



---

## CHAPTER 6

# WASTE

---





## 6. WASTE

### 6.1 Overview

Disposal and treatment of industrial and municipal wastes can produce emissions of most of the important greenhouse gases (GHG). Solid wastes can be disposed of through landfilling, recycling, incineration or waste-to-energy. This chapter will deal with emissions resulting from landfilling of solid waste, treatment of liquid wastes and waste incineration. Greenhouse gas emissions from waste-to-energy, where waste material is used directly as fuel or converted into a fuel, should be calculated and reported under the Energy Chapter.

The most important gas produced in this source category is methane ( $\text{CH}_4$ ). Approximately 5-20 per cent (IPCC, 1992) of annual global anthropogenic  $\text{CH}_4$  produced and released into the atmosphere is a by-product of the anaerobic decomposition of waste. Two major sources of this type of  $\text{CH}_4$  production are solid waste disposal to land and wastewater treatment. In each case, methanogenic bacteria break down organic matter in the waste to produce  $\text{CH}_4$ .

In previous editions of the *IPCC Guidelines* (1995), solid waste disposal sites were characterised as “open dumps” or “sanitary landfills,” both of which can produce  $\text{CH}_4$  if the waste deposited in them contains organic matter (IPCC, 1995). Open dumps were defined as shallow, open piles, generally only loosely compacted, and with no provision for control of any pollutants generated, where scavenging by animals and humans can remove much of the biodegradable wastes. Sanitary landfills, in contrast, were defined as sites specifically designed to receive wastes, which may manage these waste with practices such as compacting, use of liners, daily cover, and a final cap. Recognising that the distinction between landfills and open dumps is not always clear, the *Revised 1996 IPCC Guidelines* (this chapter) instead characterises all sites at which solid waste is deposited to land as “solid waste disposal sites” (SWDSs).

In addition to  $\text{CH}_4$ , solid waste disposal sites can also produce substantial amounts of  $\text{CO}_2$  and non-methane volatile organic compounds (NMVOCs). Decomposition of organic material derived from biomass sources (e.g., crops, forests) which are regrown on an annual basis is the primary source of  $\text{CO}_2$  released from waste. Hence, these  $\text{CO}_2$  emissions are not treated as net emissions from waste in the IPCC Methodology. If biomass raw materials are not being sustainably produced, the net  $\text{CO}_2$  release should be calculated and reported under the Agriculture and Land-Use Change and Forestry Chapters.

The process of wastewater treatment produces NMVOCs as well as  $\text{CH}_4$  (CORINAIR, 1994). These emissions are not currently addressed in the *Revised Guidelines*. Wastewater treatment is also a source of  $\text{N}_2\text{O}$ , and a methodology for estimating  $\text{N}_2\text{O}$  emissions is included in this Chapter for human sewage. (Chapter 4 of these *Revised Guidelines* addresses  $\text{N}_2\text{O}$  emissions from agriculture, using a life-cycle emissions approach.)

Waste incineration, like all combustion, can produce  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{NO}_x$ ,  $\text{N}_2\text{O}$  and NMVOCs. No detailed methodologies are provided here for this source category. Instead, the section on waste incineration later in this chapter provides references to methods available for some of the gases. For  $\text{CH}_4$  and  $\text{N}_2\text{O}$  it is only possible to report preliminary estimates and research results at this time. Further studies are needed to

give more information about GHG emissions from this source category. For additional information, refer to the discussion of emissions from combustion in Chapter 1.

The sections in this chapter dealing with land disposal of solid waste and wastewater treatment give background information on the source, describe a methodology to estimate CH<sub>4</sub> and N<sub>2</sub>O emissions, and discuss uncertainties associated with estimating emissions. This is consistent with the priorities under the IPCC Methodology programme. National experts are encouraged to report any other relevant emissions for which data are available, along with documentation of methods used. This will greatly assist in the development of more complete methods for future editions of *IPCC Guidelines*. For information on estimation procedures and emissions factors for other GHGs which are currently not provided in this chapter, experts should consult extensive existing literature developed by other emissions inventory programmes. Some key examples are:

- Default Emissions Factor Handbook (CORINAIR, 1994);
- Joint Atmospheric Emission Inventory Guidebook (1st edition) (EMEP/CORINAIR, 1996);
- US EPA's Compilation of Air Pollutant Emissions Factors (AP-42) (US EPA, 1995);
- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1987);
- Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines (US EPA, 1991; Doorn and Barlaz, 1995);
- Greenhouse Gases from Wastewater Treatment: Collection and Review of Country Specific Data and Preliminary Emission Models (Doorn and Eklund, 1995).

## **6.2 Methane Emissions from Solid Waste Disposal Sites**

### **6.2.1 Introduction**

The gases produced in solid waste disposal sites, particularly CH<sub>4</sub>, can be a local environmental hazard if precautions are not taken to prevent uncontrolled emissions or migration into surrounding land. Landfill gas is known to be produced both in managed "landfill" and "open dump" sites. Both are considered here as solid waste disposal sites (SWDSs). Gas can migrate from SWDSs either laterally or by venting to atmosphere, causing vegetation damage and unpleasant odours at low concentrations, while at concentrations of 5-15 per cent in air, the gas may form explosive mixtures.

More recently, increasing attention has focused on the role of CH<sub>4</sub> in global atmospheric change. Methane from SWDSs contributes a significant proportion of annual global CH<sub>4</sub> emissions, although the estimation is subject to a great deal of uncertainty. Estimates of global CH<sub>4</sub> emissions from SWDSs range from less than 20 to 70 Tg/yr (Bingemer and Crutzen, 1987, US EPA, 1994), or about 5 per cent to 20 per cent of the total estimated emissions of 375 Tg/yr (IPCC, 1996) from anthropogenic sources globally.

This section will describe the processes that result in gas generation from SWDSs and the factors which affect the amount of CH<sub>4</sub> produced. It will then describe two methodologies for estimating CH<sub>4</sub> emissions from SWDSs. One of these methods is a default base method which all countries can use to estimate CH<sub>4</sub> emissions from different



types of SWDSs. It is recommended that countries which have adequate data also estimate their emissions using the second method presented. Finally, this section discusses sources of uncertainty associated with any estimates of CH<sub>4</sub> emissions from SWDSs, in particular the availability and quality of data required.

