gas recovery a default estimate of recovery efficiency would be 20 percent. This is suggested due to the many uncertainties in using this methodology. There have been some measurements of efficiencies at gas recovery projects, and reported efficiencies have been between 10 and 85 percent Oonk and Boom (1995) measured efficiencies at closed, unlined SWDS to be in between 10 and 80 percent, the average over 11 SWDS being 37 percent. More recently Scharff *et al*. (2003) measured efficiencies at four SWDS to be 9 percent, 50 percent, 55 percent and 33 percent. Spokas *et al*. (2006) and Diot *et al*. (2001) recently measured efficiencies above 90 percent. In general, high recovery efficiencies can be related to closed SWDS, with reduced gas fluxes, well-designed and operated recovery and thicker and less permeable covers. Low efficiencies can be related to SWDS with large parts still being in exploitation and with e.g., temporary sandy covers.

Country-specific values may be used but significant research would need to be done to understand the impact on recovery of following parameters: cover type, percentage of SWDS covered by recovery project, presence of a liner, open or closed status, and other factors.

When the amount of CH_4 recovered is based on the total capacity of utilisation equipment or flares sold, an effort should be made in order to identify what part of this equipment is still operational. A conservative estimate of amount of CH_4 generated could be based on an inventory of the minimum capacities of the operational utilisation equipment and flares. Another conservative approach is to estimate total recovery as 35 percent of the installed capacities. Based on Dutch and US studies (Oonk, 1993; Scheehle, 2006), recovered amounts varied from 35 to 70 percent of capacity rates. The reasons for the range included (i) running hours from 95 percent down to 80 percent, due to maintenance or technical problems; (ii) overestimated gas production and as result oversized equipment; (iii) back-up flares being largely inactive. The higher rates took these considerations already into account when estimating capacity. If a country uses this method for flaring, care must be taken to ensure that the flare is not a back-up flare for a gas-to-energy project. Flares should be matched to SWDS wherever possible to ensure that double counting does not occur.

In all cases, the recovered amounts should be reported as CH_4, not as landfill gas, as landfill gas contains only a fraction of CH_4. The basis for the reporting should be clearly documented. When reporting is based on the number of SWDS with landfill gas recovery or the total capacity of utilisation equipment, it is essential that all assumptions used in the estimation of the recovery are clearly described and justified with country-specific data and references.

DELAY TIME

In most solid waste disposal sites, waste is deposited continuously throughout the year, usually on a daily basis. However, there is evidence that production of CH_4 does not begin immediately after deposition of the waste.

At first, decomposition is aerobic, which may last for some weeks, until all readily available oxygen has been used up. This is followed by the acidification stage, with production of hydrogen. The acidification stage is often said to last for several months. After which there is a transition period from acidic to neutral conditions, when CH_4 production starts.

The period between deposition of the waste and full production of CH_4 is chemically complex and involves successive microbial reactions. Time estimates for the delay time are uncertain, and will probably vary with waste composition and climatic conditions. Estimates of up to one year have been given in the literature (Gregory *et al*., 2003; Bergman, 1995; Kämpfer and Weissenfels, 2001; Barlaz, 2004). The IPCC provides a default value of six months for the time delay (IPCC, 1997). This is equivalent to a reaction start time of 1st of January in the year after deposition, when the average residence time of waste in the SWDS has been six months. However, the uncertainty of this assumption is at least 2 months.

The IPCC Waste Model allows the user to change the default delay of six months to a different value. It is *good practice* to choose a delay time of between zero and six months. Values outside this range should be supported by evidence.

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

The FOD model and other methods for estimating CH_4 generation at SWDS are constructed using scientific knowledge as well as assumptions on microbial metabolism under anaerobic conditions in the SWDS. As with all models, validation that includes some form of direct measurements to compare model predictions to actual measurements increases the user's confidence in the model and can be used to refine and improve the model predictions. These measurements can also be used to validate a model by comparing model predictions to CH_4 generation rates developed from measurements and to document the choice of country-specific values for parameters used in the model in preparing national inventories.

Measurements can be measured amounts of gas recovered in the gas collection system (in combination with an estimate of the recovery efficiency), measured amounts of diffuse CH_4 emissions to air and combinations of both.

Several studies have used measurement data from gas collection systems to develop estimates of the parameters needed for the FOD model (such as the decay rate constant and CH_4 generation potential) for specific SWDS, for classes of SWDS in specific regions, and for application to SWDS on a national basis (Oonk and Boom, 1995; Huitric *et al*., 1997; SWANA, 1998; SCS Engineers, 2003; U.S. EPA, 1998; U.S. EPA, 2005). The technique uses statistical procedures to develop best fit values for the model parameters, such as a nonlinear regression that evaluates model parameters in an iterative fashion to find the best estimate for the model parameters, based on the smallest sum of squared errors. With sufficient site-specific detail and an adequate large database of SWDS, the statistical analysis can identify the effects of variations in waste composition, geographical location, rainfall, and other factors on appropriate values for the model parameters. For example, several studies have found that the decay rate constant increases with precipitation (U.S. EPA, 2005).

The use of direct measurements of extracted amounts of gas to estimate FOD model parameters is one option for the *good practice* of developing country-specific values. This technique was used to develop some of the default values for half-life presented in Table 3.4. It is applicable for those countries with accurate measurement data from landfill gas collection systems for a representative set of SWDS with well known amounts, composition and age-distribution of waste deposited. If site-specific CH_4 collection data are used to estimate parameters for the FOD model for the national inventory, it is *good practice* to ensure that the SWDS used in the analysis are representative of all SWDS in the country in terms of the major factors that affect the values of the parameters and CH_4 emissions. Additional details on this technique are provided in Box 3.1.

BOX 3.1
DIRECT MEASUREMENTS FROM GAS COLLECTION SYSTEMS TO ESTIMATE FOD MODEL PARAMETERS

The key element in developing estimates of the parameters for the FOD model is a representative database of landfills that has the following characteristics:

(i) Contain types of wastes representative of landfills nationwide,

(ii) Include a range of sizes, waste age, and geographical regions (especially if the effect of precipitation is to be evaluated),

(iii) Have site-specific measurements of the landfill gas (LFG) collection rate and percent CH_4 that include seasonal variations over time (covering at least one year and preferably longer),

(iv) Have site-specific measurements of annual waste acceptance rates or total waste in place and year the landfill opened (i.e., the waste in place or average annual acceptance rate for the area of the landfill under the influence of the collection system,

(v) Include site-specific estimates of percent recovery (based on design and operational characteristics or other information), and

(vi) Include annual average precipitation (if this effect is to be evaluated).

Accuracy of direct measurements of LFG flow rate, percent CH_4, and annual waste disposal rates can be better than ±10 percent. The most significant source of error in using the direct measurement of CH_4 collection rates to estimate CH_4 generation rates is the determination of LFG collection efficiency. However, this error can be reduced and controlled if collection rate data are used only for landfills that are known or can be shown to have efficient and well-maintained collection systems and cover materials.

