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# Solid Waste Emissions Inventory Support

## *Review Draft:* Documentation of Methane Emission Estimates

Submitted to


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**CONTENTS**

# DOCUMENTATION FOR THE 2003 INVENTORY OF METHANE EMISSIONS FROM LANDFILLS

## 1. *Introduction*

The purpose of this report is to document the methodology for estimating methane emissions from landfills for the 2003 U.S. inventory of greenhouse gas emissions. Each step of the methodology is documented, additional details are provided in the annexes, the spreadsheets used for the inventory are explained, and example calculations are provided.

Methane emissions from landfills were estimated to equal the methane produced from municipal landfills, minus the methane recovered and combusted, plus the methane produced by industrial landfills, minus the methane oxidized before being released into the atmosphere:

$$\mathbf{E = G_{MSW} - R + G_{ind} - Ox}$$

where

$E$ = methane emissions,
$G_{MSW}$ = methane generation from municipal solid waste landfills,
$R$ = methane recovered and combusted,
$G_{ind}$ = methane generation from industrial landfills, and
$Ox$ = methane oxidized before release to the atmosphere.

The development of the methodology and its application is explained for each of these components in the following sections.

## 2. *Simple First Order Decay Model*

Previous inventory estimates of methane generation rates have been based on a linear regression model developed from methane recovery rates measured at landfills in the late 1980s (EPA, 1993). In the regression model, methane generation rates are expressed as a linear function of the 30-year waste in place (WIP). Since that time, several other studies have been performed, and more data are available. These data allow for a robust calculation of the parameters needed in the internationally accepted First Order Decay (FOD) approach. The myriad of studies allow for comparison to ensure the calculated parameters are accurate. The FOD method is presented in the Intergovernmental Panel on Climate Change (IPCC) guidance: *Good Practice Guidance and Uncertainty Measurement in National Greenhouse Gas Inventories* (Jensen and Papatti, 2002) and is also the approach recommended in EPA's AP-42 compilation of emission factors (EPA, 1998b)

This section discusses evaluating values for the two parameters that would be needed to implement the FOD model for the national inventory: the methane generation potential of the waste ($L_0$ in $m^3$/Mg waste) and the rate constant (k in $yr^{-1}$). Values developed from other studies are presented for comparison, and after considering the results of all the studies, best estimates of $L_0$ and k are recommended.

## *2.1 Database Development*

The database used in this analysis was obtained from two sources: (1) a database compiled by EPA's Landfill Methane Outreach Program (LMOP) that consists of landfill gas-to-energy (LFGTE) projects and (2) a public access database maintained by the Energy Information Administration (EIA) consisting of landfills that recover landfill gas (both for LFGTE and flares). To develop a refined database, landfills that were reported in both the LMOP and EIA databases were extracted. The waste in place (WIP) and methane recovery rates were compared, and landfills with discrepancies between the two databases were identified and eliminated.

Landfill owners or operators reported information on the amount of methane that was collected for energy projects or flaring. All of the methane that is generated by the waste is not recovered (captured by the gas collection system); however, there was no site-specific information on the percent recovered, and it difficult to measure accurately. The widely accepted range for percent recovery by these projects is on the order of 60 to 85 percent with an average of 75 percent most commonly used (Leatherwood, 2002)[1]. A value of 75 percent recovery was used in this analysis to estimate the amount of methane generated from the measured data on methane recovery.

Data for annual average rainfall for each landfill location was obtained from the National Climatic Data Center (National Oceanic and Atmospheric Administration). These rainfall data for each site are based on the 30-year annual average.

For next year's inventory, additional landfills will be added as the information is verified. In this data refinement effort, landfill specific recovery efficiencies will also be added, when available.

## *2.2 Data Analysis*

The simple first order decay model is:

$$Q = L_0 \bullet R \bullet \left(e^{-kc} - e^{-kt}\right) \qquad \textbf{(Equation 1)}$$

where

Q = methane generated in current year ($m^3$),
$L_0$ = methane generation potential ($m^3$/Mg of waste),
R = average annual waste acceptance rate (Mg/year),
k = methane generation rate constant ($year^{-1}$),
c = years since landfill closure, and
t = years since landfill opening.

[1] This reference is provided in Annex A.

For open landfills, years since closure (c) is 0 and a closed-form solution can be found for k:

$$\mathbf{k = - [ln (1 - Q/L_0R)]/t} \qquad \textbf{(Equation 2)}$$

A further refinement was made to the database used for the FOD analysis to improve the estimates of k and $L_0$. For Equation 2, no solution exists when Q is greater than $L_0R$. This is likely to occur for older landfills if waste acceptance rates progressively increased over the years. In this case, larger quantities of fresher waste are contributing to the methane generation in more recent years, and the average waste acceptance rate over the life of the landfill (as calculated from WIP divided by years of operation) does not provide a reasonable estimate of methane generation. Equation 2 was applied to active landfills in the database (for $L_0$ = 100 $m^3$/Mg). The average age of landfills with no solution for k using Equation 2 was 35 years compared to 20 years for those with a solution. For the simple FOD model analysis, only landfills with an age of 25 years or less were used to improve the estimates of k and $L_0$, resulting in a database of 52 landfills. Given that most methane is generated within the first 30 years, this data constraint should not impose a large bias.

The first step in the analysis was to develop a best fit estimate of $L_{0.}$ To do this, $L_0$ and k were both varied and simultaneously estimated directly from Equation 1 using PROC NLIN from SAS®. The best fit estimate of $L_0$ was **99 $m^3$/Mg of waste**.

Estimates of $L_0$ from other studies are summarized below:

- Peer, Thorneloe, and Epperson (1993) reviewed estimates of $L_0$ from theoretical calculations (based on stoichiometry, biodegradability, and total organic carbon), laboratory studies of methane potential, and gas recovery at landfills. These researchers recommended a range of 50 to 162 (**midrange 106**) $m^3$/Mg of waste.

- The Solid Waste Association of North America (SWANA, 1998) commissioned a study that evaluated various model for estimating methane recovery rates. The study collected detailed site-specific data for 18 landfills and evaluated four models, including the simple FOD model. The methane recovery potential was estimated as 2,100 to 2,200 $ft^3$ recovered/ton of waste. Converting this value (assuming recovery is 75% of generation) yields a range for $L_0$ of **87 to 91** $m^3$/Mg waste.

- EPA (1998b) recommends a value of **100 $m^3$/Mg** based on a best fit analysis of the data from 21 landfills. This estimate is used as the default value in EPA's AP-42 compilation of emission factors.

- SCS Engineers stated that their studies of many landfills showed most sites had $L_0$'s in the range of range of 50 to 150 $m^3$/Mg. They recommended a midrange value of **100 $m^3$/Mg** (but noted that $L_0$ may be affected by precipitation).[2]

Based on this study's results and those of other researchers, a value of **100 $m^3$/Mg** appears to be a reasonable best estimate of methane generation potential for use in the national inventory estimates. The methane generation potential may vary quite a bit from landfill to landfill depending on many factors, primarily waste composition. However, a best estimate of $L_0$ representing waste landfilled nationwide is needed for the national inventory model because it is not possible get the site-specific data that would be needed for the thousands of open and closed landfills in the U.S. Although $L_0$ may be higher or lower for specific landfills, the errors would tend to cancel when developing a nationwide total for methane generation from an unbiased estimate of $L_0$.

The next step in the analysis was to evaluate k for different ranges of precipitation. Other studies (e.g., EPA's AP-42 compilation of emission factors) have looked at landfills in arid and non-arid areas, where arid includes regions receiving less than 20 to 25 inches per year. This analysis also considered arid and non-arid areas to facilitate comparisons to the AP-42 results. In addition, the non-arid group was split into two other ranges of 20 to 40 inches and greater than 40 inches. Values of k were calculated for $L_0 = 100$ $m^3$/Mg, and the values of k were averaged for each range of precipitation. Results are presented in Table 1 and more details on the landfill database are given in Annex B. The result for arid areas (0.02 $yr^{-1}$) is the same as the AP-42 default value for arid areas. The result for non-arid areas (0.049 $yr^{-1}$) is somewhat higher than the AP-42 default value(0.04 $yr^{-1}$). The range of k for the simple FOD model presented in SWANA's 1998 study of 18 landfills is 0.03 to 0.06 $yr^{-1}$, which is in approximately the same range as these results.

EPA used the three precipitation break-down for the 2003 inventory.

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[2] There is some indication in the literature that values of $L_0$ may be lower in very arid regions where the lack of moisture inhibits the action of methane-generating bacteria. The data used in this analysis were not adequate for identifying or evaluating such an effect.

**TABLE 1. FOD RATE CONSTANT (k) FOR RANGES OF RAINFALL**

| Precipitation range | k ($yr^{-1}$) |
|---|---|
| arid (<20 in/yr) | 0.020 |
| non-arid (20 in/yr or more) | 0.049 |

| Precipitation range | k ($yr^{-1}$) |
|---|---|
| <20 in/yr | 0.020 |
| 20-40 in/yr | 0.038 |
| >40 in/yr | 0.057 |

## *3. Estimate of Annual Waste Disposal Rates*

Accurate estimates of annual quantities of waste landfilled are an important component of the national FOD model. The following sections describe the development of these estimates.

### *3.1 Waste Landfilled: 1989 to 2003*

There are two commonly used sources for annual waste generation: *Biocycle's* annual survey of State Agencies (*Biocycle*, 2004) and *Franklin Associates*' modeled MSW generation. For the purposes of this model, which is based on estimates from landfills including all types of waste in MSW landfills, *Biocycle*'s data is more comparable to the database sites. It provides the best estimates of the quantity of solid waste landfilled for 1989 through 2003. For 1988 through 2000, the survey gathered information on solid waste generated and percent landfilled. There was no survey for 2001. In 2002, the methodology was changed, and one important aspect of the change was that the percent of municipal solid waste (MSW) landfilled was reported instead of the percent of all solid waste. To put the results for 2002 on a basis consistent with previous years, the percent of total solid waste landfilled reported by each State on 2000 was applied to the total solid waste generated by each State in 2002. (Details of this calculation are given in Annex C.) For 2001, a linear interpolation was used between the results for 2000 and 2002.

For 2003, the 2002 estimate is used and will be adjusted when the 2003 survey results become available. (The apparent growth in generation from the 2002 survey results may be an anomaly due to the change in methodology rather than a real increase in waste generation rate.) An adjustment was also made to account for waste generation in U.S. Territories based on the per capita generation rate in the U.S. for each year and the population of the Territories for each year. Results are given in Table 2.