### **6.2.2 Gas Generation from Solid Waste Disposal Sites**

Organic waste in SWDSs is broken down by bacterial action in a series of stages that result in the formation of CH<sub>4</sub> and CO<sub>2</sub> (termed biogas or landfill gas) and further bacterial biomass. In the initial phase of degradation, organic matter is broken down to small soluble molecules including a variety of sugars. These are broken down further to hydrogen, CO<sub>2</sub>, and a range of carboxylic acids. These acids are then converted to acetic acid which, together with hydrogen and CO<sub>2</sub>, forms the major substrate for growth of methanogenic bacteria.

Landfill gas consists of approximately 50 per cent CO<sub>2</sub> and 50 per cent CH<sub>4</sub> by volume. However, the percentage of CO<sub>2</sub> in landfill gas may be smaller because of decomposition of substrates with a high hydrogen/oxygen ratio (e.g., fats, hemicellulose) and because some of the CO<sub>2</sub> dissolves in water within the site.

SWDSs are by nature heterogeneous. Microbiological investigations into site characteristics have shown that there are considerable differences between different SWDSs and even different regions within the same SWDS (Westlake, 1990). This makes it very difficult to extrapolate from observations on single SWDSs to predictions of global CH<sub>4</sub> emissions. Nevertheless, a better understanding of the factors thought to most significantly influence the generation of CH<sub>4</sub> from land disposal of solid waste can reduce the uncertainty associated with emissions estimates.

### **6.2.3 Factors Influencing Methane Generation in Solid Waste Disposal Sites**

This section will provide a brief summary of the most significant factors affecting CH<sub>4</sub> generation.

#### **Waste disposal practices**

Waste disposal practices of concern for CH<sub>4</sub> emissions vary in the degree of control of the placement of waste and management of the site. In general, waste disposal on land will result in CH<sub>4</sub> production if the waste contains organic matter. Managed disposal (controlled placement of waste), in particular, tends to encourage development and maintenance of anaerobic activity.

#### **Waste composition**

The composition of waste is one of the main factors influencing both the amount and the extent of CH<sub>4</sub> production within SWDSs. Municipal solid waste (MSW) typically contains significant quantities of degradable organic matter. Different countries and regions are known to have MSW with widely differing compositions.

#### **Physical factors**

Moisture content is an important physical factor influencing landfill gas production. Moisture is essential for bacterial growth and metabolism, as well as for transport of nutrients and bacteria within the SWDS. The moisture content of a SWDS depends on

the initial moisture content of the waste, the extent of infiltration from surface and groundwater sources, and the amount of water produced during the decomposition processes.

Temperature, pH, and nutrient availability will affect the growth rate of the bacteria. Under anaerobic conditions, landfill temperatures are generally between 25-40°C. These temperatures can be maintained within the SWDS regardless of the ambient surface temperatures. Outside of these temperatures, CH<sub>4</sub> production is reduced. Optimal pH for CH<sub>4</sub> production is around neutral (pH 7.0). Important nutrients for efficient bacterial growth include sulphur, phosphorus, sodium and calcium. The significance of these physical factors to CH<sub>4</sub> generation can be demonstrated within controlled laboratory conditions.

#### **6.2.4 Methodologies to Estimate Methane Emissions from Solid Waste Disposal Sites**

A number of methods have been used to estimate CH<sub>4</sub> emissions from solid waste disposal sites. These methods vary widely, not only in the assumptions that they make, but also in their complexity, and in the amount of data they require. This chapter will deal only with those methods that can be applied to whole regions or countries. There are some very complex models that are concerned with movement of CH<sub>4</sub> and other gases through individual disposal sites; however these models cannot be applied to site populations and therefore will not be considered further here.

The methods described below include the theoretical gas yield methodology, of which the default methodology is one variation, and a first order kinetics methodology.

##### **Theoretical gas yield methodology**

This is the simplest method for calculating CH<sub>4</sub> emissions from SWDSs. It is based on a mass balance approach, and does not incorporate any time factors into the methodology. Rather, this methodology assumes that all potential CH<sub>4</sub> is released from waste in the year that the waste is disposed of. Although this is not what actually occurs, it gives a reasonable estimate of the current year's emissions if the amount and composition of the waste disposed of has been relatively constant over the previous several years. If, however, there have been significant changes in the rate of waste disposal, this simple method will likely not provide a good estimate of current emissions.

##### **Default methodology**

The default methodology is a mass balance approach that involves estimating the degradable organic carbon (DOC) content of the solid waste, i.e., the organic carbon that is accessible to biochemical decomposition, and using this estimate to calculate the amount of CH<sub>4</sub> that can be generated by the waste. This is the approach taken by Bingemer and Crutzen (1987), who divided the world into four economic regions (the United States, Canada and Australia; other OECD countries; the Former USSR and Eastern and Central Europe; developing countries), and applied different DOC values to the waste generated within each of these regions. It is the most widely accessible, easy-to-apply methodology for calculating country-specific emissions of CH<sub>4</sub> from SWDSs. It requires the least amount of data to perform the calculations, and it can be modified and refined as the amount of data available for each country increases. This approach was provided as the default methodology in the *IPCC Guidelines* (IPCC, 1995).

The revised default methodology provided here modifies the *IPCC Guidelines* (IPCC, 1995) in three important ways:



- Rather than distinguishing between “landfills” and “open dumps,” the methodology uses a continuum of solid waste disposal sites, characterised by the degree of waste management and depth.
- Default DOC values are provided for different waste streams so that countries can calculate the DOC content of their waste rather than relying on single default values.
- Emphasising the fact that this methodology estimates CH<sub>4</sub> generation rather than emission, and that oxidation often occurs in the upper layers of the waste mass and in site cover material, a CH<sub>4</sub> oxidation factor (OX) is included in the equation (currently equal to 0, pending the availability of further data).