BOX 3.1 (CONTINUED)

The use of a collection efficiency will need to be researched and justified in order to be used with confidence. Several factors must be considered, such as the type of final cover, surface monitoring conducted on a regular basis showing low levels or no detectable CH_4, and a program of corrective action if CH_4 is detected (e.g., performing maintenance to improve the integrity of the cover or increasing the vacuum of collection wells). The estimate of collection efficiency can be based on site-specific considerations and adjusted to the upper or lower end of the range after considering these factors. The overall error and effect on the final results would tend to be lower when averaged over a large database of landfills because the errors would tend to cancel when using an unbiased midrange estimate.

Although surface measurements can be used to detect CH_4 as noted above, the use of surface measurements at the landfill to directly estimate collection efficiency is only recommended when the limitations of methods are fully taken into account, as discussed in more detail in the following section that describe the difficulties and inaccuracies of such measurements. Effects to take into account when measuring collection efficiencies are (i) CH_4 oxidation, that reduces the ratios of amount of CH_4 emitted and (ii) solution of CO_2 in the water phase in the waste or in the top-layer, when comparing the ratio of CH_4 and CO_2 emissions and CH_4 and CO_2 recovery.

Once a representative database has been established, measurements and collection efficiencies are estimated, the measurement data can be analyzed to determine country or region specific parameters. If a country has good waste composition data by landfill, this information could be used together with measurements and modelling to deduce parameters such as DDOC. For a country with less reliable waste composition data, parameters may have to be estimated at a broader level, considering L_o and k instead of more waste type specific parameters. It is not recommended for a country to directly estimate national emissions from measurements. Using measurements to deduce national level parameters based on the characteristics of the landfills analysed is the preferred approach to incorporating measurement data from collection systems.

Direct measurements of CH_4 emissions at the SWDS surface (rather than measuring CH_4 collection or generation) at a specific SWDS can in principle be of similar value for validating the FOD model parameters and developing national inventory estimates. In practice there are however limitations for several reasons:

(i) Monitoring and measuring CH_4 emissions at the SWDS's surface is a demanding task, and there are no generally agreed or standardised methods available for routine or long-term monitoring because the emissions come from a large area and vary throughout the year.

(ii) There are very few representative data available from direct measurements of CH_4 emissions for individual SWDS, much less to give good estimates for national emission inventories. It is therefore at the moment considered *good practice* to use emission estimates from individual sites based on monitoring and measurements only if the representativeness of the monitoring can be justified. If site-specific emissions data are used to estimate national emissions, it is *good practice* to group all SWDS in the country according to their characteristics and to base the national estimate on representative emission behaviour in each group.

Atmospheric emissions measurement techniques, their difficulties, and other considerations are discussed in more detail in Box 3.2.

BOX 3.2
DIRECT MEASUREMENTS OF METHANE EMISSIONS FROM THE SWDS SURFACE

Surface landfill gas (LFG) emissions are highly variable both spatially and temporally. Emissions vary on a daily basis as a result of changes in air-pressure and due to rainfall which affects the permeability of the top-layer. On top of that there is a seasonal variation in emissions as a result of reduced oxidation in winter. Additionally, emissions vary over the sections of the SWDS, due to differences in waste amounts, age and composition. Due to the high horizontal permeability, compared to vertical permeability, the slopes of a SWDS generally have higher emissions than the upper surface. On a more local scale, emissions are highly variable due to regions of reduced permeability in the subsurface and due to cracks in the surface. As a result, emissions at locations a few metres away from each other can vary over a factor 1000.

Measurement of diffuse CH_4 emissions in this context should give an indication of annual average emissions from the entire SWDS. So, temporal and seasonal fluctuation of gas emission (Maurice and Lagerkvist, 1997; Park and Shin, 2001) should be considered as part of the evaluation of site-specific data. The data collection period should be sufficient to cover temporal variation at the site. Seasonal variation might be comparably easily taken into consideration.

When performing measurements of diffuse emissions, one should realise that one measures the flux after oxidation, which can be a significant part of the percent of CH_4 generated that is not recovered.

Several techniques for direct measurement at the surface and/or below and above-ground have been proposed. The most important techniques are:

(i) Static or forced flux chamber measurements,

(ii) Mass balance methods,

(iii) Micrometeorological measurements,

(iv) Plume measurements.

The *flux chamber method* has been widely applied to measure the CH_4 flux on the SWDS surface (e.g., Park and Shin, 2001; Mosher *et al*., 1999; UK Environment Agency, 2004). A drawback of this method is the necessity of large number of measuring points in order to obtain reliable estimates of total emissions, which makes the method very labour intensive and thus expensive. There are a number of ways to improve the accuracy or reduce the number of measurements required, e.g., to expand the estimates from a smaller section to the whole SWDS through geostatistical methods (Börjesson *et al*., 2000; Spokas *et al*., 2003) or to identify the main emitting zones by observing cracks, stressed vegetation, interfaces between capped zone, edges and slope condition, etc. (UK Environment Agency, 2004), or to use portable gas-meter, olfaction or surface temperature as a first indicator (Yamada *et al*, 2005).

In the *mass-balance method* emissions are obtained by measuring the flux through an imaginary vertical plane on the SWDS by interpreting of wind velocity and the CH_4 concentrations at different heights over the SWDS surface. This plane can be both one-dimensional (Oonk and Boom, 1995; Scharff *et al*., 2003) or two-dimensional. The advantage of this method is that it is easily automated and can measure emissions from a large surface (in many case the whole SWDS) for longer period of times (weeks to months). Another advantage is that the both CH_4 and CO_2 emissions can be obtained which gives information on CH_4 oxidation and collection efficiencies. The disadvantage of the method is its limited scope (250 m) which makes it hard to measure emissions from the largest SWDS.

In the *micrometeorological method* emissions are measured as a flux through an imaginary horizontal plane and recalculated as vertical fluxes. CH_4 concentrations above the SWDS are used in combination with information on air transport and mixing at the scale of a few m^3 (hence micrometeorology, Fowler and Duyzer, 1989). Laurila *et al*. (2005) propose the micrometeorological Eddy-covariance method as suitable for estimation of landfill gas emission, with advantages of easy automation which enables measurements over longer periods of time and the simultaneous monitoring of CH_4 and CO_2 emissions. The drawback of the method seems to be its limited footprint (about 25 m), as a result of which it might not produce representative emissions from the entire SWDS.

BOX 3.2 (CONTINUED)

Plume measurements are designed to measure the emissions from an entire SWDS by measuring the difference in CH_4 flux in a transect screen downwind and upwind from the SWDS. Emissions might be assessed comparing increase in CH_4 concentrations with tracer concentrations (e.g., from a known amount of N_2O or SF_6 released on the SWDS) or using a dispersion model. Variations of this method are used around the world by Czepiel *et al.* (1996), Savanne *et al.* (1997), Galle *et al.*, (1999) and Hensen and Scharff (2001). The advantage of the method is its accuracy and its possibility to measure emissions from the entire SWDS, this being very effective to cope with spatial variation. However, the method is very expensive and normally only applied for one or a few specific days. Therefore the result seems to be not representative for the annual average emissions from the site (Scharff *et al.*, 2003). For this reason Scharff *et al.* (2003) developed a stationary version of the mobile plume measurement (SPM) for plume measurements around a SWDS for longer times.