## TABLE 2. ESTIMATES OF WASTE LANDFILLED FROM *BioCycle*

| Year | Solid waste generated (tons) | % landfilled | Solid waste landfilled (tons) | Solid waste landfilled in US Territories (tons) | Total solid waste landfilled (tons) | Total solid waste landfilled (million metric tons) |
|---|---|---|---|---|---|---|
| 1989 | 269,000,000 | 84 | 225,960,000 | 3,488,192 | 229,448,192 | 209 |
| 1990 | 293,613,000 | 77 | 226,082,010 | 3,494,500 | 229,576,510 | 209 |
| 1991 | 280,675,000 | 76 | 213,313,000 | 3,281,970 | 216,594,970 | 197 |
| 1992 | 291,742,000 | 72 | 210,054,240 | 3,215,314 | 213,269,554 | 194 |
| 1993 | 306,866,000 | 71 | 217,874,860 | 3,322,757 | 221,197,617 | 201 |
| 1994 | 322,879,000 | 67 | 216,328,930 | 3,290,386 | 219,619,316 | 200 |
| 1995 | 326,709,000 | 63 | 205,826,670 | 3,124,208 | 208,950,878 | 190 |
| 1996 | 327,460,000 | 62 | 203,025,200 | 3,081,195 | 206,106,395 | 187 |
| 1997 | 340,466,000 | 61 | 207,684,260 | 3,144,900 | 210,829,160 | 192 |
| 1998 | 374,631,000 | 61 | 228,524,910 | 3,443,664 | 231,968,574 | 211 |
| 1999 | 382,594,000 | 60 | 229,556,400 | 3,440,528 | 232,996,928 | 212 |
| 2000 | 409,029,000 | 61 | 249,507,690 | 3,717,678 | 253,225,368 | 230 |
| 2001 | 450,973,379 | 61 | 275,788,147 | 4,097,614 | 279,885,761 | 254 |
| 2002 | 492,917,758 | 61 | 302,068,604 | 4,473,549 | 306,542,153 | 279 |
| 2003 | 492,917,758 | 61 | 302,068,604 | 4,458,119 | 306,526,724 | 279 |

### *3.2 Waste Landfilled: 1960 to 1988*

For waste disposal rates for 1960 to 1988, four alternate approaches were developed and compared. The following approaches are based on information from EPA's 1993 Report to Congress (RTC), a 1986 survey of landfills, OSW estimates of the quantities of (1) municipal solid waste, (2) construction and demolition (C&D) waste, and (3) biosolids disposed of in landfills, and an approach used by the Energy Information Agency (EIA). The approaches are described briefly and the results compared for 1960 through 1988.

***Approach 1. 1993 Report to Congress estimates.***

EPA (1993) estimated waste disposal rates for 1960 through 1990 (see Table 3) based on a 1986 OSW survey of landfills and OSW estimates of the growth of commercial, residential, and other wastes prior to the survey.

## TABLE 3. EXCERPT FROM EPA'S 1993 RTC

| Period | Average annual quantity of waste placed in landfills (millions of metric tons) | | |
|---|---|---|---|
| | Commercial/residential | Other | Total |
| 1960s | 100 | 27 | 127 |
| 1970s | 124 | 30 | 154 |
| 1980s | 156 | 34 | 190 |
| Waste in place (1960-1990) | 3,800 | 900 | 4,700 |

Estimates of the annual quantity of waste landfilled for 1960 to 1990 were developed from these data within the following constraints:

- The total waste in place for 1960 to 1990 is 4,700 million metric tons.
- The average for each of the three decades corresponds to the estimates in Table 3.
- Waste landfilled in 1986 is 190 million metric tons (based on the OSW survey).

***Approach 2. Use OSW estimates for MSW, C&D waste, and biosolids.***

This approach uses estimates from Franklin Associates for municipal solid waste and estimates C&D and biosolids landfilled based on population growth from 1960 to 1990. Franklin Associates (EPA, 1998a) prepared a report characterizing C&D wastes in 1996. The report estimated 136 million tons of C&D waste were generated (2.8 pounds per person per day). The report also estimated that 65 to 85 percent of this waste was landfilled. Estimates of C&D wastes for other years were generated based the 1996 generation rate per person, US population in other years, and a midrange value of 75 percent landfilled. OSW (EPA, 1999) published a report on biosolids and estimated that 6.9 million tons were generated in 1998 and that 20 percent was landfilled. Based on the population in 1998, these estimates were scaled to other years based on population growth to estimate the quantity of biosolids landfilled. The three estimates (MSW, C&D wastes, and biosolids) were summed to estimate the total waste placed in landfills each year.

***Approach 3. Compare estimates from BioCycle and Franklin Associates.***

As discussed earlier, *BioCycle* provides estimates of waste landfilled based on a survey of the States. The survey results includes construction and demolition waste, biosolids, and industrial wastes sent to MSW landfills for most States, including many of the States with the highest populations and waste generation rates (e.g., California, Florida, Illinois, New Jersey, New York, Ohio, Pennsylvania). In an annual report prepared for OSW, Franklin Associates estimates the amount of municipal solid waste landfilled - excluding construction and demolition waste, biosolids, and industrial wastes (EPA, 2003). In this approach, the average ratio of *BioCycle* estimates to Franklin Associates estimates is calculated, and the ratio is applied to estimates of MSW for 1960 to 1990 from Franklin Associates to estimate the quantity of solid waste landfilled. The average shown in Table 4 is 1.7 and spans a relatively narrow range of 1.6 to 1.9.

**TABLE 4. RATIO OF TOTAL WASTE TO MSW WASTE LANDFILLED**

| Year | Tons of waste landfilled | | Ratio |
|---|---|---|---|
| | Franklin Associates[a] | *BioCycle*[b] | |
| 1990 | 140,070,000 | 226,082,010 | 1.61 |
| 1991 | 125,000,000 | 213,313,000 | 1.71 |
| 1992 | 135,690,000 | 210,054,240 | 1.55 |
| 1993 | 128,000,000 | 217,874,860 | 1.70 |
| 1994 | 131,240,000 | 216,328,930 | 1.65 |
| 1995 | 122,410,000 | 205,826,670 | 1.68 |
| 1996 | 115,800,000 | 203,025,200 | 1.75 |
| 1997 | 123,070,000 | 207,684,260 | 1.69 |
| 1998 | 127,860,000 | 228,524,910 | 1.79 |
| 1999 | 131,840,000 | 229,556,400 | 1.74 |
| 2000 | 130,550,000 | 249,507,690 | 1.91 |
| | **Average** | | **1.7** |

[a] MSW only.

[b] Includes MSW, C&D, and other non-MSW wastes.

***Approach 4. EIA estimates from ratios of waste generation***

The EIA estimates are based on comparisons with the estimates from Franklin Associates and *BioCycle* with adjustments to account for non-MSW wastes placed in landfills. Estimates were provided by Michael Mondshine of SAIC for 1940 through 1988, and the results for 1960 forward are shown in Table 5 for comparison.

***Results***

The results from the four approaches are compared in Table 5 and Figure 1. In addition, these waste disposal rates were used in the national FOD model with the values for $L_0$ and k discussed earlier. For the year 2000, all four approaches gave essentially the same values for methane generation rate and varied by only ±2 percent from the mean value. The choice of approaches does not appear to make much difference in terms of the predicted methane generation rates.

After considering several factors, the approach using the 1993 RTC and 1986 survey results was chosen for use in the national FOD model.

- The estimates are documented in the 1993 RTC, and this study has been used for several aspects of the US inventory estimates. The results from the approach are consistent with the RTC estimates of average waste disposal rates over each of the three decades and with the total 30-year waste in place in 1990.

- The approach is consistent with the 1986 survey results on the quantity of waste landfilled that year.

- As shown in Figure 1, the results track well with the Franklin Associates' estimates of MSW landfilled.

### *3.3 Waste Landfilled: 1940 to 1959*

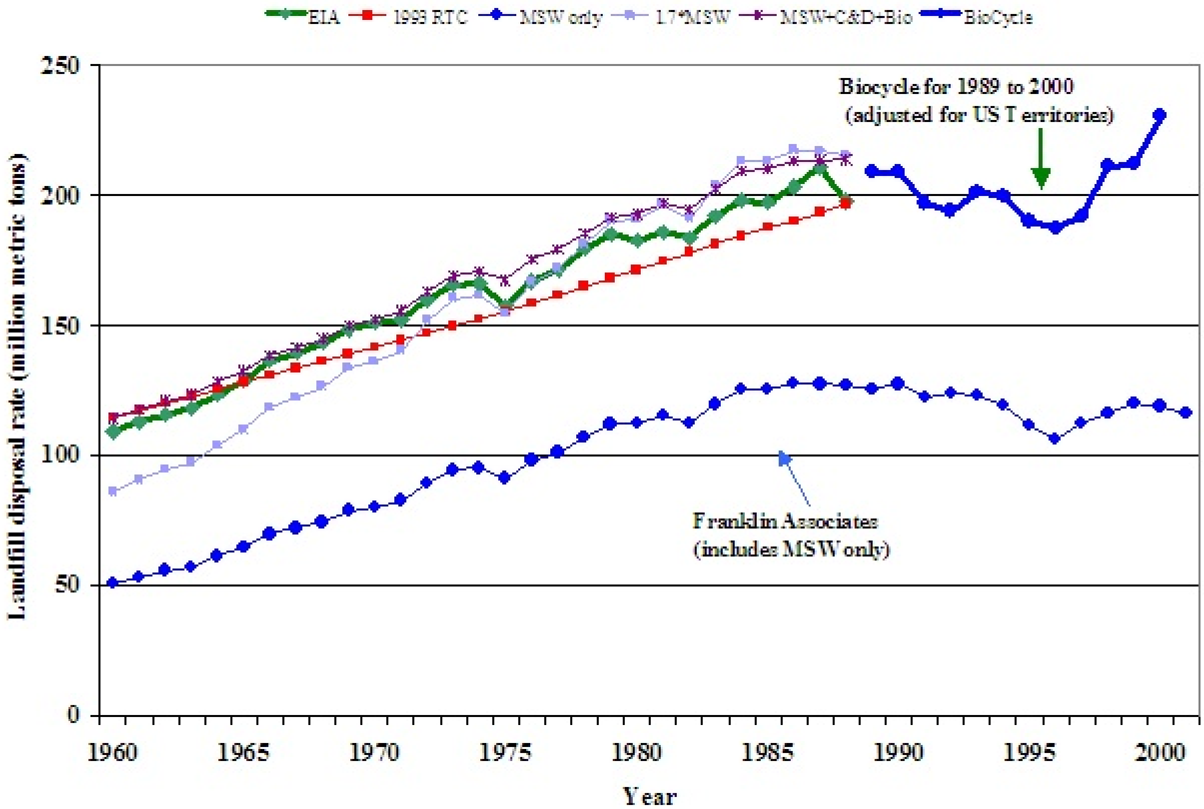
Waste landfilled from 1940 to 1959 will have only a small effect on the methane generation rates for 1990 to 2003. However, estimates were developed for the national FOD model for completeness in accounting for methane generation rates. Estimates of the population in the U.S. and Territories were obtained for these years, and the annual waste landfilled was estimated based on the per capita rate of waste landfilled in the 1960s.

## TABLE 5. COMPARISON OF ESTIMATES OF WASTE DISPOSAL IN LANDFILLS

| Year | Estimates of waste landfilled (millions of metric tons) | | | |
|---|---|---|---|---|
| | Approach 1: 1993 RTC | Approach 2: Estimates of MSW, C&D, Biosolids | Approach 3: 1.7 times Franklin's MSW estimate | Approach 4: EIA |
| 1960 | 115 | 114 | 86 | 109 |
| 1961 | 117 | 118 | 90 | 113 |
| 1962 | 120 | 121 | 94 | 116 |
| 1963 | 123 | 123 | 97 | 118 |
| 1964 | 125 | 128 | 104 | 123 |
| 1965 | 128 | 132 | 110 | 129 |
| 1966 | 131 | 138 | 118 | 136 |
| 1967 | 133 | 142 | 122 | 139 |
| 1968 | 136 | 145 | 126 | 143 |
| 1969 | 139 | 150 | 134 | 148 |
| 1970 | 142 | 152 | 136 | 151 |
| 1971 | 144 | 156 | 140 | 152 |
| 1972 | 147 | 163 | 152 | 160 |
| 1973 | 150 | 169 | 160 | 166 |
| 1974 | 152 | 171 | 162 | 166 |
| 1975 | 155 | 167 | 155 | 157 |
| 1976 | 158 | 175 | 166 | 167 |
| 1977 | 162 | 179 | 172 | 171 |
| 1978 | 165 | 186 | 181 | 179 |
| 1979 | 168 | 192 | 190 | 185 |
| 1980 | 171 | 193 | 191 | 182 |
| 1981 | 175 | 197 | 196 | 186 |
| 1982 | 178 | 194 | 191 | 184 |
| 1983 | 181 | 202 | 203 | 192 |
| 1984 | 184 | 209 | 213 | 198 |
| 1985 | 188 | 210 | 213 | 197 |
| 1986 | 190 | 213 | 217 | 203 |
| 1987 | 193 | 213 | 217 | 210 |
| 1988 | 197 | 214 | 215 | 198 |
| 1989 | 209[a] | 213 | 213 | 205[b] |
| 1990 | 209[a] | 216 | 216 | 205[b] |

[a] From *BioCycle* (adjusted to include US Territories).
[b] From *BioCycle* (not adjusted to include US Territories).