The determination of annual CH<sub>4</sub> emissions for each country or region can be calculated from Equation 1:

**EQUATION 1**

Methane emissions (Gg/yr)

=

$$(MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times 16/12 - R) \times (1-OX)$$

where:

MSW <sub>T</sub>	=	total MSW generated (Gg/yr)
MSW <sub>F</sub>	=	fraction of MSW disposed to solid waste disposal sites
MCF	=	methane correction factor (fraction)
DOC	=	degradable organic carbon (fraction)
DOC <sub>F</sub>	=	fraction DOC dissimilated
F	=	fraction of CH <sub>4</sub> in landfill gas (default is 0.5)
R	=	recovered CH <sub>4</sub> (Gg/yr)
OX	=	oxidation factor (fraction - default is 0)

Total MSW (MSW<sub>T</sub>) can be calculated from Population (thousand persons) x Annual MSW generation rate (Gg/thousand persons/yr). Per capita MSW generation rates are provided for many countries and regions in Table 6-1. The components of MSW may vary from country to country. These differences can play an important role in the resulting emissions estimate, as each waste stream may have a different DOC content and hence a different CH<sub>4</sub> generation potential. In general, countries should include the following waste streams in their estimate of total MSW generated:

1. household waste;
2. yard/garden waste; and
3. commercial/market waste.

In some countries, significant quantities of organic industrial solid waste are generated. The default values in Table 6-1 should not include industrial waste or construction and demolition material. If a significant quantity of organic industrial solid waste is generated

and disposed of in solid waste disposal sites, this waste should be included in the MSW generation rates and reflected in the corresponding DOC value chosen (see below under Degradable Organic Carbon).

In countries where no organised waste collection or disposal takes place in rural areas, the population considered should include only the urban population. The default values in Table 6-1 for developing countries and countries with economies-in-transition do not include rural area information.

Region/Country	MSW Generation Rate (kg/cap/day)	Fraction of MSW disposed to SWDS	Fraction of DOC of MSW	MSW disposal Rate (kg/cap/day)
<b>North America</b>			0.18-0.21	
USA <sup>a</sup>	2.0	0.62		1.24
Canada <sup>b</sup>	1.81	0.75		1.35
<b>Oceania</b>				
Australia <sup>c</sup>	1.26	1.00	0.15	1.26
New Zealand <sup>l</sup>	1.33	1.0	0.19	1.33
<b>UK/Western Europe/Scandinavia</b>			0.08-0.19	
UK <sup>m</sup>	1.9	0.9	0.10	1.7
Ireland <sup>b</sup>	0.85	1.00		0.85
Austria <sup>d</sup>	0.92	0.40		0.36
Belgium <sup>b</sup>	1.10	0.43		0.47
Denmark <sup>b</sup>	1.26	0.20		0.25
Finland <sup>b</sup>	1.70	0.77		1.3
France <sup>b</sup>	1.29	0.46		0.60
Germany <sup>b</sup>	0.99	0.66		0.65
Greece <sup>b</sup>	0.85	0.93		0.79
Italy <sup>e</sup>	0.94	0.88		0.83
Luxembourg <sup>b</sup>	1.34	0.35		0.47
Netherlands <sup>f</sup>	1.58	0.67	0.14	1.06
Norway <sup>b</sup>	1.40	0.75		1.05
Portugal <sup>b</sup>	0.90	0.86		0.78
Spain <sup>b</sup>	0.99	0.85		0.83
Sweden <sup>b</sup>	1.01	0.44		0.44
Switzerland <sup>b</sup>	1.10	0.23		0.25
<b>Eastern Europe</b>				
Poland <sup>g</sup>			0.15	0.54
Russia <sup>h</sup>	0.93	0.94	0.17	0.87





**TABLE 6-1 (CONTINUED)**  
**COUNTRY WASTE GENERATION, COMPOSITION, AND DISPOSAL DATA**

Region/Country	MSW Generation Rate (kg/cap/day)	Fraction of MSW disposed to SWDS	Fraction of DOC of MSW	MSW disposal Rate (kg/cap/day)
<b>Asia</b>				
Japan <sup>b</sup>	1.12	0.38		0.43
India <sup>i</sup>	0.33	0.6	0.18	0.2
China <sup>j</sup>			0.09	0.84
Indonesia <sup>j</sup>			0.17	0.51
<b>Central America</b>				
Guatemala <sup>j</sup>			0.13	0.46
<b>South America</b>				
Brazil <sup>l</sup>			0.12	1.47
Peru <sup>j</sup>			0.15	0.98
Chile <sup>j</sup>			0.18	0.59
<b>Africa</b>				
Egypt <sup>t</sup>			0.21	0.40
Nigeria <sup>j</sup>			0.11	0.40
South Africa <sup>k</sup>		1.00		

Note: The values in Table 6-1 represent the best data available to the Expert Group. Note that all values may not reflect identical assumptions regarding MSW composition (and hence corresponding DOC values). Where updated national data are available corresponding to the definitions used here, they should be used for comparison instead of the values given in Table 6-1.

<sup>a</sup> US EPA, 1995

<sup>b</sup> OECD, 1995

<sup>c</sup> Tom Beer, CSIRO, 1996

<sup>d</sup> Carolin Ziegler, University of Vienna, 1996

<sup>e</sup> Domenico Gaudioso, ENEA Italy, 1995

<sup>f</sup> Hans Oonk, TNO Environment & Energy Research, The Netherlands, 1995

<sup>g</sup> Piotr Manczarski, Warsaw University, Poland, 1995

<sup>h</sup> Alexander Lifshits, Geopolis Consulting, Moscow, 1995

<sup>i</sup> A.D. Bhide, NEERI, India, 1995

<sup>j</sup> Cal Recovery Inc., California, USA - based on experience in country.

<sup>k</sup> Les Venter, Solid Waste Dept., Johannesburg, South Africa, 1995

<sup>l</sup> E. Gray, New Zealand Ministry of Environment, 1996

<sup>m</sup> UK DoE, 1995

The Fraction MSW Disposed to Solid Waste Disposal Sites ( $MSW_F$ ) and Methane Correction Factor (MCF) reflect the way in which MSW is managed and the effect of 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 three categories of solid waste disposal sites (Table 6-2).