At this moment (2006), there is no scientific agreement on what methodology is preferred to obtain annual average emissions from an entire SWDS. Intercomparisons of methods are performed by Savanne *et al.* (1995) and Scharff *et al.* (2003) and the conclusion is more or less that no single method can deal with spatial and temporal variability and is yet affordable. According to Scharff *et al.* (2003) the mass-balance method and the static plume method are the best candidates for further development and validation. However there has been little scientific discussion on this conclusion at the moment of writing of the *Guidelines*.

3.4 CARBON STORED IN SWDS

Some carbon will be stored over long time periods in SWDS. Wood and paper decay very slowly and accumulate in the SWDS (long-term storage). Carbon fractions in other waste types decay over varying time periods (see Half-life under Section 3.2.3.)

The amount of carbon stored in the SWDS can be estimated using the FOD model (see Annex 3A.1). The long-term storage of carbon in paper and cardboard, wood, garden and park waste is of special interest as the changes in carbon stock in waste originating from harvested wood products which is reported in the AFOLU volume (see Chapter 12, Harvested Wood Products). The FOD model of this Volume provides these estimates as a by-product. The *waste composition* option calculates the long-term stored carbon from wood, paper and cardboard, and garden and park waste in the SWDS, as this is simply the portion of the DOC that is not lost through decay (the equations to estimate the amount are given in Annex 3A.1). When using *the bulk waste* option it is necessary to estimate the appropriate portion of DOC originating from harvested wood products in the total DOC of the waste, before finding the amounts of long-term stored carbon. When country-specific estimates are not available, the IPCC default fractions of paper and cardboard, wood, and garden and park waste can be used.

The long-term stored carbon in SWDS is reported as an information item in the Waste sector. The reported value for waste derived from harvested wood products (paper and cardboard, wood and garden and park waste) is equal to the variable 1B, $\Delta C_{HWP\ SWDS\ _{DC}}$, i.e., the carbon stock change of HWP from domestic consumption disposed into SWDS of the reporting country used in Chapter 12, Harvested Wood Products, of the AFOLU Volume. This parameter as well as the annual CH_4 emissions from disposal of HWP in the country can be estimated with the FOD model (see sheet HWP in the spreadsheet).

3.5 COMPLETENESS

Previous versions of the *IPCC Guidelines* have focused on emissions from MSW disposal sites, although inventory compilers were encouraged to consider emissions from other waste types. However, it is now recognised that there is often a significant contribution to emissions from other waste types. The *2006 Guidelines* therefore provide default data and methodology for estimating the generation and DOC content of the following waste types:

- Municipal Solid Waste (MSW) – the default definition and composition is given in Chapter 2,
- Sewage sludge (from both municipal and industrial sewage treatment),
- Industrial solid waste (including waste from wood and paper industries and construction and demolition waste, which may be largely inert materials, but also include wood as a source of DDOCm),

- Residues from mechanical-biological treatment plants (see Chapter 4, Biological Treatment of Solid Waste).

Countries should provide their own estimates of the fractions of these waste types disposed in SWDS, incinerated or recycled.

Waste types addressed elsewhere in the *2006 Guidelines*:

- Emissions from manure management (included in the AFOLU sector.)

Waste management types to include:

- Managed SWDS,
- Unmanaged SWDS (open dumps, including above-ground piles, holes in the ground and dumping into natural features such as ravines).

Waste management types addressed elsewhere in the *2006 Guidelines*:

- Emissions from incineration (Chapter 5 of this Volume),
- Emissions from open burning at SWDS (Chapter 5 of this Volume),
- Emissions from biological treatment of solid waste including centralised composting facilities, and home composting (Chapter 4 of this Volume).

Closed SWDS continue to emit CH_4. This is automatically accounted for in the FOD method because historical waste disposal data are used.

All of the management types listed above should be included in this sector where they occur to a significant extent.

3.6 DEVELOPING A CONSISTENT TIME SERIES

Two major changes from the *1996 Guidelines* are introduced in the *2006 Guidelines*. These are:

- Replacing the old default (mass balance) method with the first-order decay (FOD) method,
- Inclusion of industrial waste and other non-MSW categories for all countries.

Both of these changes may require countries to recalculate their results for previous years, so that the time series will be consistent. The new spreadsheet provided for the IPCC FOD method automatically calculates emissions for all past years. However, it is important to ensure that the data input into the model form a consistent time series. The FOD model requires historical data as far back as 1950, so this is a significant task.

Guidance is given in Section 3.2.2 to enable countries to estimate past MSW and industrial waste disposal based on urban population, GDP and other drivers.

As waste statistics generally improve over time, countries may find that country-specific data are available for recent years but not for the whole time series. It is *good practice* to use country-specific data where possible. Where default data and country-specific data are mixed in a time series, it is important to check for consistency. It may also be necessary to use backward extrapolation or splicing techniques to reconcile the two datasets. The general guidance on these techniques is given in Chapter 6 of Volume 1 (Time Series Consistency).

3.7 UNCERTAINTY ASSESSMENT

There are two areas of uncertainty in the estimate of CH_4 emissions from SWDS: (i) the uncertainty attributable to the method; and (ii) the uncertainty attributable to the data (activity data and parameters).

3.7.1 Uncertainty attributable to the method

The FOD model consists of a pre-exponential term, describing the amount of CH_4 generated throughout the life-time of the SWDS, and an exponential term that describes how this CH_4 is generated over time. Therefore the uncertainties in using the FOD model can be divided into uncertainties in the total amount of CH_4 formed throughout the life-time of the SWDS and uncertainties in the distribution of this amount over the years.

The uncertainties in the total amount of CH_4 formed during the life-time of the SWDS stem from uncertainties in the amount and the composition of the waste disposed in SWDS (W and DOC), the decomposition (DOC_f) and the CH_4 correction factor (MCF). These uncertainties are addressed hereafter.

The uncertainties in distribution of CH_4 generation over the years are highly dependent on the specific situation. When amounts of waste disposed and waste management practices only slowly develop over the years, the uncertainty due to the model will be low. For example, when decomposition is slower than expected, an underestimation of CH_4 formation in 2005 from waste disposed in 1990 will be counteracted by an overestimation of amounts formed from waste disposed in e.g., 2000. However, when the annual amounts of waste or waste composition change significantly, errors in the model are of importance.

The best way of evaluating the error due to the model in a specific case can be obtained from the model by performing a sensitivity analysis, varying the k-values within the error ranges assumed (see Table 3.5 for default uncertainty values) or in a Monte Carlo analysis using the model and varying all relevant variables.