**FIGURE 1. ESTIMATES OF ANNUAL WASTE DISPOSAL RATES**



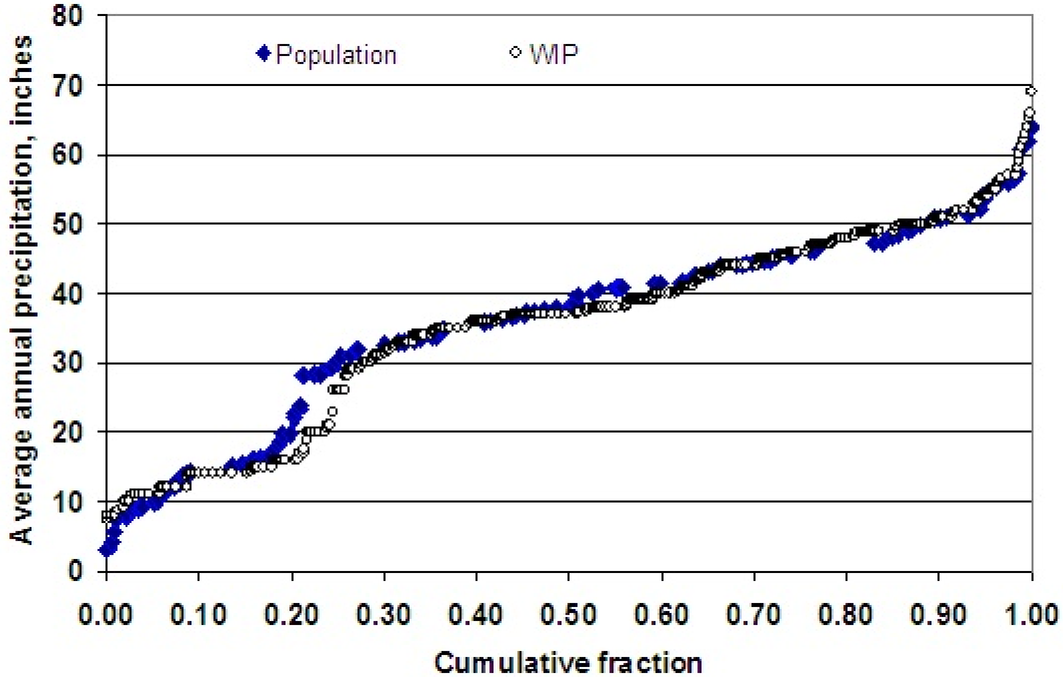

### *4. Distribution of Waste and Population vs. Precipitation*

Information on the distribution of precipitation vs. population and waste in place was obtained to gain insight into how the results might be applied to the national FOD model. For example, estimates of annual waste disposal rates (national totals) for the past 50 years have been developed. The totals for each year could be apportioned for different ranges of precipitation and an appropriate value of k assigned for that portion of waste landfilled.

Data were obtained on the distribution of U.S. population (U.S. Bureau of the Census) vs. rainfall presuming waste landfilled in an area is proportional to population. The distribution of WIP vs. precipitation was also evaluated from a database of over 400 landfills from the EIA and LMOP databases. The results are shown in Figure 2 as the cumulative distribution.[3] Population and WIP appear to track well together and suggest either might be appropriate for distributing the nationwide waste disposal rates into ranges of precipitation.

[3] The graph is read as the fraction (or percent) of the total WIP or population that has rainfall less than the value on the y-axis. For example, 50% of the population lives in areas that receive 38 inches of rainfall or less.

**FIGURE 2. DISTRIBUTION OF WIP AND POPULATION vs. RAINFALL (YEAR = 2000)**

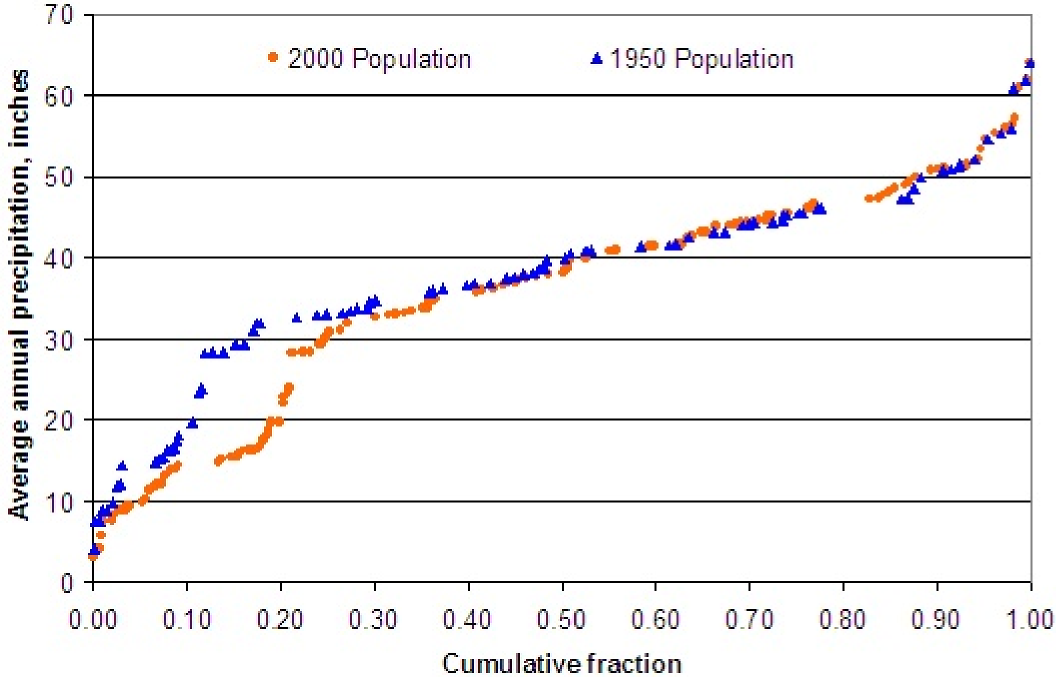



The distribution of population for 1950 was examined to see if the distribution may have changed over time. As shown in Figure 3, there has been a shift in population to more arid areas. For example, in 1950 about 10 percent of the population lived in arid areas (less than 20 inches per year) compared to 20 percent in 2000. This effect is due primarily to population growth in such States as California, Arizona, Nevada, and Utah. Consequently, distributions of population were developed for each decade of census information from 1950 to 2000 to use in apportioning the annual waste landfilled to different values of k (Table 6).

**TABLE 6. POPULATION AND PRECIPITATION OVER TIME**

| | Percent of US population in the precipitation range | | | | | |
|---|---|---|---|---|---|---|
| **Precipitation** | **1950** | **1960** | **1970** | **1980** | **1990** | **2000** |
| <20 in/yr | 11 | 13 | 14 | 16 | 19 | 20 |
| 20-40 in/yr | 40 | 39 | 38 | 36 | 34 | 33 |
| >40 in/yr | 49 | 48 | 48 | 48 | 47 | 47 |

**FIGURE 3. CHANGE IN POPULATION vs. RAINFALL SINCE 1950**




## 5. *The Energy Information Agency (EIA) Database*

The EIA maintains a public access database from voluntary reporting on greenhouse gases (EIA Form 1605B). This database was obtained and records on direct methane reductions from landfills were extracted. The effort was labor intensive in that each project reported at a landfill was examined, and great care was used to eliminate duplicate records. In some cases, the landfill operator, electric utility, and others reported reductions for the same site. Waste Management, Inc. was the most significant contributor to methane reduction information. The EIA data improved the quality of estimates for flares (in the flare vendor database) because they are based on site-specific measurements of gas flow and percent methane. Another significant advantage in improving the estimates is that changes in reductions over time (1991 to 2002) are reported. The resulting database included 309 records (where in many cases a flare and gas-to-energy project at the same landfill are counted as two records because reductions for the two were reported separately).

The EIA information provided a much larger database of higher quality information on landfills with flares (primarily provided by Waste Management, Inc.) that was used to replace the estimates developed from information supplied by flare vendors. For example, estimates for 269 flares in the flare vendor database was replaced by data from the EIA database.

### *6. Percent Methane*

A typical value of 50 percent methane is used in the LMOP database (for gas projects) and the flare vendor database to estimate methane reductions. A database of methane concentrations from Waste Management, Inc. was analyzed to evaluate the default value of 50 percent. The database included 32 projects at closed landfills and 163 projects at open landfills. The analysis showed an average value of 50.3 percent (across projects) and 50.6 percent (average weighted by gas flow). These results indicate that the 50 percent default value is reasonable, and no change in methodology is required. Details are provided in Annex D.

### *7. Percent Oxidation*

A value of 10 percent is used to estimate the amount of methane that is oxidized (for that portion of methane that is not recovered). A literature search was conducted to obtain more insight into methane oxidation. Several studies indicated that most or all of the methane escaping capture may be oxidized when an efficient gas recovery system is in place. These studies suggest that we may be greatly underestimating the percent of the methane oxidized at landfills with gas recovery systems.

However, there is support in the literature for a value of 10 percent for landfills without gas recovery systems. Jensen and Papatti (2002) note that experts at an IPCC workshop in 1995 and at an international symposium in 1997 agreed to use 10 percent oxidized as a standard value. This estimate has been implemented in several national inventories. In guidance provided to the States for estimating emissions, EPA recommended a factor of 10 percent oxidized (EPA 1995). In a life-cycle assessment of emissions and sinks, EPA (2002) estimated that 10 percent of the methane is oxidized and recommended using that factor when estimating methane emissions from landfills.

The estimate of 10 percent oxidized is apparently based on a few laboratory and field studies of oxidation. Mancinelli and McKay (1985) performed laboratory experiments on a simulated landfill gas mixture and showed 10 percent of the methane was oxidized. Czepiel et al (1996) performed laboratory studies of soil samples from a New Hampshire landfill and concluded that 20 percent of the methane was oxidized at the time the methane flux measurements were made (in October with no gas recovery). Using a soil climate model, the annual whole landfill oxidation rate was estimated as 10 percent. Other studies report a range of 10 to 30 percent oxidized.

The conclusions from the literature review were that the rate of methane oxidation and the fraction of methane oxidized vary widely and depend on many site-specific factors. The recommended value of 10 percent oxidized appears to be a reasonable but very conservative estimate. Additional details on the literature review are provided in Annex E.

In the future, EPA may look into oxidation at landfills with recovery projects.

### *8. Industrial Landfills*

Industrial landfills receive waste from factories, processing plants, and other manufacturing activities. Because no data were available on methane generation at industrial landfills, emissions from industrial landfills were assumed to equal seven percent of the total methane emitted from MSW landfills (EPA 1993). This estimate was based on the relative quantities and organic content of industrial waste compared to municipal waste at the time of the EPA study, as shown in the equations below (EPA 1993):

*8.6 MMT organic waste in industrial landfills ÷ 65% organic content of MSW = 13.2 MMT of equivalent total MSW*

*13.2 MMT ÷ 190 MMT total MSW in MSW landfills = **7%***

### *9. Methane Emissions Avoided*

The estimate of methane emissions avoided (e.g., combusted) was based on landfill-specific data on landfill gas-to-energy (LFGTE) projects and flares. The spreadsheets used for these estimates are explained in Section 10, and example calculations are provided.