**TABLE 6-2**  
**SWDS CLASSIFICATION AND METHANE CORRECTION FACTORS**

Type of site	Methane correction factor (MCF) default values
Managed	1.0
Unmanaged - deep ( $\geq 5$ m waste)	0.8
Unmanaged - shallow (<5m waste)	0.4
Default value - uncategorised SWDSs	0.6

1. **Managed solid waste disposal sites.** These must have controlled placement of waste (i.e., waste directed to specific deposition areas and a degree of control of scavenging and a degree of control of fires) and will include at least one of the following:
  - cover material;
  - mechanical compacting; or
  - levelling of the waste.
2. **Unmanaged-deep solid waste disposal sites.** All SWDSs not meeting the criteria of managed SWDSs and which have depths of greater than or equal to 5 metres.
3. **Unmanaged-shallow solid waste disposal sites.** All SWDSs not meeting the criteria of managed SWDSs and which have depths of less than 5 metres.

A methane correction factor (MCF) is assigned to each of these categories, as shown in Table 6-2. The MCF reflects the lower methane-generating potential of unmanaged sites. The classification recognises that some developing countries or countries with economies-in-transition may have a small number of well-managed waste disposal sites, with the majority of sites less well-managed or unmanaged, often shallow and with lower methane-generating potential. 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.

Degradable Organic Carbon (DOC) content is based on the composition of waste, and can be calculated from a weighted average of the carbon content of various components of the waste stream. Country/region default data for DOC, where available, are presented in Table 6-1 (in general, these values are for wet waste). It is highly recommended, however, for countries where the composition of the fractions in the waste stream are known, that these be combined with a knowledge of the carbon content of these various fractions to produce a country-specific value for DOC. It is critical that the DOC value corresponds to the waste generation/disposal rate on which the CH<sub>4</sub> estimate is based. For example, a country that includes industrial waste in its MSW estimate should ensure that the DOC value used reflects this component of the waste stream.

To assist countries to calculate the DOC of waste streams, a set of default DOC values for different waste types is given in Table 6-3. Note that these values are for wet (or fresh) waste.



Waste Stream		Per cent DOC (by weight)
A.	Paper and textiles	40
B.	Garden and park waste, and other (non-food) organic putrescibles	17
C.	Food waste	15
D.	Wood and straw waste <sup>a</sup>	30

<sup>a</sup> excluding lignin C  
Source: Bingemer and Crutzen, 1987.

Using the values in Table 6-3, the DOC content of a country's waste could be calculated as shown in Equation 2.

**EQUATION 2**

$$\text{Per cent DOC (by weight)} = 0.4 (A) + 0.17 (B) + 0.15 (C) + 0.30 (D)$$

where:

- A = per cent MSW that is paper and textiles
- B = per cent MSW that is garden waste, park waste or other non-food organic putrescibles
- C = per cent MSW that is food waste
- D = per cent MSW that is wood or straw

Fraction dissimilated DOC ( $\text{DOC}_F$ ) is the portion of DOC that is converted to landfill gas. To date, estimates of how much carbon may be dissimilated have relied on a theoretical model that varies only with the temperature in the anaerobic zone of a landfill:  $0.014T + 0.28$ , where T = temperature (Tabasaran, 1981). If one assumes that the temperature in the anaerobic zone of a SWDS remains constant at about 35°C, regardless of ambient temperature (Bingemer and Crutzen, 1987), this method yields a figure of 0.77 dissimilated DOC. This value is currently under review.

Recovered  $\text{CH}_4$  (R) is the amount of  $\text{CH}_4$  that is captured for flaring or use. No default values are provided for the quantity of  $\text{CH}_4$  recovered, as this value is country-specific. See Section 6.2.6 below for more information.

Oxidation Factor (OX) accounts for the  $\text{CH}_4$  that is oxidised in the upper layers of the waste mass and in cover material, where oxygen is present. Because the default methodology relies on an estimate of  $\text{CH}_4$  generation, it is important to recognise the oxidation may reduce the quantity of  $\text{CH}_4$  generated that is ultimately emitted. A number of researchers are investigating and quantifying the effects of  $\text{CH}_4$  oxidation in waste disposal sites. However, as yet there is no internationally accepted factor that can be applied to account for  $\text{CH}_4$  oxidation. The  $\text{CH}_4$  oxidation factor in the equation has therefore been set equal to 0, pending the availability of new data. A better

understanding of the factors influencing CH<sub>4</sub> oxidation, and more accurate quantification of it, may allow for a revised oxidation factor (or default values) in future editions of the *IPCC Guidelines*. It is important that the oxidation factor be applied after subtraction of CH<sub>4</sub> recovered, as this CH<sub>4</sub> is generally pulled from well below the surface of the SWDS, before oxidation can occur.

It is proposed that the default methodology, based on the theoretical gas yield methodology developed by Bingemer and Crutzen (1987), remain as the methodology that can be used by all countries to calculate CH<sub>4</sub> emissions from their SWDSs. The Workbook provides a detailed step-by-step version of this methodology.

### Theoretical first order kinetics methodologies

More complex methods for estimating CH<sub>4</sub> emissions from SWDSs acknowledge the fact that CH<sub>4</sub> is emitted over a long period of time rather than instantaneously. A kinetic approach therefore needs to take into account the various factors which influence the rate and extent of CH<sub>4</sub> generation and release from SWDSs. A number of countries have applied this or similar modelling approaches to their own situation (Aitchison et al., 1996; UK, DOE, 1993; Van Amstel et al., 1993; Environment Canada, 1992).

#### *First Order Decay Model*

A first order decay model (Equation 3) can be used to model the rate of CH<sub>4</sub> generation over time. This approach has been used extensively to model landfill gas generation rate curves for individual landfills. It can also be used to model gas generation for a set of SWDSs to develop country emissions estimates or can be applied in a more general way to entire regions.

#### EQUATION 3

$$Q = L_0 R (e^{-kc} - e^{-kt})$$

where:

- Q = methane generated in current year (m<sup>3</sup>/yr)
- L<sub>0</sub> = methane generation potential (m<sup>3</sup>/Mg of refuse)
- R = average annual waste acceptance rate during active life (Mg/yr)
- k = methane generation rate constant (1/yr)
- c = time since SWDS closure (yr)
- t = time since SWDS opened (yr)

Methane generation potential (L<sub>0</sub>). The methane generation potential depends upon the composition of the waste. Values for L<sub>0</sub> can vary widely, and are difficult to estimate accurately for a particular SWDS or set of SWDSs. L<sub>0</sub> values may range from less than 100 to over 200 m<sup>3</sup>/Mg.