The use of the mass balance method, which was the default (Tier 1) method in previous versions of the IPCC guidance, tends to lead to over-estimation of emissions in cases where the trend is for increased disposal of waste to SWDS over time. It was assumed that all CH_4 would be released in the same year that the waste was deposited. The use of the FOD method removes this error and reduces the uncertainty associated with the method. However, it is important to remember that the FOD method is a simple model of a very complex and poorly understood system. Uncertainty arises from the following sources:

- Decay of carbon compounds to CH_4 involves a series of complex chemical reactions and may not always follow a first-order decay reaction. Higher order reactions may be involved, and reaction rates will vary with conditions at the specific SWDS. Reactions may be limited by restricted access to water and local variations in populations of bacteria.
- SWDS are heterogeneous. Conditions such as temperature, moisture, waste composition and compaction vary considerably even within a single site, and even more between different sites in a country. Selection of 'average' parameter values typical for a whole country is difficult.
- Use of the FOD method introduces additional uncertainty associated with decay rates (half-lives) and historical waste disposal amounts. Neither of these are well understood or thoroughly researched.

However, it is likely that the main source of uncertainty lies in selection of values for parameters for the model, rather than with the methodology of the model itself.

3.7.2 Uncertainty attributable to data

This source of uncertainty is simply the uncertainty attributable to each of the parameter inputs. The uncertainty attributable to the data can be classified into activity data and parameters.

3.7.2.1 UNCERTAINTIES ASSOCIATED WITH ACTIVITY DATA

The quality of CH_4 emission estimates is directly related to the quality and availability of the waste generation, composition and management data used to derive these estimates. The activity data in the waste sector include the total municipal solid waste, total industrial waste, waste composition, and the fraction of solid waste sent to solid waste disposal sites.

The uncertainty in waste disposal data depends on how the data is obtained. Uncertainty can be reduced when the amounts of waste in the SWDS are weighed. If the estimates are based on waste delivery vehicle capacity or visual estimation, uncertainty will be higher. Estimates based default activity data will have the highest uncertainties.

If waste scavenging takes place at the SWDS, it needs to be taken into account with the waste disposal data, otherwise, the uncertainty in waste disposal data will increase. Scavenging will also increase uncertainties in the composition of waste disposed in the SWDS, and hence also the total DOC in the waste. Uncertainty estimates for the default model parameters are given in Table 3.5. The estimates are based on expert judgement.

Waste generation may be estimated from population (or urban population) and per-capita waste generation rates. Uncertainty can be introduced if the population does not match the population whose waste is collected. Typically, in many countries, waste is only collected from urban populations. Urban population could fluctuate daily or seasonally by migration of the workforce.

3.7.2.2 UNCERTAINTIES ASSOCIATED WITH PARAMETERS

Methane correction factor (MCF)

There are two sources of uncertainty in the MCF.

- Uncertainty in the value of the MCF for each type of site (managed-anaerobic, managed-semi-aerobic, unmanaged deep and/or high water table, unmanaged shallow): These MCF values are based on one experimental study and expert judgement and not on measured data.
- Uncertainty in the classification of sites into the different site types: For example, the distinction between deep and shallow sites (5 m depth of waste) is based on expert opinion. Inevitably, few, if any, countries will be able to classify their unmanaged waste disposal sites into deep and shallow based on measured data. It can also be difficult to determine the sites that meet the IPCC criteria for managed sites.

Degradable organic carbon (DOC)

There are two sources of uncertainty in DOC values.

- Uncertainty in setting the DOC for different types of waste types/materials (paper, food, etc.): There are few studies of DOC, and different types of paper, food, wood and textiles can have very different DOC values. The water content of the waste also has an influence. DOC for industrial waste is very poorly known.
- Uncertainty in the waste composition affects estimates of total DOC in the SWDS: Waste composition varies widely even within countries (for example, between urban and rural populations, between households on different incomes, and between seasons) as well as between countries.

Fraction of degradable organic carbon which decomposes (DOC_f)

The uncertainty in DOC_f is very high. There have been few studies, and it is difficult to replicate real SWDS conditions in experimental studies.

Fraction of CH_4 in landfill gas (F)

The CH_4 fraction of generated landfill gas, F, is usually taken to be 0.5, but can vary between 0.5 and 0.55, depending on several factors (see Section 3.2.3). The uncertainty in this figure is relatively low, as F depends largely on the stoichiometry of the chemical reaction producing CH_4. The concentration of CH_4 in recovered landfill gas may be lower than the actual value because of potential dilution by air, so F values estimated in this way will not necessarily be representative.

Methane recovery (R)

CH_4 recovery is the amount of CH_4 generated at SWDS that is recovered and burned in a flare or energy recovery device. The uncertainty depends on the method used to estimate recovered CH_4. The uncertainty is likely to be relatively small compared to other uncertainties if metering is used. If other methods are used, for example by estimating the efficiency of CH_4 recovery equipment, the uncertainty will be larger. (See Section 3.2.3.)

Oxidation factor (OX)

The oxidation factor is very uncertain because it is difficult to measure, varies considerably with the thickness and nature of the cover material, atmospheric conditions and climate, the flux of methane, and the escape of methane through cracks/fissures in the cover material. Field and laboratory studies which determine oxidation of CH_4 only through uniform and homogeneous soil layers may lead to over-estimations of oxidation in landfill cover soils.

The half-life

There is high uncertainty in the estimates of half-life because it is difficult to measure decay rates under conditions equivalent to those prevailing in real SWDS. Also, since there is considerable variation in half-life with waste composition, climate and site type, it is difficult to select values representative of a whole country.

Uncertainty estimates for MSW_T (total MSW generated) and MSW_F (fraction of MSW_T disposed at SWDS) and the default model parameters are given in Table 3.5. The estimates are based on expert judgement.

TABLE 3.5
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)[7]	**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 country-specific value** ± 10% for countries based on the experimental data over longer time periods.
Methane Correction Factor (MCF) = 1.0 = 0.8 = 0.5 = 0.4 = 0.6	**For IPCC default value:** –10%, +0% ±20% ±20% ±30% –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.

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[7] 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.

3.8 QA/QC, Reporting and Documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 6, Quality Assurance and Quality Control and Verification, in Volume 1, General Guidance and Reporting. Some examples of specific documentation and reporting relevant to this source category are provided below.

- Countries using the IPCC FOD model should include the model in the reporting. Countries using other methods or models should provide similar data (description of the method, key assumptions and parameters).
- If country-specific data are used for any part of the time series, it should be documented.
- The distribution of waste to managed and unmanaged sites for the purpose of MCF estimation should also be documented with supporting information.
- If CH4 recovery is reported, an inventory of known recovery facilities is desirable. Flaring and energy recovery should be documented separately from each other.
- Changes in parameters from year to year should be clearly explained and referenced.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

It is *good practice* to conduct quality control checks and an expert review of the emissions estimates as outlined in Chapter 6 of Volume 1, Quality Assurance and Quality Control, and Verification.