### *9.1 Estimate Methane Emissions Avoided Through Landfill Gas-to-Energy (LFGTE) Projects*

The quantity of methane avoided due to LFGTE systems was estimated based on information from two sources: (1) a database maintained by the Energy Information Agency (EIA) for the voluntary reporting of greenhouse gases (EIA 2004) and (2) a database compiled by EPA's Landfill Methane Outreach Program (LMOP) (EPA 2004). The EIA database included location information for landfills with LFGTE projects, estimates of methane reductions, descriptions of the projects, and information on the methodology used to determine the methane reductions. Generally the methane reductions for each reporting year were based on the measured amount of landfill gas collected and the percent methane in the gas. For the LMOP database, data on landfill gas flow and energy generation (i.e., MW capacity) were used to estimate the total direct methane emissions avoided due to the LFGTE project. Detailed information on the landfill name, owner or operator, city, and state were available for both the EIA and LMOP databases; consequently, it was straightforward to identify landfills that were in both databases. The EIA database was given priority because reductions were reported for each year, and landfills in the LMOP database that were also in the EIA database were dropped to avoid double counting. The combined database included 358 landfills with operational LFGTE projects.

### *9.2 Methane Emissions Avoided Through Flaring*

The quantity of methane flared was based on data from the EIA database and on information provided by flaring equipment vendors. To avoid double counting, flares associated with landfills in the EIA and LMOP databases were excluded from the flare vendor database. As with the LFGTE projects, reductions from flaring landfill gas in the EIA database were based on measuring the volume of gas collected and the percent methane in the gas. The information provided by the flare vendors included information on the number of flares, flare design flow rates, year of installation, and generally the city and state location of the landfill. The median landfill gas flow rate provided by vendors was used to estimate methane recovered from each remaining flare (i.e., for each flare not associated with a landfill in the EIA or LMOP databases). However, several vendors provided information on the size of the flare rather than the landfill gas flow rate. To estimate a median flare rate for flares associated with these vendors, the size of the flare was matched with the size and corresponding flow rates provided by other vendors. Total methane avoided through flaring from the flare vendor database was estimated by summing the estimates of methane recovered by each flare for each year.

### *9.3 Reduce Methane Emissions Avoided Through Flaring*

As mentioned in Section 9.2, flares in the flare vendor database associated with landfills in the EIA and LMOP databases were excluded from the flare reduction estimates in the flare vendor database. If EPA had comprehensive data on flares, each LFGTE project in the EIA and LMOP databases would have an identified flare because most LFGTE projects have flares. However, given that the flare vendor data only covers approximately 50 to 75 percent of the flare population, an associated flare was not identified for all LFGTE projects. These LFGTE projects likely have flares; however, EPA was unable to identify a flare due to one of two reasons: 1) inadequate identifier information in the flare vendor data; or 2) the lack of the flare in the flare vendor database. For those projects for which a flare was not identified due to inadequate information, EPA would be overestimating methane avoided as both the methane avoided from flaring and the LFGTE project would be counted. To avoid overestimating emissions avoided from flaring, EPA determined the methane avoided from LFGTE projects for which no flare was identified and reduced the flaring estimate from the flare vendor database by this quantity on a state-by-state basis. This step likely results in an underestimate of methane avoided due to flaring. EPA took this approach to be conservative in the estimates of methane emissions avoided.

## *10. Explanation of Spreadsheets*

This section explains the spreadsheets for the 2003 inventory and provides example calculations.

### *10.1 Methane Generation.xls*

The spreadsheet ***Methane Generation.xls*** presents the estimates of methane generation from municipal solid waste (MSW) landfills using the first order decay (FOD) model. The sheet ***Annual Waste Disposal*** has the estimates of the annual quantity of waste placed in landfills from 1940 through 2003. For 1940 through 1959, the annual quantity is estimated from the population (given in Column A) of the U.S. and its territories by multiplying this population by the per capita rate in 1960 (115 million metric tons for 183 million people). The estimates for 1960 through 1988 are based on EPA's 1993 report to Congress (EPA 1993) and an Office of Solid Waste survey of landfills in 1986 (EPA, 1988). The constraints used to develop these estimates are given in the Sheet ***1993 RTC***.

For 1989 through 2003, the estimates are derived from BioCycle's annual survey of State agencies (BioCycle, 2004). The development of these estimates is shown in the Sheet ***BioCycle***. This sheet shows the U. S. population and that of its territories, which are used to adjust the BioCycle estimates to include the territories. For example, in 1989 BioCycle estimates that 247 million people in the U.S. generated 269 million tons of waste. Applying this ratio to the population if the U.S. Territories (3.8 million) gives a waste generated in the territories of 4.1 million tons (Cell C3).

The Sheet ***Distributions*** gives the distribution of population in the three ranges of rainfall for each decade of the census data and also shows the corresponding value for the rate constant (k) for each range. These distributions are used in the Sheet ***Methane Generation*** to apply the FOD model. Column B of that sheet has the annual waste quantity placed in landfills (in millions of metric tons) for each year from the Sheet ***Annual Waste Disposal***.

The FOD model from the IPCC guidelines (Jensen and Papatti, 2002) is:

$$\mathbf{Q_{T,x} = k \cdot R_x \cdot L_o \cdot e^{-k(T-x)}}$$

where

$Q_{T,x}$ = the amount of methane ($m^3$) generated in year T by the waste $R_x$,
T = current year,
x = the year of waste input,
k = methane generation rate constant ($yr^{-1}$),
$R_x$ = the amount of waste disposed of in year x (Mg), and
$L_o$ = methane generation potential ($m^3$/Mg of waste).

There are three values of k and $R_x$ for each year corresponding to the three ranges of precipitation, and they are used in the equation as shown:

$$\mathbf{Q_{T,x} = [f_1 \cdot R_x \cdot k_1 \cdot L_o \cdot e^{-k_1(T-x)}] + [f_2 \cdot R_x \cdot k_2 \cdot L_o \cdot e^{-k_2(T-x)}] + [f_3 \cdot R_x \cdot k_3 \cdot L_o \cdot e^{-k_3(T-x)}]}$$

where $f_1$, $f_2$, and $f_3$ are the fractions of waste ($R_x$) in each of the three precipitation ranges and are given in Columns C, D, and E, respectively. Columns F, G, and H are the calculation of **$f \cdot R_x \cdot k \cdot L_o$** for each of the three ranges. Using 1940 (Row 3) as an example:

$\mathbf{f_1 \cdot R_x \cdot k_1 \cdot L_o}$ = 0.11 * 83.9 *$10^{12}$g/yr * 0.02 ($yr^{-1}$) * 100 $m^3/10^6$g = 18.5 million $m^3$ [Cell F3]
$\mathbf{f_2 \cdot R_x \cdot k_2 \cdot L_o}$ = 0.40 * 83.9 *$10^{12}$g/yr * 0.038 ($yr^{-1}$) * 100 $m^3/10^6$g = 128 million $m^3$[Cell G3]
$\mathbf{f_3 \cdot R_x \cdot k_3 \cdot L_o}$ = 0.49 * 83.9 *$10^{12}$g/yr * 0.057 ($yr^{-1}$) * 100 $m^3/10^6$g = 234 million $m^3$ [Cell H3]

The millions of $m^3$ for each year (Columns I through V) are calculated by multiplying each of the three values of **$f \cdot R_x \cdot k \cdot L_o$** by the three vaules of the exponential term $\mathbf{e^{-k(T-x)}}$ (i.e., three values of k for each precipitation range). For Cell I3 (methane generation in 1990 by waste landfilled in 1940), T= 1990, x = 1940, and T-x = 50:

$\mathbf{e^{-k_1(T-x)}}$ = $e^{-.02\,(50)}$ = 0.368 * 18.5 = 6.8
$\mathbf{e^{-k_2(T-x)}}$ = $e^{-.038\,(50)}$ = 0.150 * 128 = 19.2
$\mathbf{e^{-k_3(T-x)}}$ = $e^{-.057\,(50)}$ = 0.0578 * 234 =13.5

Summing these gives a value of 39.5 million $m^3$ in Cell I3 (39.44 is the actual value in the cell because the spreadsheet carries many more significant figures in the calculations). The methane generation is then summed for each year of waste disposal (Cells I67 to V67) using the following equation:

$$\mathbf{Q_T = \sum Q_{T,x}} \ \textbf{(for x equal to initial year to year T)}$$

where

$Q_T$ =total methane generated ($m^3$) in year T from waste disposed of in previous years (including year T).

Methane generation is converted from $m^3$ to Gg in Cells I68 to V68 using a density of 676 g/$m^3$ from the Inventory Annex:"Constants, Units, and Conversions."

### *10.2 EIA Database.xls*

The database from the Energy Information Agency (EIA) is from Form 1605b voluntary reporting and is available at <<ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/>>. Extensive review was required to eliminate duplicate reporting from multiple companies and ensuring that reductions were all reported as direct reductions of methane. This spreadsheet was cross checked with the database from the Landfill Methane Outreach Program (LMOP): ***LFGTE_spreadsheet2003.xls***. Both databases contain fairly detailed information on the landfill name, owner or operator, city and state. If a landfill from LMOP was in the EIA database, it was identified as such in Column A and the LMOP landfill ID is given in Column E.

Methane reductions were reported in Mg (metric tons) and are generally based on measured gas flow rates and percent methane. The EIA reporting time frame for the data is 1991 to 2002. For 2003, the reduction was assumed to be the same as for 2002 (and will be updated when the 2003 EIA data become available). In some cases, the reductions were not reported for the earlier years because the gas flow rate was not measured. In those cases, the reductions were extrapolated back to the project start date given in Column I.

The EIA database was also checked against the flare vendor database (***Flare Database.xls***). When a match was found between the two databases, the flare ID from the flare database was entered into Column F, and the landfill ID from the EIA database was entered into the flare database. Column AI through AV provide the methane reductions for landfills for which no associated flare was matched in the flare vendor database. The reductions for unmatched projects are compiled in the Sheet ***By State***. This sheet is a pivot table that sums these unmatched reductions by State and by year. These results are linked to and used in the flare vendor spreadsheet to calculate the flare correction factor, which is explained in the next section.

### *10.3 Flare Database.xls*

The flare vendor database has been compiled over the past few years from information vendors have supplied on flares they have sold for use at landfills. It is updated each year. The type of flare information that is supplied varies by vendor - some provide a maximum flow capacity, others provide a range of applicable flows, and some provide only the flare dimensions. All provide some information on the name of the landfill or user, the date the flare was shipped, city, and state. When a landfill in the flare database was matched with one in the EIA database, reductions were not counted in the flare vendor database. Flares matched to landfills in the EIA database are in a separate Sheet called ***In EIA Database*** and are not included in the flare vendor calculations.

To estimate a typical gas flow rate for the flare, a midrange value is used. This is simply the midpoint if the vendor provides a applicable range of flow for the flare. One vendor (Zink) provided information on flare dimensions and provided a range of flows for flares with specific dimensions. This information is given in the Sheet ***Conversions*** in Cells B20 to F42. When flare dimensions are provided, a code is assigned that places the flare in the appropriate flow range for those dimensions, and the midpoint of the range is used to estimate typical flow. When a maximum capacity is given, it is compared to the ranges of flow for various flare sizes and a range is chosen that includes the capacity. Again, the midpoint of the range is then used to estimate typical landfill gas flow rates.