Quantity of waste landfilled (R). This is the average annual waste acceptance rate during the SWDS's active life.

Methane generation rate constant (k). This value is based on the environment in which the SWDS is located. Higher k values are associated with greater moisture in the



SWDSs and other factors discussed in Section 6.2.3 above. Values for  $k$  may range from less than 0.005 per year to 0.4 per year (LANDTEC, 1994; US EPA 1991).

Time since SWDS closure ( $c$ ). This is the length of time in years, not including the year of closure, since the SWDS stopped accepting waste.

Time since initial refuse replacement ( $t$ ). This is the length of time in years since the SWDS began to accept waste.

Countries with sufficient data on annual waste disposal to SWDSs are encouraged to apply the derivative of the first order decay model (Equation 4), to provide a comparison to the default methodology as well as to test the feasibility of including this approach in future inventories guidelines.

To allow for variances in annual acceptance rates, the derivative of Equation 3 with respect to  $t$  can be used to estimate  $\text{CH}_4$  generation from waste landfilled in a single year ( $R_x$ ). In this equation, the variable  $t$  is replaced with  $T-x$ , which represents the number of years the waste has been in the SWDS. The resulting equation thus becomes:

**EQUATION 4**

$$Q_{T,x} = k R_x L_O e^{-k(T-x)}$$

where:

- $Q_{T,x}$  = the amount of methane generated in the current year ( $T$ ) by the waste  $R_x$
- $x$  = the year of waste input
- $R_x$  = the amount of waste disposed in year  $x$  (Mg)
- $T$  = current year

In order to estimate the current emissions from waste placed in all years, Equation 4 can be solved for all values of  $R_x$  and the results summed (see Equation 5).

**EQUATION 5**

$$Q_T = \sum Q_{T,x}$$

for  $x = \text{initial year to } T$

### 6.2.5 Sources of Uncertainty

There are two areas of uncertainty in the estimate of  $\text{CH}_4$  emissions from solid waste disposal sites: (1) the uncertainty attributable to the method; and (2) data uncertainty.

Uncertainty attributable to the method. As discussed previously, the default methodology assumes that waste disposal into solid waste disposal sites is relatively constant and that the  $\text{CH}_4$  generated by the waste is released in the same year the waste is deposited. However, if waste disposal into solid waste disposal sites is increasing over time, then the

default method will overestimate CH<sub>4</sub> emissions. For example, it can be shown that if waste disposal into solid waste disposal sites is increasing at about 2 per cent per year over a 20- to 30-year period, then the default method will overestimate emissions by about 20-25 per cent. This is the principal type of uncertainty attributable to the default methodology itself. The amount of waste disposed of is therefore a sensitive parameter in this default methodology.

Data uncertainty. This source of uncertainty is simply the uncertainty attributable to each of the data inputs. In the case of the default methodology, this includes the uncertainty in the estimates for each of the factors used in Equation 1 (e.g., total MSW generated, fraction of MSW disposed to solid waste disposal sites). Although the uncertainty in any single one of these factors may be relatively large, if the sources of uncertainty for one factor are not related to the uncertainty for the other factors, then the uncertainty of the overall CH<sub>4</sub> emissions estimate can remain relatively low. For example, if the values for each of the factors used in Equation 1 are assumed to have an uncertainty of  $\pm 10$  per cent, then the overall uncertainty in the CH<sub>4</sub> emissions estimate will be about  $\pm 20$  per cent. If the uncertainty for each factor increases by  $\pm 20$  per cent, then the overall uncertainty in the CH<sub>4</sub> emissions estimate increases to  $\pm 40$ -50 per cent.

The following key uncertainties related to the data are discussed further below:

- The quantity and composition of landfilled waste;
- The quantity of CH<sub>4</sub> that is actually *generated* from the waste in the SWDS;
- The quantity of CH<sub>4</sub> that is actually *emitted* to the atmosphere.

Waste quantity and composition: The quality of CH<sub>4</sub> emissions estimates is directly related to the quality and availability of the waste management data used to derive these estimates. However, an accurate knowledge of the quantity and composition of wastes already in place may not be available. For most countries, limitations on funds available will prevent extensive investigations of old and smaller sites. It is therefore more cost-effective to concentrate efforts on improving the quality of data being collected on existing landfilling operations, including total waste quantity as well as more detailed site-specific data.

Quantity of methane generated: The degradable organic carbon (DOC) content of waste is an essential component in all calculations of CH<sub>4</sub> generated, and small variations in the assumed values for DOC can result in large variations in the overall estimate of CH<sub>4</sub> emissions. Different countries have widely differing MSW compositions and therefore DOC content. Both the rate and the extent of degradation of the various waste fractions need to be taken into account where data are available. Waste management practices also have significant effects on CH<sub>4</sub> generation, for example the method of landfilling and the water management practices. Future changes in waste management practices may change the composition of waste to SWDSs considerably, resulting in different CH<sub>4</sub> emissions levels.

Quantity of methane generated that is emitted to the atmosphere: The main uncertainty influencing the quantity of CH<sub>4</sub> emitted is the degree of oxidation that occurs as the gas diffuses through the landfill cover material. The presence, thickness, and other characteristics of SWDS cover materials can play a large role in determining the quantity of CH<sub>4</sub> ultimately emitted from a site.



### 6.2.6 Flaring and Gas Recovery Schemes

Flaring and gas recovery schemes successfully reduce CH<sub>4</sub> emissions from SWDSs. Any national inventory of CH<sub>4</sub> emissions from SWDSs must therefore take into account the reductions achieved by these practices.