Inventory compilers should cross-check country-specific values for MSW generated, industrial waste generated and waste composition against the default IPCC values, to determine whether the national parameters used are considered reasonable relative to the IPCC default values.

Where survey and sampling data are used to compile national values for solid waste activity data, QC procedures should include:

(i) Reviewing survey data collection methods, and checking the data to ensure that they were collected and aggregated correctly. Inventory compilers should cross-check the data with previous years to ensure the data are reasonable.

(ii) Evaluating secondary data sources and referencing QA/QC activities associated with the secondary data preparation. This is particularly important for solid waste data, since most of these data are originally prepared for purposes other than greenhouse gas inventories.

Inventory compilers should provide the opportunity for experts to review input parameters.

Inventory compilers should compare national emission rates with those of similar countries that have comparable demographic and economic attributes. Inventory compilers should study significant discrepancies to determine if they represent errors in the calculation or actual differences.

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Annex 3A.1 First Order Decay Model

3A1.1 INTRODUCTION

The first order decay (FOD) model introduced in Chapter 3 is the default method for calculating methane (CH_4) emissions from solid waste disposal sites (SWDS). This Annex provides the supplementary information on this model:

- mathematical basis for the FOD model (see Section 3A1.2),
- key issues in the model, such as the estimation of the mass of degradable organic carbon available for anaerobic decomposition at SWDS (DDOCm) (Section 3A1.2) and the delay time from disposal of waste in the SWDS till the decomposition starts (Section 3A1.3),
- introduction of the spreadsheet model developed to facilitate the use of the FOD method (3A1.4),
- how to estimate the long-term storage of carbon in SWDS (Section 3A1.5),
- different approaches to the FOD model, including an explanation of the differences between the current and earlier IPCC methods (Section 3A1.6).

3A1.2 FIRST ORDER DECAY (FOD) MODEL – BASIC THEORY

The basis for a first order decay reaction is that the reaction rate is proportional to the amount of reactant remaining (Barrow and Gordon, 1996), in this case the mass of degradable organic carbon decomposable under anaerobic conditions (DDOCm). The DDOCm reacted over a period of time *dt* is described by the differential equation 3A.1.1:

EQUATION 3A1.1
DIFFERENTIAL EQUATION FOR FIRST ORDER DECAY

$$d(DDOCm) = -k \bullet DDOCm \bullet dt$$

Where:

DDOCm = mass of degradable organic carbon (DOC) in the disposal site at time *t*

k = decay rate constant in y^{-1}

The solution to this equation is the basic FOD equation.

EQUATION 3A1.2
FIRST ORDER DECAY EQUATION

$$DDOCm = DDOCm_0 \bullet\ e^{-kt}$$

Where:

DDOCm = mass of degradable organic carbon that will decompose under anaerobic conditions in disposal site at time *t*

$DDOCm_0$ = mass of DDOC in the disposal site at time 0, when the reaction starts

k = decay rate constant in y^{-1}

t = time in years.

Substituting *t* =1 into Equation 3A1.2 shows that at the end of year 1 (the year after disposal), the amount of DDOCm remaining in the disposal site is:

EQUATION 3A1.3
DDOCM REMAINING AFTER 1 YEAR OF DECAY

$$\text{At t = 1,}\quad DDOCm = DDOCm_0 \bullet\ e^{-k}$$

The DDOCm decomposed into CH_4 and CO_2 at the end of year 1 (DDOCm decomp) will then be:

EQUATION 3A1.4
DDOCm DECOMPOSED AFTER 1 YEAR OF DECAY

$$\text{At } t = 1, \quad DDOCm\,decomp = DDOCm_0 \bullet (1 - e^{-k})$$

The equation for the general case, for DDOCm decomposed in period T[8] between time (t–1) and t, will be:

EQUATION 3A1.5
DDOCm DECOMPOSED IN YEAR T

$$DDOCm\,decomp_T = DDOCm_0 \bullet \left[e^{-k(t-1)} - e^{-kt} \right]$$

Equations 3A1.4 and 3A1.5 are based on the mass balance over the year.

In Section 3.2.3, the parameter half-life time of the decay is discussed. Half-life is the time it takes for the amount of reaction to be reduced by 50 percent. The relationship between half-life time and the reaction rate constant k is found by substituting DDOCm in Equation 3A1.2 with 1/2DDOCm$_0$, and t with $t_{1/2}$:

EQUATION 3A1.6
RELATIONSHIP BETWEEN HALF-LIFE AND REACTION RATE CONSTANT

$$k = \text{In}(2) / t_{1/2}$$

3A1.3 CHANGING THE TIME DELAY IN THE FOD EQUATION

In most SWDS, waste is disposed continuously throughout the year, usually on a daily basis. However, there is evidence that production of CH_4 does not begin immediately after disposal of the waste (see Section 3.2.3 in Chapter 3).

Equations 3A1.3 and 3A1.4 assume that the decay reaction starts on January 1 in the year **after** disposal, i.e., an average six month delay before the reaction commences.

The equations can easily be transformed to model an earlier start to the decay reaction, i.e., start of the decay reaction in the year of disposal. This is done by moving the e^{-kt} curve backwards along the time axis. For example, to model a reaction start on the first of October in the year of disposal (i.e., an average time delay of three months before the decay reaction commences, instead of six months), Equation 3A1.2 will be transformed into the following:

EQUATION 3A1.7
FOD EQUATION FOR DECAY COMMENCING AFTER 3 MONTHS

$$DDOCm = DDOCm_0 \bullet e^{-k(t+0.25)}$$

Then there will be two solutions, one for the year of disposal and one for the rest of the years:

EQUATION 3A1.8
DDOCm DECOMPOSED IN YEAR OF DISPOSAL (3 MONTH DELAY)

$$DDOCm\,decomp_Y = DDOCm_0 \bullet \left(1 - e^{-0.25k}\right)$$

EQUATION 3A1.9
DDOCm DISSIMILATED IN YEAR (T) (3 MONTH DELAY)

$$DDOCm\,decomp_T = DDOCm_0 \bullet \left[e^{-k(T-0.75)} - e^{-k(T+0.25)} \right]$$

---

[8] T denotes the year for which the estimate is done in relation to deposition year.

Where:

DDOCm $decomp_Y$ = DDOCm decomposed in year of disposal

DDOCm $decomp_T$ = DDOCm decomposed in year *T* (from point *t*–1 to point *t* on time axis)

T = year from point *t*–1 to *t* on the time axis, where year 1 is the year after disposal.

Y = disposal year

The same can be done to find the equations for reaction start within the year after disposal.

3A1.3.1 Disposal profile

The method presented here assumes that CH_4 production from all of the waste disposed during the first year (Year *Y*) begins on the 1st of January on the year after disposal. Year 1 is defined as the year after disposal.