The midpoint of the flow range is given in Column AD in standard cubic feet per minute (scfm). This is converted to an estimate of million metric tons of carbon equivalent (MMTCE) in Column AG using conversion factors in the Sheet ***Conversions***. The calculation assumes 50 percent of the gas is methane and uses a methane density of 0.0423 lb/$ft^3$. Metric tons (MT) of methane are converted to MMTCE based on a global warming potential of 21, molecular weight of carbon (12), and molecular weight of $CO_2$ (44):

$$MMTCE = 21 * (12/44) * (10^{-6} \text{ million MT/MT}) = 5.73\text{x } 10^{-5} * \text{MT methane}$$

The calculation is shown below for Cell AD8 with 520.5 scfm:

$$520.5 \text{ ft}^3\text{/min} * 1{,}440 \text{ min/day} * 365 \text{ days/yr} * 0.5 \text{ (fraction methane)} * 0.0423 \text{ lb/ft}^3 * (1 \text{ MT/2,205 lb}) * 5.73\text{x } 10^{-5} \text{ MMTCE/MT} = \mathbf{0.015 \text{ MMTCE}} \text{ in Cell AG8.}$$

Overall, the calculation reduces to MMTCE = $2.89 \times 10^{-5}$ * scfm.

The landfills in the flare database were compared to those in the LMOP database (***LFGTE_spreadsheet2003.xls***) and duplicates were identified. The matches and LMOP information are in Columns U through Y of the Sheet ***Flare Data***. If a flare is associated with a gas-to-energy project in the LMOP database, the flare reductions are not counted. The following logic sequence is used to determine how a flare reduction is counted for a specific year.

- Column Q determines when a flare is assumed to be operational based on the date it was shipped. If the flare was shipped after September of a given year (if the month is known), it is assumed to be operational the next year. Otherwise, it is assumed to be operational in the year shipped. It is assumed to be operational in the year shipped if no month is given for the shipment.

- If there is no LFGTE project associated with the flare, its reductions are counted for the year it became operational and for the years thereafter.

- If the flare is associated with a LFGTE project and was shipped before the project became operational, flare reductions are counted up to the year the project became operational (see Column X "Year LFGTE was installed").

- If the LFGTE project shutdown, flare reductions are counted for the years following the shutdown date (given in Column Y) or the year the flare became operational, whichever is later.

The Sheet ***Total by State*** contains a pivot table that sums the reductions in the flare database by State and by Year in Column B. Column K contains the reductions from operational projects in the LFGTE database without identified flares also summed by year and by State. Column M contains the same information for LFGTE projects that have shutdown. (These values are linked to the LFGTE spreadsheet and are explained more fully in the next section.) Column M contains the estimated reductions for flares and LFGTE projects with no matches to the flare vendor database summed by year and by State. The difference is calculated in Column N as follows to determine the flare correction factor. If the sum of emissions avoided by unmatched projects in the LFGTE and EIA database is less than the flare reduction for a given year and State, the sum from those reductions is placed in the difference column, otherwise the flare reduction is placed in the difference column. This approach is designed to be conservative and ensures that the unmatched reductions are subtracted from the flare reductions to avoid any chance of double counting. The flare correction factor for each year is determined in the pivot table at Cell T26, which sums the differences across States and determines the total by year. These values are the flare correction factor that will be subtracted from the flare reduction totals for each year.

The totals for the flare vendor database are given in the Sheet ***Flare Data*** in Cells AH611 through AU613. Row 611 has the flare total without the correction factor, Row 612 has the correction factor, and Row 613 has the final estimate based on subtracting the correction factor from the total reductions by flares. The Sheet ***Flare Summary*** presents the estimates with and without the correction factor and includes other summary information. The estimates from previous inventory years are also presented to show how the estimates changed over time. The flare reductions in the vendor database are lower for 2003 because there were more matches due to flares at landfills in the EIA database.

### *10.4 LFGTE_spreadsheet 2003.xls*

The LFGTE spreadsheet is based on a database provided by EPA's LMOP in July 2004 on gas-to-energy projects in their voluntary program. The Sheet ***LFGTE Master*** contains all of the landfills in the LMOP database. The Sheet ***Operational*** contains the operating projects that are used to estimate emissions avoided, and similar information on shutdown projects is provided in the Sheet ***Shutdown***. Projects include those that generate electricity and those that use the gas directly (e.g., direct thermal projects). Methane reductions for electricity projects are based on generating capacity in megawatts (MW), and the gas flow to the project is used for gas projects. Column AC determines if the project is for electricity (1) or for gas (0) based on the project description in Column AB. The project utilization start year in Column AK is determined from the project start date. Projects starting after September are given the next year as the start year. Column AN identifies landfills that are in the EIA database (yes=0), and no reductions are calculated for these landfills. Column AT identifies landfills that have been matched to flares, and, if matched, the flare ID is given in Column AU.

The procedure to estimate methane reductions from electricity projects was developed by LMOP,[4] and the inputs are given in the Sheet ***conversions*** (Columns A and B)[5]. The first step calculates the kW-hr/yr for 1 MW of capacity based on an availability factor of 0.93:

kW-hr/yr = 1 MW * 8,760 hr/yr * 0.93 * 1,000 kW/MW = 8,146,800 [Cell B20]

The tons of methane reduced by one MW capacity is based on a heating rate of 11,700 Btu/kW-hr, a methane heating value of 1,012 Btu/$ft^3$, and a methane density of 0.0423 lb/$ft^3$:

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[4] Memo from ERG to LMOP dated November 18, 2002 entitled "Draft Revised LMOP Emission Reduction Equations for Landfill Gas Energy Projects." Provided in Annex F.

[5] The example calculations are keyed to operational projects; however, the same procedure is used for shutdown projects.

$$8{,}146{,}800 \text{ kW-hr/yr} * 11{,}700 \text{ Btu/kW-hr} * 0.0423 \text{ lb/ft}^3 / 1{,}012 \text{ Btu/ft}^3 / (1 \text{ ton}/2{,}000 \text{ lb}) = 1{,}993 \text{ tons [Cell B21]}$$

The electricity project is assumed to be operating 93 percent of the time. However, when the project is not operating, the landfill gas is flared. Methane reduced by flaring for a one MW project is estimated as:

$$0.07 * [1{,}993 \text{ tons}/0.93] = 150 \text{ tons [Cell B22]}$$

which gives a total of 2,143 tons of methane for 1 MW of capacity (1,993 + 150). This is converted to MMTCE based on a global warming potential of 21, molecular weight of carbon (12), and molecular weight of $CO_2$ (44):

$$2{,}143 \text{ tons} * 21 (12/44) / (0.907 \text{ tons/MT}) * (10^{-6} \text{ million MT/MT}) = 0.011 \text{ MMTCE [Cell B25]}$$

This factor (0.011 MMTCE per MW) is multiplied by the MW capacity in Column U (for electricity projects) to estimate the reductions in MMTCE.

Methane reductions for gas projects are based on the gas flow rate in Column AE (million $ft^3$/day), 365 days per year of operation, 50 percent methane in the gas, and a density of 0.0423 lb/$ft^3$. One million $ft^3$ per day produces 3,862 tons per year of methane:

$$10^6 \text{ ft}^3\text{/day} * 365 \text{ days/yr} * 0.5 * 0.04233 \text{ lb/ft}^3 / (2000 \text{ lb/ton}) = 3{,}862 \text{ tons [Cell F21].}$$

This is converted to MMTCE based on a global warming potential of 21, molecular weight of carbon (12), and molecular weight of $CO_2$ (44):

$$3{,}862 \text{ tons} * 21 (12/44) / (0.907 \text{ tons/MT}) * (10^{-6} \text{ million MT/MT}) = 0.020 \text{ MMTCE [Cell F25].}$$

This factor (0.020 MMTCE per million $ft^3$/day) is multiplied by the gas flow rate in Column AE (for gas projects) to estimate the reductions in MMTCE.

Emissions avoided by projects not matched to a flare in the flare vendor database are given in Columns AY through BL for operational LFGTE projects and in Columns AV through BI for shutdown projects (for the years they were operating). The MMTCE avoided for these projects are summed by year and by State in the Sheet ***By State*** and are linked to the flare vendor database as described earlier for use in determining the flare correction factor. (This is explained in the discussion in Section 10.3 for the Sheet ***Total by State*** in ***Flare Database.xls***.)

Reductions for LFGTE projects (not in the EIA database) are summed in the Sheet ***2003 Inventory***. For operational projects, Column B provides the sum for each project start year, and Column C calculates the cumulative emissions avoided for each year. Column K gives the reductions for shutdown projects for each project start year, and Column L gives the cumulative values, which are placed in Column D (using a vertical lookup table). Column O provides reductions based on the shutdown year, and the cumulative values are in Column P. The cumulative values are used in Column E and are subtracted from the shutdown totals to account for the fact that after the shutdown date, the project was no longer achieving reductions. The totals reductions are given in Column F (calculated as [reductions from operational projects] plus [reductions from shutdown projects] minus [reductions for shutdown projects after the shutdown date]). The MMTCE is converted to Tg in Cells F30 to F43 (multiplying by [44/12]/[21]).

The results for the 2002 inventory are given in Column G for comparison. The reductions are lower for the 2003 inventory because many of the projects included in the 2002 inventory are now included in the EIA database.

### *10.5 Landfills 04.xls*

The spreadsheet ***Landfills 04.xls*** summarizes and compiles the results from other spreadsheets and has the inventory reporting tables. The Sheet ***Methane Emissions*** provides the results for methane generation from MSW and for industrial landfills (assumed to be 7% of MSW generation). Reductions from flares in the vendor database and EIA database are given and summed. Reductions from LFGTE projects in the LMOP and EIA databases are presented and summed. Oxidation is estimated for MSW (10 percent of generation minus avoided) and for industrial landfills (10 percent of generation).

The Sheet ***Summary*** presents the results for 2003 in Gg, Tg, and Tg of $CO_2$ equivalents. The Sheet ***Annual Changes*** show how the inventory estimates have changed over the past 4 years.

## *11. Estimates for the 2003 Inventory with Changes in Methodology*

The changes in methodology discussed in previous sections were implemented for the 2003 inventory and the results are compared to the 2002 inventory estimates in Table 7.

The FOD model from the IPCC guidelines (Jensen and Papatti, 2002) for generating regional or national estimates is derived from Equation 1[6] and allows the use of variable waste disposal rates each year rather than assuming a constant annual average waste disposal rate:

$$\mathbf{Q_{T,x} = k \bullet R_x \bullet L_o \bullet e^{-k(T-x)}} \qquad \textbf{(Equation 3)}$$

where

$Q_{T,x}$ = the amount of methane ($m^3$) generated in year T by the waste $R_x$,
T = current year,
x = the year of waste input,
k = methane generation rate constant ($yr^{-1}$),
$R_x$ = the amount of waste disposed of in year x (Mg), and

[6] Equation 3 is the first derivative of Equation 1 with $t = T - x$.

$L_o$ = methane generation potential ($m^3$/Mg of waste).

To estimate all methane generation in the year T from waste landfilled in previous years, Equation 3 is solved for all values of $R_x$ and the results summed using Equation 4:

$$\mathbf{Q_T = \sum Q_{T,x}} \quad \textbf{(for x equal to initial year to year T)} \qquad \textbf{(Equation 4)}$$

where

$Q_T$ = total methane generated ($m^3$) in year T from waste disposed of in previous years (including year T).

The methodology used in the 2003 inventory apportions $R_x$ for each year according to the population vs. precipitation distributions for each decade as described earlier. The appropriate k value is assigned to each portion of $R_x$ for the three ranges of rainfall. Equation 3 is then used for the three values of k and $R_x$ to estimate waste generation in year T, and then Equation 4 is used to sum methane generation for each year in the time series (1990 to 2003).

Table 7 compares the estimates for the 2002 inventory to those for the 2003 inventory with the changes as discussed in this paper. The table shows that the estimate of methane generated from MSW decreased by 25% for the year 2002 using the new approach (from 15,221 to 11,364 Gg). Approximately one half of this reduction is due to changing the estimates of annual disposal rates, and the other half is due to changing from the regression equation to the FOD model.