For sites recovering CH<sub>4</sub> for energy use, the quantity of gas utilised is generally well documented. Estimates of the extent of flaring are more difficult to achieve with accuracy, and generally have to be estimated from a knowledge of the state of SWDS management within the country. If data on gas flaring are not readily available for a country, the following steps might be useful in development of this information:

1. Creation of an inventory of gas flares purchased in the country for use with landfill gas, including year purchased, estimated useful life, and flow rates.
2. Use of this inventory to estimate quantity of landfill gas flared each year.

### 6.2.7 Conclusion

A default methodology is presented here that allows simple calculation of CH<sub>4</sub> emissions from SWDSs by all countries. Countries are encouraged to use more sophisticated methods that incorporate country-specific data, if available. In particular, countries with sufficient data are encouraged to apply the first order decay model presented in Section 6.2.4 above, and compare the results to the basic default approach. If such data are not available, countries are encouraged to collect data for future application of a first order methodology. The additional information required includes: i) the CH<sub>4</sub> generation potential of the waste; ii) the rate at which CH<sub>4</sub> is generated from the waste each year; iii) the year of waste input; and iv) the amount of waste disposed of to SWDSs each year.

## 6.3 Methane Emissions from Wastewater Handling

### 6.3.1 Introduction

Methane production from wastewater handling (WWH) under anaerobic conditions is estimated to range from 30 to 40 teragrams per year (Tg/yr). This represents 8 to 11 per cent of total global anthropogenic CH<sub>4</sub> emissions estimated at 375 Tg/yr. Industrial WWH sources are estimated to be the major contributor to WWH emissions, accounting for 26 to 40 Tg/yr. Domestic and commercial WWH is estimated to emit approximately 2 Tg/yr (IPCC, 1995; US EPA 1994).

Wastewater can produce CH<sub>4</sub> if it is handled anaerobically. Anaerobic methods are used to handle wastewater from municipal sewage and from food processing and other industrial facilities, particularly in developing countries. In contrast, developed countries typically use aerobic processes for municipal wastewater treatment or anaerobic processes in enclosed systems where CH<sub>4</sub> is recovered and utilised.

This section provides the default methodology for estimating CH<sub>4</sub> emissions from WWH.

### 6.3.2 Background

Handling of wastewater and its residual solids by-product (sludge) under anaerobic conditions results in CH<sub>4</sub> production. The extent of CH<sub>4</sub> production depends primarily on the following factors:

A) *Wastewater Characteristics*

The principal factor in determining the CH<sub>4</sub> generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the BOD (Biochemical Oxygen Demand) and COD (Chemical Oxygen Demand). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH<sub>4</sub> than wastewater with lower COD (or BOD) concentrations.

B) *Handling Systems*

Handling systems vary in the environment that they provide for CH<sub>4</sub> production. Systems that provide anaerobic environments will generally produce CH<sub>4</sub> whereas systems that provide aerobic environments will normally produce little or no methane.

For example, the depth of a lagoon treatment system is a critical factor in CH<sub>4</sub> production. Shallow lagoons, less than 1 metre in depth, generally provide aerobic conditions and little CH<sub>4</sub> is likely to be produced. Lagoons deeper than about 2-3 metres will generally provide anaerobic environments and significant methane production is expected.

C) *Temperature*

With increases in temperature, the rate of CH<sub>4</sub> production increases. This is especially important in uncontrolled systems and in warm climates. CH<sub>4</sub> production typically requires a temperature higher than 15°C. Fermentation and thus CH<sub>4</sub> production is negligible at temperatures below 15°C, at which point the lagoon serves principally as a sedimentation tank (Gloyna, 1971). Below 15°C significant amounts of CH<sub>4</sub> will be produced only in instances where sedimentation and extended sludge retention occur.

Other factors that influence CH<sub>4</sub> generation in wastewater are retention time, degree of wastewater treatment, and other site specific characteristics.

D) *BOD vs. COD*

The BOD (Biochemical Oxygen Demand) concentration indicates only the amount of carbon that is aerobically biodegradable. The standard measurement for BOD is a 5-day test<sup>1</sup>, denoted as BOD<sub>5</sub>. The time period used in the BOD indicates whether only easily biodegradable materials or more resistant compounds are taken into account. COD (Chemical Oxygen Demand) measures the total material available for oxidation (both biodegradable and non-biodegradable). Since the BOD is an aerobic parameter, it may be less appropriate for determining the organic components in anaerobic environments. Also, both the type of wastewater and the type of bacteria present in the wastewater influence the BOD concentration of the wastewater. Although BOD is the more

---

<sup>1</sup> A seven day test, denoted as BOD<sub>7</sub>, is used in some countries instead of BOD<sub>5</sub>. The conversion between BOD<sub>5</sub> and BOD<sub>7</sub> is dependent on the characteristics of the wastewater. Experts within individual countries should be consulted to obtain appropriate conversion coefficients.





frequently reported parameter, reported COD/BOD ratios can be used to determine the COD if the BOD is known.<sup>2</sup>

### 6.3.3 Methodology for Wastewater Handling

Wastewater handling systems involve processes that transfer wastewater from its source to a disposal site. In most developed countries, wastewater treatment systems are used to chemically or biologically stabilise the wastewater before disposal. In many developing countries however, wastewater receives little or no formal treatment and is simply handled by transporting untreated wastewater to a disposal site.

Formal wastewater treatment methods can be classified as primary, secondary, and tertiary treatment. In primary treatment, physical barriers remove larger solids from the wastewater. Remaining particulates are then allowed to settle. Secondary treatment consists of a combination of biological processes that promote biodegradation by microorganisms. These may include aerobic and anaerobic stabilisation ponds, trickling filters, and activated sludge processes. Tertiary treatment processes are used to further purify the wastewater of contaminants and pathogens. This is achieved using one or a combination of processes, including maturation/polishing ponds, advanced filtration, carbon adsorption, ion exchange, and disinfection.

Sludge is produced in both the primary and secondary stages of treatment. Sludge that is produced in primary treatment consists of solids that are removed from the wastewater. Sludge produced in secondary treatment is a result of biological growth in the biomass, as well as the collection of small particles (Lexmond and Zeeman, 1995). This sludge must be treated further before it can be safely disposed of. Methods of sludge treatment include aerobic and anaerobic stabilisation (digestion), conditioning, centrifugation, composting, and drying. *Anaerobic* stabilisation will produce CH<sub>4</sub>.