Some inaccuracy will be introduced by the fact that, in reality, waste disposed at the beginning of the year will begin to produce CH_4 earlier, and waste disposed at the end of the year will begin to produce CH_4 later. Comparison of results calculated with the simple FOD method presented here and the exact day-by-day method, which is presented in Section 3A1.6.3, has been used to evaluate this error. With a half-life time of 10 years, evaluating CH_4 emissions with the exact method gives a decay profile only 1 day difference from the simplified version of the method. With a half-life time of 3 years, the simple method gives 3.5 days difference from the exact method. Even with a half-life time of 1 year, the difference between the exact and simple methods is just 10 days. The error introduced by the assumption in this simple method is very small in comparison with other uncertainties in the parameters, especially given that the uncertainty in delay time is at least two months.

3A1.4 SPREADSHEET FOD MODEL

In order to estimate CH_4 emissions for all solid waste disposal sites in a country, one method is to model the emissions from the waste disposed in each year as a separate row in a spreadsheet. In the *IPCC Waste Model*, CH_4 formation is calculated separately for each year of disposal, and the total amount of CH_4 generated is found by a summation at the end. A typical example, for six years of disposal of 100 units of DDOCm each year, with a decay rate constant of 0.1 (half-life time of 6.9 years), and CH_4 generation beginning in the year after disposal, is shown in the table below. The figures in the table are the DDOCm decomposed from that waste each year, from which the CH_4 emissions can be calculated.

When considered over a period of 50 years, which is necessary for the FOD method, this leads to a rather large calculation matrix. The spreadsheet uses a more compact and elegant approach to the calculations. This is done by adding the DDOCm disposed into the disposal site in one year to the DDOCm left over from the previous years. The CH_4 emission for the next year is then calculated from this 'running total' of the DDOCm remaining in the site. In this way, the full calculation for one year can be done in only three columns, instead of having one column for each year (see Table 3A1.1).

The basis for this approach lies in the first order reaction. With a first order reaction the amount of product (here DDOCm decomposed) is always proportional to the amount of reactant (here DDOCm). This means that the time of disposal of the DDOCm is irrelevant to the amount of CH_4 generated each year - it is just the total DDOCm remaining in the site that matters.

This also means that when we know the amount of DDOCm in the SWDS at the start of the year, every year can be regarded as year number 1 in the estimation method, and all calculation can be done by these two simple equations:

EQUATION 3A1.10
MASS OF DEGRADABLE ORGANIC CARBON ACCUMULATED AT THE END OF YEAR T

$$DDOCma_T = DDOCmd_T + \left(DDOCma_{T-1} \bullet e^{-k} \right)$$

EQUATION 3A1.11
MASS OF DEGRADABLE ORGANIC CARBON DECOMPOSED IN YEAR T

$$DDOCm\, decomp_T = DDOCma_{T-1} \bullet \left(1 - e^{-k} \right)$$

Where:

the decay reaction begins on the 1st of January the year after disposal.

$DDOCma_T$ = DDOCm accumulated in the SWDS at the end of year *T*

$DDOCmd_T$ = mass of DDOC disposed in the SWDS in year *T*

$DDOCma_{T-1}$ = DDOCm accumulated in the SWDS at the end of year (*T*–1)

DDOCm $decomp_T$ = DDOCm decomposed in year *T*

TABLE 3A1.1
NEW FOD CALCULATING METHOD

year	DDOCm disposed	DDOCm accumulated	DDOCm decomposed
0	100	100	0
1	100	190.5	9.5
2	100	272.4	18.1
3	100	346.4	25.9
4	100	413.5	33.0
5	100	474.1	39.3
6	100	529.0	45.1

3A1.4.1 Introducing a different time delay into the spreadsheet model

The table and equations presented above assume that anaerobic decomposition of DDOCm to CH_4 begins on 1st of January in the year after disposal (an average delay of 6 months before the decay reaction begins).

If the anaerobic decomposition is set to start earlier than this, i.e., in the year of disposal, separate calculations will have to be made for the year of disposal. As the mathematics of every waste category or waste type/fraction is the same, only parameters are different, indexing for different waste categories and types/fractions are omitted in the equations 3A1.12-17, and 3A1.19:

EQUATION 3A1.12
DDOCm REMAINING AT END OF YEAR OF DISPOSAL

$$DDOCm\, rem_T = DDOCmd_T \bullet e^{-k \bullet (13-M)/12}$$

(Column F in CH_4 calculating sheets in the spreadsheet model)

EQUATION 3A1.13
DDOCm DECOMPOSED DURING YEAR OF DISPOSAL

$$DDOCm\, dec_T = DDOCmd_T \bullet \left[1 - e^{-k \bullet (13-M)/12} \right]$$

(Column G in the CH_4 calculating sheets in the spreadsheet model)

Where:

DDOCm rem_T = DDOCm disposed in year *T* which still remains at the end of year *T* (Gg)

$DDOCmd_T$ = DDOCm disposed in year *T* (Gg)

DDOCm dec_T = DDOCm disposed in year *T* which has decomposed by the end of year *T* (Gg)

T = year *T* (inventory year)

M = month when reaction is set to start, equal to the average delay time + 7 (month)

k = rate of reaction constant (y^{-1})

Equations 3A1.10 and 3A1.11 will then become:

EQUATION 3A1.14
DDOCm ACCUMULATED AT THE END OF YEAR T

$$DDOCma_T = DDOCm\,rem_T + \left(DDOCma_{T-1} \bullet e^{-k} \right)$$

(Column H in the CH_4 calculating sheets in spreadsheet model)

EQUATION 3A1.15
DDOCm DECOMPOSED IN YEAR T

$$DDOCm\,decomp_T = DDOCm\,dec_T + DDOCma_{T-1} \bullet \left(1 - e^{-k} \right)$$

(Column I in the CH_4 calculating sheets in the spreadsheet model)

Where:

$DDOCma_T$ = DDOCm accumulated in the SWDS at the end of year *T*, Gg

$DDOCma_{T-1}$ = DDOCm accumulated in the SWDS at the end of year (*T*–1), Gg

$DDOCm\ decomp_T$ = DDOCm decomposed in year *T*, Gg

The spreadsheets are based on Equations 3A1.12 to 3A1.15. If the reaction start is set to the first of January the year after disposal, this is equivalent to an average time delay of 6 months (month 13). Equations 3A1.14 and 3A1.15 will then be identical to Equations 3A1.10 and 3A1.11.