Another change of note is in regards to the reductions. EPA accounts for LFGTE projects and flares through three separate databases: EIA, LMOP, and a flare vendor database. Since LFGTE projects have back-up flares associated with them, EPA performs a number of comparisons and adjustments to ensure that there is no double counting. The new flare data from the EIA database is more accurate than the flare vendor database and thus the EIA data was the priority dataset for flares. Flares in the vendor database were removed from the reduction calculation if matched to a flare in the EIA database. The end result of these changes is a lower estimate of reductions since the EIA reported estimates were, on average, half of the estimates based on the instrument specifications in the flare vendor database. Another impact of including an additional dataset is that the flare reductions in the flare vendor database are estimated for those flares for which there is no match or potential match in either the EIA or LMOP database, to ensure no double counting of flares as back-ups at LFGTE projects. When a project in either database cannot be matched to a flare, that project is assumed to have a flare and the reduction is subtracted from the flare reduction:

Flare reductions = unmatched flare reductions - unmatched LMOP and EIA reductions.

This conservative approach is applied on a state-by-state basis and is used to avoid any double counting of reductions (i.e., an unmatched flare may actually be a flare associated with an unmatched project in the LMOP or EIA database). The EIA database decreased the number of unmatched flares from 712 in 2002 to 449 in 2003. Thus, flare reductions calculated from the flare vendor database were decreased by about 1,000 Gg in 2002 because of the additional flare matches with the EIA database, and the EIA database estimate for these flares was about 600 Gg (a net decrease of 400 Gg). However, incorporating the EIA database had only a small overall effect on total emissions avoided– a decrease of about 10% (from 6,074 Gg to 5,450 Gg for 2002).

# TABLE 7. COMPARISON OF INVENTORY ESTIMATES FOR 2002 AND 2003

## 2002 INVENTORY ESTIMATES (Gg or 1,000 metric tons)

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MSW Generation** | 11,599 | 11,837 | 12,175 | 12,510 | 12,863 | 13,238 | 13,520 | 13,802 | 14,047 | 14,385 | 14,659 | 14,954 | 15,221 |
| **Industrial Generation**[1] | 812 | 829 | 852 | 876 | 900 | 927 | 946 | 966 | 983 | 1007 | 1026 | 1047 | 1065 |
| **Potential Emissions** | 12,411 | 12,665 | 13,027 | 13,385 | 13,764 | 14,165 | 14,466 | 14,768 | 15,030 | 15,392 | 15,685 | 16,001 | 16,287 |
| | | | | | | | | | | | | | |
| **Gas-to-energy projects** | (824) | (860) | (927) | (1,005) | (1,129) | (1,164) | (1,360) | (1,618) | (1,938) | (2,177) | (2,376) | (2,630) | (2,748) |
| **Flaring** | (478) | (703) | (849) | (1,024) | (1,270) | (1,705) | (2,059) | (2,390) | (2,692) | (2,750) | (2,764) | (3,146) | (3,325) |
| **Emissions Avoided** | (1,302) | (1,563) | (1,776) | (2,029) | (2,399) | (2,869) | (3,419) | (4,007) | (4,631) | (4,927) | (5,140) | (5,776) | (6,074) |
| **Oxidation at MSW Landfills**[2] | (1,030) | (1,027) | (1,040) | (1,048) | (1,046) | (1,037) | (1,010) | (979) | (942) | (946) | (952) | (918) | (915) |
| **Oxidation at Industrial Landfills**[2] | (81) | (83) | (85) | (88) | (90) | (93) | (95) | (97) | (98) | (101) | (103) | (105) | (107) |
| **Net Emissions** | 9,998 | 9,992 | 10,126 | 10,220 | 10,228 | 10,166 | 9,942 | 9,685 | 9,360 | 9,419 | 9,491 | 9,202 | 9,192 |

## PRELIMINARY 2003 INVENTORY ESTIMATES (Gg or 1,000 metric tons)

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MSW Generation** | 9,391 | 9,543 | 9,679 | 9,831 | 9,973 | 10,080 | 10,175 | 10,279 | 10,435 | 10,588 | 10,785 | 11,045 | 11,364 | 11,669 |
| **Industrial Generation**[1] | 657 | 668 | 678 | 688 | 698 | 706 | 712 | 720 | 730 | 741 | 755 | 773 | 795 | 817 |
| **Potential Emissions** | 10,048 | 10,211 | 10,357 | 10,520 | 10,671 | 10,786 | 10,887 | 10,999 | 11,166 | 11,329 | 11,540 | 11,818 | 12,160 | 12,486 |
| | | | | | | | | | | | | | | |
| **Gas-to-energy projects** | (669) | (694) | (766) | (846) | (902) | (1,110) | (1,336) | (1,652) | (2,018) | (2,287) | (2,472) | (2,738) | (2,814) | (2,946) |
| **Flaring** | (266) | (377) | (456) | (568) | (823) | (1,083) | (1,317) | (1,551) | (1,821) | (1,951) | (2,154) | (2,403) | (2,635) | (2,599) |
| **Emissions Avoided** | (935) | (1,070) | (1,222) | (1,414) | (1,724) | (2,193) | (2,654) | (3,202) | (3,839) | (4,238) | (4,626) | (5,140) | (5,450) | (5,545) |
| **Oxidation at MSW Landfills**[2] | (846) | (847) | (846) | (842) | (825) | (789) | (752) | (708) | (660) | (635) | (616) | (590) | (591) | (612) |
| **Oxidation at Industrial Landfills**[2] | (66) | (67) | (68) | (69) | (70) | (71) | (71) | (72) | (73) | (74) | (75) | (77) | (80) | (82) |
| **Net Emissions** | 8,202 | 8,226 | 8,221 | 8,195 | 8,052 | 7,733 | 7,410 | 7,017 | 6,595 | 6,382 | 6,223 | 6,010 | 6,039 | 6,246 |

[1] Estimated as 7% of MSW generation.
[2] Estimated as 10% of generation for industrial landfills and 10% of (MSW generation - emissions avoided) for MSW landfills.

## *12. References*


BioCycle (2004). *"14th Annual BioCycle Nationwide Survey: The State of Garbage in America,"* S. Kaufman, N. Goldstein, K. Millrath, and N. Themelis. January.

Czepiel, P., B. Mosher, P. Crill, and R. Harriss. (1996), "Quantifying the Effect of Oxidation on Landfill Methane Emissions," *Journal of Geophysical Research*, 101( D11):16721-16730.

Energy Information Agency (2004). *Documentation for Emissions of Greenhouse Gases in the United States 2002*, Section 2.1.6: Methane Emissions from Landfills, U.S. Department of Energy, Washington, DC. DOE/EIA-0638(2002). January.

EPA (2003). *Municipal Solid Waste in the United States: 2001 Facts and Figures*, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. EPA530-R-03-011. October.

EPA (2002), *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks,* U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C., EPA/530-R-02-006, June.

EPA (1999). *Biosolids Generation, Use, and Disposal in the United States*, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. EPA530-R-99-009. September.

EPA (1998a). *Characterization of Building-Related Construction and Demolition Debris in the United States*, U.S. Environmental Protection Agency, Office of Solid Waste, Washington, DC. EPA530-R-98-010. June.

EPA (1998b), *Compilation of Air Pollution Emission Factors*, Publication AP-42, Section 2.4 Municipal Solid Waste Landfills. November.

EPA (1995)*, State Workbook: Methodologies for Estimating Greenhouse Gas Emissions,* U.S. Environmental Protection Agency, EPA/230-B-95-001, January.

EPA (1993). *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress*, U.S. Environmental Protection Agency, Office of Air and Radiation, Washington, DC. EPA/430-R-93-003. April.

EPA (1988). *National Survey of Solid Waste (Municipal) Landfill Facilities*, U.S. Environmental Protection Agency, Washington, DC. EPA/530-SW-88-011. September.

IPCC/UNEP/OECD/IEA (1997), *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment

Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Jensen, J. and R. Papatti (2002), "$CH_4$ Emissions from Solid Waste Disposal," *Background Papers- IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*.

Leatherwood, L. (2002), "Review of Available Data and Industry Contacts Regarding Landfill Gas Collection Efficiency," *Memorandum to Brian Guzzone and Meg Victor, EPA*. November 18.

Liptay, K., J. Chanton, P. Czepiel, and B. Mosher (1998), "Use of Stable Isotopes to Determine Methane Oxidation in Landfill Cover Soils," *Journal of Geophysical Research*, 103( D7):8243-8250.

Mancinelli, R. and C. McKay (1985), "Methane-Oxidizing Bacteria in Sanitary Landfills," *Proceedings of the First Symposium on Biotechnical Advances in Processing Municipal Wastes for Fuels and Chemicals*, August 1984, Minneapolis, Minnesota, pp. 437-450.

Peer, R., S. Thorneloe, and D. Epperson (1993), "A Comparison of Methods for Estimating Global Methane Emissions from Landfills," *Chemosphere*, 26(1-4): 387-400.

Solid Waste Association of North America (1998), "Comparison of Models for Predicting Landfill Methane Recovery," Publication No. GR-LG 0075, March.

## *Annex A. Percent Recovery*

EASTERN RESEARCH GROUP, INC.

**DRAFT MEMORANDUM**

TO: Brian Guzzone, Meg Victor, U.S. Environmental Protection Agency

CC: Chris Voell, U.S. Environmental Protection Agency

FROM: Chad Leatherwood, Eastern Research Group, Inc.

DATE: November 18, 2002

SUBJECT: Review of Available Data and Industry Contacts Regarding Landfill Gas Collection Efficiency

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## 1.0 INTRODUCTION

The purpose of this memorandum is to summarize current information and data regarding the collection efficiency of landfill gas (LFG) collection systems at municipal solid waste landfills. The current EPA *AP-42* emission factor document that addresses municipal solid waste landfills states that reported collection efficiencies range from 60 to 85 percent, with an average of 75 percent most commonly used. However, these reported collection efficiencies are not based on test data and are somewhat dated. The review of LFG collection efficiency information was conducted by contacting industry and academic experts and through a search and review of available information (i.e., technical papers, test reports, landfill progress reports). Section 2.0 discusses the findings of this review. Section 3.0 provides a summary of contacts and literature reviewed.

## 2.0 SUMMARY OF FINDINGS

Overall, there is minimal data on LFG collection system efficiency. Based on discussions with several industry contacts, this shortage of available collection efficiency data is due to difficulty in documenting uncontrolled LFG emissions. Accurately measuring uncontrolled LFG emissions is troublesome due to several reasons. Emissions from landfills do not come from a single point, or even a specific area. The fact that LFG can migrate horizontally, as well as vertically, within a landfill before entering the atmosphere results in uncontrolled emissions emanating from almost anywhere above a landfill cell. Given the size of municipal solid waste landfills, attempting to accurately measure emission rates from the entire landfill surface is complex. LFG generation rates are variable. Due to the heterogeneous nature of municipal solid waste, temperature variation within the landfill, variation in rainfall levels, and ongoing placement of waste in landfills, emission levels vary spatially across the surface of the landfill as well as temporally. Thus, short-term measurements of uncontrolled LFG emissions only provide a snapshot of a changing emission dynamic. Since the calculation of LFG collection efficiency depends on uncontrolled emission levels, it too is a changing value. Another reason for the lack of collection efficiency data is due to the fact that the last remaining percentages of uncontrolled methane are very expensive to capture. Not that this analogy is numerically correct, but the LFG collection falls under the 80/20 rule where it's relatively easy to get 80 percent of the generated gas, but the last 20 percent becomes much more difficult to collect. Therefore, the argument is why go through the effort to try to accurately assess collection efficiency when it would not be cost effective to collect the last percentages of LFG not currently controlled by modern landfill collection systems at landfills designed for gas collection.

Some studies of specific landfills and theoretical calculations of LFG production have resulted in models to predict uncontrolled LFG emission levels. However, these models have shown wide variation when applied to specific landfills, probably due to the site-specific factors that effect LFG generation and that measurements and models represent snapshots of a dynamic process. One recent reference (*Predicting LFG Generation and Extraction Using the EMCON Model*, 1997) states that a model will not actually replicate the site specific LFG generation, but should only bracket the potential range of LFG generation and that the extraction system efficiency must be determined by judgement.