### 6.3.4 Wastewater Handling Methods in Developed and Developing Countries

Wastewater handling methods differ between developed and developing countries. The most common methods of wastewater handling in developed countries are *aerobic* wastewater treatment plants and lagoons (Lexmond and Zeeman, 1995). To avoid high discharge fees, many large industrial facilities pretreat their wastewater before releasing it into the sewage system. There is also an increasing trend towards anaerobic treatment systems, which can be cheaper and produce less sludge than aerobic systems.

The degree of wastewater treatment is variable in most developing countries. Most industrial wastewater is discharged directly into local bodies of water, and only a few major industries have comprehensive in-plant treatment facilities. Less than half of municipal wastewater produced is collected in a sewage system. Collected wastewater is usually discharged into unmanaged lagoons or waterways; in coastal cities it is discharged directly into the ocean. In many cases, the domestic wastewater handling facilities are pit

---

<sup>2</sup> Lexmond and Zeeman estimated a minimum value of the wastewater COD/BOD ratio to be 1.70 (Lexmond and Zeeman 1995). The COD/BOD ratio may vary significantly depending upon the characteristics of the wastewater. This is especially true for industrial wastewater which may include inorganic oxidisable materials. Some countries report BOD<sub>7</sub> (or other) values rather than BOD<sub>5</sub> values. In this case, domestic wastewater experts should be consulted to convert the available BOD data into the BOD<sub>5</sub> form.

latrines. Table 6-4 presents the main wastewater handling methods in developed and developing countries.

### **Wastewater streams**

Wastewater originates from a variety of domestic and industrial sources. Domestic wastewater streams include wastewater from toilets, bathrooms, kitchens, and in some cases, urban run-off. Industry classifies sources of wastewater into different industrial sectors (Lexmond and Zeeman, 1995), for example:

- Food and Beverages
- Paper and Pulp
- Textile
- Petrochemical
- Fertiliser
- Iron and Steel
- Non-Ferrous Metals
- Miscellaneous

Assessment of CH<sub>4</sub> production potential from industrial wastewater streams is based on the concentration of degradable organic matter in the wastewater, the volume of wastewater, and the propensity of the industry to treat their wastewater in anaerobic lagoons. Using these criteria, Doorn and Eklund (1995) prioritised industrial wastewater sources with high CH<sub>4</sub> gas production potential. These are characterised as follows:

- Paper and Pulp manufacture
- Slaughterhouses
- Alcohol, Beer, Starch
- Organic Chemicals
- Others (vegetable oil production, textiles, rubber, petroleum refineries, fruits and vegetables)

Both the paper and pulp industry and the meat and poultry processing industries produce large volumes of wastewater that contain high levels of degradable organics. Additionally, both industries utilise large facilities that often have their own wastewater handling systems. The meat and poultry processing facilities commonly employ anaerobic lagoons to treat their wastewater, while the paper and pulp industry is known to use lagoons.

The non-animal food and beverage industries collectively produce considerable amounts of waste water with significant BOD levels.



<b>TABLE 6-4 METHODS OF WASTEWATER HANDLING</b>	
Handling Method	Exceptions to Expected CH <sub>4</sub> Production
<b>Mostly aerobic disposal and handling methods (little or no CH<sub>4</sub> production)</b>	
<u>Developing countries</u> <ul style="list-style-type: none"> <li>• Open Pits/Latrines</li> <li>• Aerobic shallow ponds</li> <li>• River Discharge</li> </ul>	<ul style="list-style-type: none"> <li>• Pits/latrines may produce methane when temperature and retention time are favourable</li> <li>• Aerobic shallow ponds over 3 metres deep may produce methane</li> <li>• Stagnant, oxygen-deficient rivers may allow for anaerobic decomposition</li> </ul>
<u>Developed countries</u> <ul style="list-style-type: none"> <li>• Sewer systems with aerobic treatment</li> </ul>	<ul style="list-style-type: none"> <li>• Poorly designed or managed aerobic treatment systems produce methane</li> </ul>
<b>Mostly anaerobic disposal and handling methods (high CH<sub>4</sub> production)</b>	
<u>Developing countries</u> <ul style="list-style-type: none"> <li>• Anaerobic deep ponds</li> <li>• Sewer systems with anaerobic treatment</li> </ul>	<ul style="list-style-type: none"> <li>• Poorly designed or managed anaerobic systems may allow for aeration and reduced methane production</li> </ul>
<u>Developed and developing countries</u> <ul style="list-style-type: none"> <li>• Septic Tanks</li> </ul>	<ul style="list-style-type: none"> <li>• Frequent solids removal reduces methane production</li> </ul>
<b>Anaerobic Methods with Methane Recovery (mainly for sludge handling)</b>	
Primarily developed countries	

### 6.3.5 Methodology for Estimating Emissions from Wastewater Handling

Methane emissions from wastewater handling should be calculated for two different wastewater and resulting sludge types:

- 1 Domestic Wastewater.
- 2 Industrial Wastewater.
- 3 Domestic Sludge.
- 4 Industrial Sludge.

For each category, the method for estimating CH<sub>4</sub> emissions from wastewater handling requires three basic steps:

**Step 1 - Determine the total amount of organic material in the wastewater produced for each wastewater handling system.** The principal factor in determining the CH<sub>4</sub> generation potential of wastewater is the amount of degradable organic material of the wastewater. The most common parameters used to measure the degradable organic component (DC) of the wastewater are the BOD (Biochemical Oxygen Demand) and COD (Chemical Oxygen Demand). Data permitting, COD is the recommended parameter for estimating the DC of wastewater. The DC indicator, usually indicated in units of mass DC per unit volume (e.g., kg COD per m<sup>3</sup> wastewater) is multiplied by the volume of the source of wastewater (e.g., industry or domestic) to estimate the total amount of organic wastewater produced.

**Step 2 - Estimate emissions factors for each wastewater handling system in kg CH<sub>4</sub> per kg DC.** The emissions factors depend on the fraction of wastewater managed by each wastewater handling method, maximum CH<sub>4</sub> producing capacity of the wastewater, and the characteristics of the wastewater handling process (principally, the degree to which it is anaerobic).