3A1.4.2 Calculating DDOCm from amount of waste disposed

Data on waste disposal is entered into the spreadsheet. The data can be given by waste type (waste composition option) or as bulk waste. In the waste composition option, waste is split by waste type/material (paper and cardboard, food garden and park waste, wood, textiles and other waste). In the bulk waste option, waste is split only by main waste category (MSW and industrial waste). Not all DOCm entering the site will decompose under the anaerobic conditions in the SWDS. The parameter DOC_f is the fraction of DOCm which will actually degrade in the SWDS (see Section 3.2.3 in Chapter 3). The decomposable DOCm (DDOCm) entering the SWDS is calculated as follows:

EQUATION 3A1.16
CALCULATION OF DECOMPOSABLE DOCm FROM WASTE DISPOSAL DATA

$$DDOCmd_T = W_T \bullet DOC \bullet DOC_f \bullet MCF$$

(Column D in the CH_4 calculating sheet in the spreadsheet model)

Where:

$DDOCmd_T$ = DDOCm disposed in year *T*, Gg

W_T = mass of waste disposed in year *T*, Gg

DOC = Degradable organic carbon in disposal year (fraction), Gg C/Gg waste

DOC_f = fraction of DOC that can decompose in the anaerobic conditions in the SWDS (fraction)

MCF = CH_4 correction factor for year of disposal (fraction) (see Section 3.2.3)

3A1.4.3 Calculating CH_4 generation from DDOCm decomposed

The amount of CH_4 generated from the DDOCm which decomposes is calculated as follows:

EQUATION 3A1.17
CH_4 GENERATED FROM DECOMPOSED DDOCm

$$CH_4\ generated_T = DDOCm\ decomp_T \bullet F \bullet 16/12$$

(Column J in the CH_4 calculating sheets in the spreadsheet model)

Where:

$CH_4\ generated_T$ = amount of CH_4 generated from the DDOCm which decomposes

DDOCm $decomp_T$ = DDOCm decomposed in year T, Gg

F = fraction of CH_4, by volume, in generated landfill gas

16/12 = molecular weight ratio CH_4/C (ratio).

The CH_4 generated by each category of waste disposed is added to get total CH_4 generated in each year. Finally, emissions of CH_4 are calculated by subtracting first the CH_4 gas recovered from the disposal site, and then CH_4 oxidised to carbon dioxide in the cover layer.

EQUATION 3A1.18
CH_4 EMITTED FROM SWDS

$$CH_4\ emitted_T = \left(\sum_x CH_4\ generated_{x,T} - R_T \right) \bullet \left(1 - OX_T \right)$$

(The final result calculating column in the Results sheet)

Where:

CH_4 $emitted_T$ = CH_4 emitted in year T, Gg

x = waste type/material or waste category

R_T = CH_4 recovered in year T, Gg

OX_T = Oxidation factor in year T, (fraction)

3A1.5 CARBON STORED IN SWDS

Only part of the DOCm in waste disposed in SWDS will decay into both CH_4 and CO_2. An MCF value lower than 1, means that part of the DOCm will decompose aerobically to CO_2, but not to CH_4. The DOCm available for anaerobic decay will not decompose completely either. The decomposing part of this DOCm (DDOCmd) is given in Equation 3A1.16. The part of DOCm that will not decompose will be stored long-term in the SWDS, which will then be:

EQUATION 3A1.19
CALCULATION OF LONG-TERM STORED DOCm FROM WASTE DISPOSAL DATA

$$DOCm\ long\text{-}term\ stored_T = W_T \bullet DOC \bullet \left(1 - DOC_f \right) \bullet MCF$$

Using the default value for DOC_f = 0.5, 50 percent of the disposed DOCm will remain there for long term. Equation 19 describes the annual increase in the stock of long-term stored carbon in the SWDS. The long-term stored carbon in harvested wood products (HWP) disposed in SWDS (see Chapter 12 in the AFOLU volume) can be estimated using this equation. For the waste composition option, the amount of DOCm which is long-term stored in HWP waste disposed in SWDS is calculated directly from material information in the Activity sheet. Using the bulk waste option, the fraction of waste originating from HWP needs to be estimated first. If this is not known, the regional or country-specific default fractions for paper and cardboard, garden and park and wood waste can be used (see Section 2.3). The calculations are performed in the spreadsheet model in the sheet called ‘Stored C’ and ‘HWP’.

3A1.6 DIFFERENT FOD APPROACHES

Different FOD approaches have been used to estimate the CH_4 emissions from SWDS. The differences between the approach used in these *Guidelines*, previous IPCC approaches and the so-called exact FOD method are discussed below. The approach used in this Volume has been chosen mainly for the following reasons:

- the method describes the FOD reaction mathematically more accurately than the previous IPCC approaches,
- it is easy to understand,
- it is easy to use in a spreadsheet model,
- it gives, as a by-product, an estimate of changes in carbon stored in SWDS (annual changes in carbon stock, for both long-term and short-term storage as the mass-balance of conversions of carbon into CH_4 and CO_2 in the SWDS are maintained by the approach).

3A1.6.1 *1996 Guidelines* - The rate of reaction approach

In the *Revised 1996 IPCC guidelines* (*1996 Guidelines*, (IPCC, 1997)) the estimation of the CH_4 emissions from SWDS was based on the rate of reaction equation. This is a common way of looking at the mass transformation in a chemical reaction. This is obtained by differentiating Equation 3A1.2 with respect to time:

EQUATION 3A1.20
FIRST ORDER RATE OF REACTION EQUATION

$$DDOCm\ reaction\ rate = -\,d\left(DDOCm\right)/\,dt = k \bullet DDOCm_0 \bullet e^{-kt}$$

The rate of reaction equation shows the rate of reaction at any time, and the rate of reaction moves along a curve. Therefore it has to be integrated to find the amount of reacted DDOCm over a period of time.

We want to find the DDOCm decomposed into CH_4 and CO_2 per calendar year. The start is year number 1 going from point 0 to point 1 on the time axis. Year number 1 is associated to point 1 on the time axis. Therefore the integration has to be performed from t–1 to t, which leads to an equation identical to Equation 3A1.5.

However, the equation presented in the *1996 Guidelines* (Equation 4, Chapter 6) is:

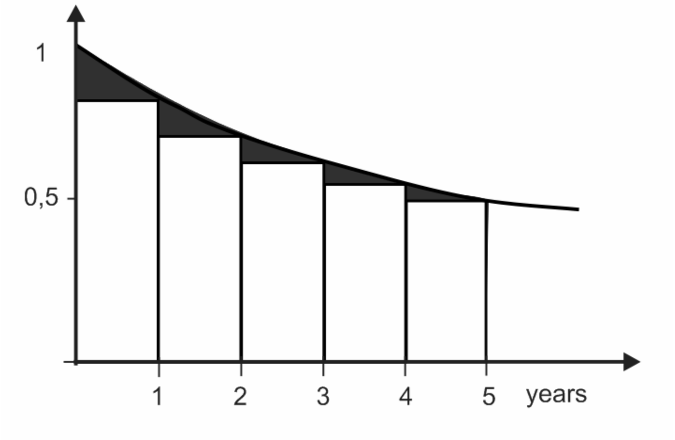
EQUATION 3A1.21
IPCC *1996 GUIDELINES* EQUATION FOR DOC REACTING IN YEAR T

$$DDOCm\ \ decomp_T = k \bullet DDOCm_0 \bullet\ \ e^{-kt}$$

In fact, this is the rate of reaction equation. Effectively this means that the yearly CH_4 production is calculated from the rate of reaction at the end of the year. This is an approximation which involves summing a series of rectangles under the rate of reaction curve, instead of accurately integrating the whole area under the curve. An error is introduced by the approximation; the small triangles shown on the top of the columns in Figure 3A1.1 are neglected, and mass balance over the year is not obtained. The method based on the equation in the *1996 Guidelines* using a half-life time of 10 years would give results 3.5 percent lower than the full mass balance calculations used in these *Guidelines* (see equations 3A.1.4-5).