From the review of contact and literature review summaries, it was clear that the efficiency of a LFG collection system is greatest when the landfill is designed and constructed with gas recovery in mind. The most important factor is lining the landfill and incorporating a geomembrane type cover. The lining and cover, along with maintaining negative pressure within the landfill, appear to be the most important factors in maximizing gas extraction.

As far as specific claims of collection efficiencies, Pacific Energy did claim to get 85 percent collection efficiency at their Toyon Landfill, 90 percent at their Penrose Landfill, and 95 percent at their Sheldon-Arleta Landfill. A comprehensive LFG fate study was recently conducted in France. The results of this study on two landfills reported LFG collection efficiencies of 94 percent and 98 percent. However, at the French facility that reported 94 percent LFG collection efficiency, this efficiency was based on the lowest of three predicted LFG generation levels for that facility. When the highest estimate of LFG generation is used, then the LFG collection efficiency drops to 84 percent. This raises the issue again that a major difficulty in determining LFG collection efficiencies is accurately estimating LFG generation levels. Based on discussions with an author of the paper documenting the French landfill studies, she noted that landfill methane generation models typically over-predict generation levels.

No other references provided collection efficiencies for individual landfills. One reference stated that collection efficiency should be in the range of 50 to 85 percent during landfilling operation and 80 to 95 percent after the final landfill cover is in place. The lower value represents landfills without a geomembrane component and has a relatively permeable soil cover and the upper value is representative of a final cover system with a geomembrane component. A few other contacts and references stated that newer landfills that are lined and capped with a geomembrane cover should achieve greater than 90 percent collection efficiency. Another contact uses an assumption of 85 percent collection efficiency when a landfill is fully lined and 70 to 75 percent when a landfill has a clay cover. Yet another contact noted a proprietary study where an operating landfill was achieving a 60 percent collection efficiency. Most contacts and references noted that collection efficiency is a site-specific variable.

Overall, the ranges provided in *AP-42* seem to correlate with current conventional wisdom of collection efficiency at landfills without a geomembrane component in the cover, where *AP-42* reports collection efficiencies of 60 to 85 percent, with an average of 75 percent. Many believe that 90 percent or greater collection efficiency can be achieved at newer landfills designed with gas recovery in mind.

## 3.0 CONTACT SUMMARIES AND LITERATURE REVIEW

**<u>Review of Available References:</u>**

*Compilation of Air Pollutant Emission Factors (AP-42). Volume I: Stationary Point and Area Sources. Section 2.4: Municipal Solid Waste Landfills. Fifth Edition With Current Updates. U.S. Environmental Protection Agency. Page 2.4-6.*

> *"Reported collection efficiencies range from 60 to 85 percent, with an average of 75 percent most commonly assumed. Higher collection efficiencies may be achieved at some sites (i.e., those engineered to control gas emissions). If site-specific collection efficiencies are available (i.e., through a comprehensive surface sampling program), then they should be used instead of the 75 percent average."*
>
> This discussion does not have any direct reference in the bibliography to this section. We reviewed the AP-42 background document to determine possible references. See below.

*Compilation of Air Pollutant Emission Factors (AP-42). Volume I: Stationary Point and Area Sources. Section 2.4: Municipal Solid Waste Landfills. Background Information Document. Fifth Edition With Current Updates. U.S. Environmental Protection Agency. Pages 2-9, 4-4, and 4-22.*

> *"The effectiveness of a LFG collection system is also dependent upon its design and operation. Active gas collection systems are generally more efficient than passive gas collection systems."* (Reference: *Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines. EPA-450/3-90-011a*)
>
> *"Uncontrolled methane emissions may be estimated for individual landfills by using a theoretical first-order kinetic model of methane production. This method of estimating emissions could result in conservative (i.e. high) estimates of emissions, since it provides estimates of LFG generation and not release to the atmosphere*."
>
> *"Reported gas collection efficiencies range from 60 to 85 percent, with an average of 75 percent most commonly assumed.* (Reference: *Augenstein, D. and J. Pacey. "Modeling Landfill Methane Generation." EMCON Associates, San Jose, CA.* 1992. Unable to locate.). *Higher efficiencies may be achieved at some sites (i.e., at lined landfills with well-designed collection systems). If a site-specific collection efficiency is available (i.e. derived from a surface sampling program), it should be used instead of the 75 percent average.*"

*"Analysis of Factors Affecting Methane Gas Recovery from Six Landfills." EPA-AEERL. EPA 600/2-91-055. September 1991.*

> After a review of this document, the following information on collection efficiency was found: "*The main problem was that the collection efficiencies of the methane recovery systems were not known. Where emission control was one (or the only) reason for the collection system's existence, efficiency appeared to be high. However, this is a qualitative assessment based on visual inspection of the landfills and an assessment of operating practices at the landfills. Perhaps landfills where methane recovery systems are used for emissions control can be used as a benchmark, if enough of them can be found."*
>
> The main objectives of this study were to determine landfill data on methane recovery rates, gas composition, etc. at landfills with gas recovery systems, use these data to determine trends in the effects of climate, refuse age, etc., and use the results of the emissions testing and data analysis to assess the relationship between gas recovery and gas generation.

*Augenstein, D. and J. Pacey. "Modeling Landfill Methane Generation." EMCON Associates, San Jose, CA. 1992.*

I forwarded this reference title to Juene Franklin at EMCON in hopes that he might be able to retrieve it. He was unable to locate this document.

*"Methodologies for Quantifying Pollution Prevention Benefits From LFG Control and Utilization." EPA 600/R-95-089.*

Not available on-line. Can order hard copy for $30.00.

*"LFG-to-Energy Project Opportunities." EPA 430/K-99-002.*

Reference was available on-line. No data regarding landfill collection efficiencies.

*"Turning a Liability Into an Asset: A Landfill Gas-to-Energy Project Development Handbook" EPA-430/B-96-0004. September 1996.*

Reference was available on-line. Based on review, no references for collection efficiency. Document notes collection system efficiencies of 50 - 90 percent, with newer systems achieving 75 - 85 percent.

*Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines. EPA-450/3-90-011a. March 1991.*

"*Based on theoretical evaluations, well-designed active collection systems are considered the most effective means of gas collection*." (Reference: *EPA Handbook. Remedial Action at Waste Disposal Sites. EPA 625/6-85-006.* October 1985.)

"*The collection efficiency has not been determined at any landfill. However, one landfill facility operator estimated that a well-designed system can typically collect about 50 to 60 percent of the gas generated within a landfill*." (References: Telecon. McGuinn, Radian Corp. with L. Crosby, GSF Energy. February 1987. Meeting Report. Comments received at the NAPTAC Meeting. May 1989.)

*California Air Resources Board Web Site*

No additional LFG collection efficiency studies were identified other than the study referenced in the *AP-42* section, and that study referred to the EPA on the assumed collection efficiency.

*M. Diot, et al. "LFG Mass Balance: A Key to Optimise LFG Recovery"*

This paper documents LFG mass balances at two landfill facilities in France that use recovery systems and one cell where no LFG recovery is in place. The study on these landfills was conducted in France and the authors take a very detailed look at methane fate in controlled landfills. Based on their findings, they determined that the collection efficiency was 94% at one site and 98% at the second. It appears that the first site (94% recovery) has a clay cover, while the cover type at the second site (98% recovery) is unknown. In this study, three methods were also used to estimate methane generation at one landfill. The estimates ranged from 1.52 $x10^6$ $m^3$ (methane) to 1.7 x $10^6$ $m^3$ (methane), averaging 1.63 x $10^6$ $m^3$ (methane). The authors noted that the lowest generation estimate, using the LMGM model, provided an accurate estimate of the produced methane and was used to determine LFG collection efficiency. However, if the highest LFG generation estimate provided by the authors is used, this results in an LFG collection efficiency of 84%.

**<u>Papers Received From Juene Franklin and Mike Michels of EMCON/OWT, Inc.</u>**

*Frederick Rice, Roy F. Weston, Inc. "The Impact of Geomembrane Covers on LFG System Design and Operation." No date.*

This document covered the impacts of geomembrane covers on landfills. There is some discussion as to the effect on LFG collection efficiency, but it only states that the use of geomembrane covers increases the collection efficiency. No data or reference was noted on that claim.

*EMCON Guideline. "Predicting LFG Generation and Extraction Using the EMCON Model." September 1997.*

This paper provides background information and limitations of the EMCON model for LFG growth and decay cycles. It covers many of the factors (moisture, landfill composition, internal temperature) that can effect the generation of methane from a landfill. The paper states that moisture is the most important parameter in the determination of LFG generation rates and yield at moderate to wet landfills. It also states that due to the heterogeneous nature of refuse, the variety of the landfill internal refuse conditions which impact the decomposition process, and a host of other variables, a model will not actually replicate site-specific LFG generation, but should only bracket the potential range of LFG generation. Regarding LFG collection efficiency, the paper states that:

*"The extraction system efficiency is a constantly changing value as new refuse is placed daily and a new phase of an extraction system will be place infrequently. Only when the final extraction system is installed will the efficiency remain constant. At various points in time during the landfill operation, the LFG extraction system efficiency may be determined by judgement which considers the combined effect of the extraction system and the cover system. The EMCON model can readily predict the LFG rate of generation and yield, but the LFG extraction system efficiency must be determined by judgement. During landfilling operation the extraction system efficiency should be in the range of 50 to 85 percent. When the landfill is completed and the final cover is in place, it should be in the range of 80 to 95 percent (the lower value is for a landfill where the final cover does not contain a geomembrane component and has a relatively permeable soil cover: the upper value is reflective of a final cover system with a geomembrane component.)"*

The paper goes further into the difficulty in predicting LFG generation:

*"We must never forget that the conditions within any landfill are heterogeneous, the microorganisms that work to degrade the various organic matter contained in the refuse are varied and inconsistent, the parameters favoring the rate and yield of LFG are never uniform, and so on. Therefore, we must temper our findings with actual values, or similar values from what might appear to be similar landfills."*

*EMCON Associates. "State of the Art of Landfill Gas Recovery." February 1981.*

This paper discusses the most current technologies in LFG recovery. However, no data or recovery efficiencies are presented. In discussion of actual LFG generation at a landfill, the paper states:

*"Development of this and other models is based on "point-in-time" measurements of existing landfills; however, no study to date has measured all the gas produced from a large mass of refuse."*

*Pacific Energy/Dr. Stan Zison. Comments on the Draft Suggested Control Measure for Landfill Gas Emissions and Draft Landfill Evaluation Guidelines. May 1990.*

These comments cover a wide variety of issues related to landfills, including flux box measurements and work done by Pacific Energy to quantify emissions. While little supporting data is presented, Pacific Energy does state that with some confidence they achieve 90 percent collection efficiency at the Penrose Landfill, 95 percent collection efficiency at the Sheldon-Arleta Landfill, and 85 percent collection efficiency at the

Toyon Landfill. They indicate that these efficiencies were based on surface-probe monitoring data taken from the landfills.

*EMCON Associates. "Controlled Landfill Project. Mountain View California." Fifth Annual Report. 1985.*

Report discusses the current status of the landfill, but does not discuss landfill collection efficiencies.

*EMCON Associates. "Potential Application of Gradient Analysis Concepts to LFG Field Testing."*

This paper discusses a model that defines how LFG flows inside the refuse when influenced by an extraction well. There is no discussion on LFG collection efficiencies.

*Alan Young, Nigel Gay. "Interactions Between Gas Extraction Wells." December 1993.*

This paper discusses the effects of LFG well placement and the interaction of neighboring wells. There is no discussion on LFG collection efficiencies.