**Step 3 - Multiply the emissions factors for each wastewater handling system by the total amount of organic material in the wastewater produced for each system,** and sum across the wastewater systems to estimate total CH<sub>4</sub> emissions.

**Approach for Estimating Methane Emissions from Wastewater and Wastewater Sludge Handling**

This approach is adapted from Doorn and Ecklund (1995) and Lexmond and Zeeman (1995).

**Step 1 -Total Organic Wastewater and Sludge**

The greenhouse gas (GHG) generation potential of the wastewater is driven by the organic content of the wastewater stream and the volume of wastewater. For the categories of wastewater types defined (domestic and industrial), the following is the method for estimating the total organic wastewater (TOW):

Domestic

Data needed are:

1. Degradable organic component (DC) indicator in kg DC per 1000 persons per year. For domestic wastewater and sludge, BOD is the recommended DC indicator. Although COD is considered a more appropriate indicator for the organic component of the waste, BOD is the more frequently reported indicator for domestic wastewater. Consequently, the use of BOD estimates will result in more precise calculations than when COD is used. (Default BOD values are provided for different regions in Table 6-5).
2. Country population in thousands (developing countries may choose to estimate wastewater and sludge handling emissions based only on the urban population of the country if wastes produced in rural areas decompose in an aerobic environment - see Table 6-4 for a list of anaerobic and aerobic handling methods).
3. Fraction of BOD removed as sludge.

Equation 6 presents the total domestic organic wastewater (TOW<sub>dom</sub>) calculation.

<p><b>EQUATION 6</b></p> $TOW_{dom} = P \times D_{dom} \times (1 - DS_{dom})$
---



Equation 7 presents the total domestic organic sludge ( $TOS_{dom}$ ) calculation.

**EQUATION 7**

$$TOS_{dom} = P \times D_{dom} \times DS_{dom}$$

where:

- $TOW_{dom}$  = total domestic/commercial organic wastewater in kg BOD/yr
- $TOS_{dom}$  = total domestic/commercial organic sludge in kg BOD/yr
- P = population in 1000 persons
- $D_{dom}$  = domestic/commercial degradable organic component in kg BOD/1000 persons/yr
- $DS_{dom}$  = fraction of domestic/commercial degradable organic component removed as sludge

Industrial

Data needed are:

1. Degradable organic component (DC) indicator in kg DC per m<sup>3</sup> of industrial wastewater/sludge produced per unit product. For industrial wastewater and sludge streams COD is the appropriate DC indicator. Data on COD values should be available in most countries. It is recommended that country-specific information, if available, be used. Default COD values are provided for different industries by region in Table 6-6. (Although the default values in Table 6-6 are provided by region, in most cases the default values are based on estimates for a single country within each region.)
2. Wastewater produced per unit product by industry in m<sup>3</sup>/tonne of product. Default values are provided in Table 6-6. (Although the default values in Table 6-6 are provided by region, in most cases the default values are based on estimates for a single country within each region.)
3. Total industrial output in tonnes per year.
4. Fraction of COD removed as sludge.

Equation 8 presents the total organic wastewater ( $TOW_{ind}$ ) calculation for a particular industry.

**EQUATION 8**

$$TOW_{ind} \text{ (kg COD/yr)} = W \times O \times D_{ind} \times (1 - DS_{ind})$$

Equation 9 presents the total organic sludge ( $TOS_{ind}$ ) calculation for a particular industry.

<p><b>EQUATION 9</b></p> $TOS_{ind} \text{ (kg COD/yr)} = W \times O \times D_{ind} \times DS_{ind}$
--

where:

- $TOW_{ind}$  = total industrial organic wastewater in kg COD/yr
- $TOS_{ind}$  = total industrial organic sludge in kg COD/yr
- $W$  = wastewater consumed in  $m^3$ /tonne of product
- $O$  = total output by selected industry in tonnes/yr
- $D_{ind}$  = industrial degradable organic component in kg COD/ $m^3$  wastewater
- $DS_{ind}$  = fraction of industrial degradable organic component removed as sludge

### Step 2 - Emissions Factors

To calculate emissions factors for each wastewater and sludge type, a weighted average of methane conversion factors (MCF) is calculated using estimates of wastewater managed by each wastewater handling method. The average MCF is then multiplied by the maximum methane producing capacity ( $B_o$ ) of the wastewater type.

- *Maximum methane producing capacity ( $B_o$ ):* The methane producing potential,  $B_o$ , is the maximum amount of  $CH_4$  that can be produced from a given quantity of wastewater or sludge. The  $CH_4$  producing potential varies by the composition of the wastewater/sludge and its degradability. The default (theoretical) value for  $B_o$  is 0.25 kg  $CH_4$ /kg BOD for wastewater and for sludge (Lexmond et al., 1995).<sup>3</sup>
- *Fraction of wastewater treated by certain handling systems (WS%):* These are the fractions of wastewater treated by a specific handling system, i.e., aerobic or anaerobic. Country specific estimates for WS should be used where available. Default estimates of WS per cent for different countries are provided in Table 6-7 to 6-9.
- *Fraction of sludge treated by certain handling systems (SS%):* These are the fractions of sludge treated by a specific handling system, i.e., aerobic or anaerobic. Country-specific estimates for SS should be used where available.
- *Methane conversion factor:* The amount of methane that is actually emitted depends on the  $CH_4$  conversion factor. The MCF defines the portion of  $CH_4$  producing potential ( $B_o$ ) that is achieved. The MCF varies between 0.0 for a completely aerobic system to 1.0 for a completely anaerobic system. Countries should contact wastewater experts to

---

<sup>3</sup>  $B_o$  is expressed in units of kg  $CH_4$ /kg DC, where DC is the indicator of degradable component of the waste (either COD or BOD). By definition, BOD is less than or equal to COD; the maximum BOD possible is, in fact, the COD. Therefore, when estimating the maximum  $CH_4$  producing potential from BOD or COD, the maximum potential  $CH_4$  produced per unit of BOD is equivalent to the maximum potential  $CH_4$  produced per unit of COD. This value is 0.25 kg  $CH_4$ /kg COD.