However, where the method in the *1996 Guidelines* is used with half life times developed specifically for this method, calculations will be correct.

Figure 3A1.1 Error introduced by not fully integrating the rate of reaction curve



3A1.6.2 IPCC 2000 Good Practice Guidance

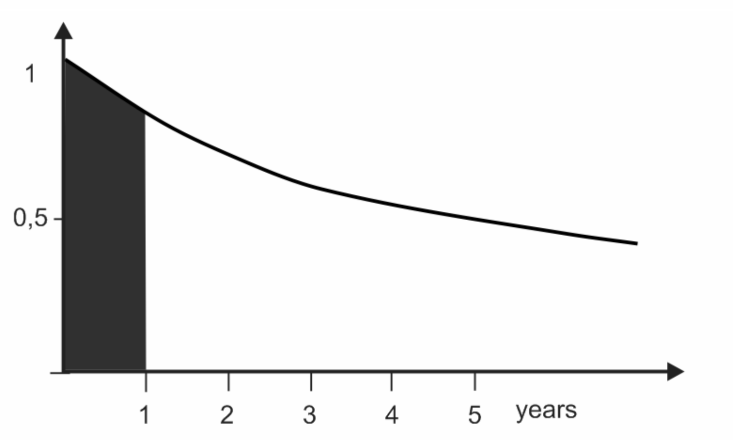
In the *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (*GPG2000*, IPCC, 2000), Equation 5.1, a normalisation factor A is introduced into the rate of reaction equation. When this 'normalisation factor' is multiplied into Equation 5.1 the result is a solved integral:

EQUATION 3A1.22
IPCC *2000GPG* FOD EQUATION FOR DDOCm REACTING IN YEAR T

$$DDOCm\,decomp_T = DDOCm_0 \bullet \left[\; e^{-kt} - e^{-k(t+1)} \;\right]$$

This is equivalent to the correct equation (Equation 3A1.5) as it integrates the decay curve. However, for year 1 it integrates from point 1 to point 2 on the time axis, and therefore the CH_4 formed in the first year of reaction is not counted (see Figure 3A1.2). This means that with a half life time of 10 years the *GPG2000* equation calculates results that are 7 percent lower than those calculated with approach taking the full mass balance into account.

Figure 3A1.2 Effect of error in the *GPG2000* equation



The intention of the normalisation factor has obviously been to fill in the small triangles on top of the columns in Figure 3A1.1. It fails because the normalisation factor used is equivalent to an integration going from point t to (t +1) on the time axis. As the integration using year number as a basis has to go from t-1 to 1, the normalisation factor filling in the whole area under the rate of reaction curve would be $A = ((1/e^{-k}) - 1)/k$.

3A1.6.3 Mathematically Exact First-Order Decay Model

The First Order Decay (FOD) model as described above can be shown to be mathematically equivalent to a model for which the total amount of DOC is assumed to be disposed at a single point in time in each disposal year, i.e., on a single date. If there is no delay in the commencement of the decay process, this date would be the middle of the year, i.e., 1st of July, with a delay of 6 months the assumed reaction start with the full amount of material is 31st December/1st January. This assumption, though counter-intuitive, leads to numerical errors that are small compared to the uncertainty in the understanding of the chemical processes, activity data, emission factors and other parameters of the emission calculation.

An alternative formulation of the FOD method is presented here for completeness. The delay in the commencement of the decay process can be represented, and simple recursive formulations can be given.

Equation 3A1.23 represents the formulation of the FOD with disposal rate D(t). The first term in the bracket represents the inflow into the carbon pool in the SWDS (disposal), the second term represents the outflow from the site (carbon in form of CH_4); the sum of the two terms represents the overall change in carbon stock in the SWDS.

EQUATION 3A1.23
FOD WITH DISPOSAL RATE D(t)

$$dDOCm(t) = \left[\; D(t) - k \bullet DDOCm(t) \;\right]\, dt$$

Where:

dDDOCm(t) = change in DDOCm at time t

D(t) = DDOCm disposal rate at time t

DDOCm(t) = DDOCm available at time t for decay

If there is a delay of Δ years in the commencement of the decay process after the DDOCm has been disposed, it will be necessary to distinguish the part of the stock that is available for decay, to which Equation 3A1.23

applies, and the inert part of the stock. For a disposal rate D(t) that is constant during each disposal year (and equal to the amount of DDOC disposed during that year divided by one year) it can be shown that the carbon stocks at the end of year *i* can be expressed in terms of the carbon stocks at the end of year *i*–1 and the amounts of disposal in year *i* and year *i*–1 (Pingoud and Wagner, 2006):

EQUATION 3A1.24
DEGRADABLE ORGANIC CARBON ACCUMULATED DURING A YEAR

$$DDOCma(i+1) = a \bullet DDOCma(i) + b \bullet DDOCmd(i-1) + c \bullet DDOCmd(i)$$

Where:

DDOCma (i) = DDOCm stock in the SWDS at the beginning of year *i*, Gg C

DDOCmd (i) = DDOCm disposed during year *i*, Gg C

$a = e^{-k}$ (constant)

$b = 1/k \bullet (e^{-k(1-\Delta)} - e^{-k}) - \Delta \bullet e^{-k}$ (constant)

$c = 1/k \bullet (1 - e^{-k(1-\Delta)}) + \Delta$ (constant)

Δ = delay constant, in years (between 0 and 1 years)

For an immediately starting decay (Δ=0), the constant b is equal to zero, so that Equation 3A1.24 reduces to an equation that relates the carbon pool in a given year *i* to the carbon pool in the previous year *i*-1 and the amount of DOC being deposited during year *i*.

It can further be shown (Pingoud and Wagner, 2006) that this form can be used to calculate recursively the corresponding CH_4 produced in a given year:

EQUATION 3A1.25
CH_4 GENERATED DURING A YEAR

$$CH_4\,gen(i) = q \bullet \left[a' \bullet DDOCma(i) - b' \bullet DDOCmd(i-1) + c' \bullet DDOCmd(i)\right]$$

Where:

CH_4 gen (i) = CH_4 generated during year *i*, Gg C

DDOCma(i) = DDOC stock in the SWDS at the beginning of year *i*, Gg C

DDOCmd(i) = DDOC disposed during year *i*, Gg C

$q = MCF \bullet F \bullet 16/12$

$a' = 1 - e^{-k} = 1 - a$ (constant)

$b' = 1/k \bullet (e^{-k(1-\Delta)} - e^{-k}) - \Delta \bullet e^{-k} = b$ (constant)

$c' = 1 - \Delta - 1/k \bullet (1 - e^{-k(1-\Delta)}) = 1 - c$ (constant)

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