*A. Leach. "A Practical Study of the Performance of Various Gas Cell Designs and of Combined Gas and Leachate Abstraction Systems." October 1991.*

This paper discusses the performance characteristics of different well types, specifically installation and long term performance. However, there is no discussion of LFG collection efficiencies.

*Hydro-Geo-Chem's Gradient. Trends in Environmental Science and Technology. July 2002.*

This paper discusses the baro-pneumatic method for estimating LFG generation rates. They claim that this method is more accurate and technically defensible that other methods, and is also less expensive to perform. There is no discussion of LFG collection efficiencies.

*J. Bogner, P. Scott. "Landfill Methane Emissions: Guidance for Field Measurements." September 1994.*

This paper discusses various methods for estimating uncontrolled LFG emissions. There is no discussion of LFG collection efficiencies.

*F. Dair. "Landfill Methane Recovery Shows Promise, But Projections May Be Too Optimistic." October 1976.*

This paper discusses the gas production, migration, and recovery operations that take place at landfills. There is no discussion of LFG collection efficiencies.

*J. Carlson/EPA. "Recovery of Landfill Gas at Mountain View. Engineering Site Study." May 1977.*

This report discusses the composition of the LFG, extraction rate of LFG, total LFG production rate, and the effect of moisture on LFG production. There is no discussion of LFG collection efficiency.

*EMCON Associates. "Methane Generation and Recovery From Landfills." 1982.*

This report covers the whole process of LFG generation to utilization. However, there is no data or discussion regarding LFG collection efficiency.

**Summary of Industry Contacts:**

Dr. Debra Reinhart. University of Central Florida. 407-823-2156. I contacted Dr. Reinhart on September 11. She has never researched collection efficiency and did not have any good leads. She suggested looking into fugitive emissions data at facilities with gas collection systems to do an evaluation. Also, look into flux measurements to compare with collection levels. She also suggested that we contact Susan Thorneloe at EPA.

Juene Franklin. EMCON/OWT, Inc. 713-996-4581. I contacted Juene on September 12. He did not know of any definitive tests or data regarding collection efficiencies. However, he is going to have Mike Michels do a quick search for any documents or papers on the subject. He said that it is going to be tough to find an exact efficiency number because it's difficult to determine the exact generation rate from a landfill. Often times you compare the generation estimate of EPA's LandGEM model to the measured collection rate, but given the variation in the model estimate versus actual generation, the accuracy may be suspect. Typically, Juene assumes an 85 percent collection efficiency when a landfill is full lined and 70 to 75 percent when the landfill has a clay cap. Juene considered doing a paper on LFG collection efficiency, but found out that it was going to be difficult to get accurate generation data. Juene provided me with other contacts that might be able to provide some input on this subject: Mike Michels (414-659-7075), Tom Bilgri (630-771-9213), and John Pacey (415-455-

0174).

Dr. Robert Ham. University of Wisconsin. 608-592-2255. I contacted Dr. Ham on September 12. He has done a lot of work with the LFG industry, but did not know of any exact data or studies on collection efficiencies. He uses a 90 percent collection efficiency assumption for fully lined landfills and believes that you can achieve closer to 100 percent collection efficiency, but has no way to prove it. He knew of some proprietary studies where open/operating landfills were achieving 60 percent collection efficiency. He said that we should talk to Dr. Jean Bogner regarding the flux box and flux studies that she has conducted. From that, you could compare total uncontrolled emissions to actual LFG collection to arrive at a collection efficiency value.

Don Augenstein. 650-856-2850. I called Don Augenstein on September 11. No answer, so I left a message. Don returned my call on September 20th. He started the conversation with the statement that collection efficiency is good, but not great. There is not much hard data collected and any data collected is guarded by lawyers to shield liability issues. He noted that to come up with a definitive collection efficiency number will be complex because the available papers do not reference actual data. When landfills were first welled, the goal was to capture all the available methane. One possible contact provided by Mr. Augenstein was Stanley Zison, who used to be with PG&E. He has noted collection efficiencies up to 90 percent. Another reason for the lack of collection efficiency data is due to the fact that the last percentages of uncollected methane are very expensive to get. Don believes that 95 percent recovery is achievable with full membrane cover and negative pressure inside the cell. The only data that he can site is work done by Dr. Zison. He also suggested contacting Hanz Oonk (TNO-Netherlands) for more info. Don noted that from the 19 landfill model study, we can get default yield and recovery, but sometimes those relations provide recovery estimates that are greater than the landfill production. Don is currently working on a letter to Peter Anderson to refute Mr. Anderson's assertion of 10 to 20 percent collection efficiency. Don said that to gather all his references would require project monies.

Dr. Fred Pohland. University of Pittsburgh. 412-624-1880. I talked to Dr. Pohland on September 16th. His comments were that collection efficiency depends on how well the landfill system was designed and constructed. Also, the timing of the liner and cover system installation is important. Overall, he thinks collection efficiency is site-specific.

Ron Myers. EPA/EFIG. 919-541-5407. I contacted Ron Myers regarding the source of the collection efficiency values presented in the *AP-42* section on landfill emissions, since there was no direct reference. He said that the numbers were taken from the *Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed*

*Standards and Guidelines.*

Mike Michels. EMCON/OWT, Inc. 414-659-7075. Contacted on September 16. Michael returned my call with an e-mail on Sept. 23rd. In his e-mail he noted several references that he had found. He is copied and sent them to me. These references are summarized in the previous section.

Tom Bilgri. EMCON/OWT, Inc. 630-771-9213. Contacted on September 16th, left message, no response.

John Pacey 415-455-0174. Contacted on September 16th, no answer and no answering machine.

Dr. Jean Bogner. Landfills Plus, Inc. 630-665-0872. I contacted Dr. Bogner on November 8. We discussed some of her work regarding LFG pathway characterization. She has been working on LFG studies at several landfills in France and is co-authoring several papers on the findings. She sent one paper that she and several other authors have recently written entitled, "LFG Mass Balance: A Key to Optimise LFG Recovery" (See the *Review of Available References* section earlier in this memorandum for further discussion of this paper). Dr. Bogner said that there are a couple other papers that she is working on that address LFG fate and those papers are currently under review by Environmental Science & Technology. Dr. Bogner noted that some of the difficulty in accurately determining LFG collection efficiency is that most methods of determining LFG production overestimate total LFG generation.

## *Annex B. Database for the FOD Model*

| WIP (Mg) | WIP year | Annual Precipitation (inches) | Collected CH4 (Q, m3/year) | Generated CH4 (Q, m3/year) | Methane year | Yr since landfill opened (t) | Yr since closure (c) | Annual waste (R, Mg/yr) | Yrs landfilled used | Landfill Closure Year | k (1/yr) | Average k by precipitation range | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11,763,194 | 2000 | 8 | 1.8E+07 | 2.41E+07 | 2000 | 10 | 0 | 1,176,319 | 10 | 2041 | 0.023 | | |
| 6,727,273 | 2000 | 12 | 8.0E+06 | 1.06E+07 | 2000 | 14 | 0 | 480,519 | 14 | 2050 | 0.018 | | |
| 4,363,636 | 2000 | 16 | 6.9E+06 | 9.24E+06 | 2000 | 11 | 4 | 623,377 | 7 | 1996 | 0.026 | | |
| 4,363,636 | 2000 | 16 | 3.7E+06 | 4.89E+06 | 2000 | 18 | 11 | 623,377 | 7 | 1989 | 0.014 | **0.020** | **for <20 inches/yr** |
| 5,100,000 | 2000 | 21 | 9.8E+06 | 1.31E+07 | 2000 | 25 | 0 | 204,000 | 25 | 2030 | 0.041 | | |
| 8,103,500 | 2000 | 23 | 1.7E+07 | 2.23E+07 | 2000 | 7 | 0 | 1,157,643 | 7 | 2016 | 0.031 | | |
| 8,076,157 | 2000 | 29 | 9.1E+06 | 1.21E+07 | 2000 | 11 | 0 | 734,196 | 11 | 2007 | 0.016 | | |
| 4,877,533 | 2000 | 30 | 4.0E+06 | 5.32E+06 | 2000 | 25 | 0 | 195,101 | 25 | 2042 | 0.013 | | |
| 5,471,432 | 2000 | 30 | 5.0E+06 | 6.65E+06 | 2000 | 16 | 0 | 341,965 | 16 | 2007 | 0.014 | | |
| 5,942,650 | 2000 | 30 | 8.0E+06 | 1.06E+07 | 2000 | 15 | 0 | 396,177 | 15 | 2005 | 0.021 | | |
| 4,687,608 | 2000 | 31 | 8.7E+06 | 1.16E+07 | 2000 | 22 | 0 | 213,073 | 22 | 2008 | 0.036 | | |
| 5,166,273 | 2000 | 32 | 3.8E+06 | 5.02E+06 | 2000 | 19 | 0 | 271,909 | 19 | 2005 | 0.011 | | |
| 1,400,000 | 2000 | 33 | 6.3E+06 | 8.42E+06 | 2000 | 15 | 0 | 93,333 | 15 | 2005 | 0.155 | | |
| 2,460,040 | 2000 | 35 | 1.3E+07 | 1.72E+07 | 2000 | 24 | 0 | 102,502 | 24 | | no solution | | |
| 6,794,160 | 2000 | 36 | 7.1E+06 | 9.52E+06 | 2000 | 22 | 0 | 308,825 | 22 | 2032 | 0.017 | | |
| 3,683,509 | 2000 | 36 | 6.8E+06 | 9.10E+06 | 2000 | 18 | 0 | 204,639 | 18 | 2007 | 0.033 | | |
| 3,968,965 | 2000 | 36 | 6.2E+06 | 8.24E+06 | 2000 | 14 | 0 | 283,498 | 14 | 2026 | 0.025 | | |
| 5,188,031 | 2000 | 37 | 7.0E+06 | 9.32E+06 | 2000 | 24 | 0 | 216,168 | 24 | 2007 | 0.024 | | |
| 2,943,025 | 2000 | 37 | 1.7E+07 | 2.24E+07 | 2000 | 10 | 0 | 294,303 | 10 | 2022 | 0.143 | | |
| 20,000,000 | 2000 | 37 | 1.9E+07 | 2.56E+07 | 2000 | 20 | 0 | 1,000,000 | 20 | 2025 | 0.015 | | |
| 11,424,171 | 2000 | 38 | 2.1E+07 | 2.79E+07 | 2000 | 18 | 0 | 634,676 | 18 | 2007 | 0.032 | | |
| 3,100,000 | 2000 | 38 | 4.4E+06 | 5.89E+06 | 2000 | 24 | 7 | 182,353 | 17 | 1993 | 0.030 | | |
| 6,591,180 | 2000 | 39 | 1.1E+07 | 1.52E+07 | 2000 | 19 | 0 | 346,904 | 19 | | 0.030 | | |
| 909,091 | 2000 | 40 | 3.0E+06 | 4.03E+06 | 2000 | 17 | 5 | 75,758 | 12 | 1995 | no solution | **0.038** | **for 20 to 40 in/yr** |
| 8,158,234 | 2000 | 41 | 1.1E+07 | 1.48E+07 | 2000 | 21 | 4 | 479,896 | 17 | 1996 | 0.024 | | |

| WIP (Mg) | WIP year | Annual Precipitation (inches) | Collected CH4 (Q, m3/year) | Generated CH4 (Q, m3/year) | Methane year | Yr since landfill opened (t) | Yr since closure (c) | Annual waste (R, Mg/yr) | Yrs landfilled used | Landfill Closure Year | k (1/yr) | Average k by precipitation range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11,445,619 | 2000 | 41 | 1.3E+07 | 1.71E+07 | 2000 | 24 | 0 | 476,901 | 24 | | 0.019 | |
| 1,298,000 | 2000 | 41 | 9.1E+06 | 1.21E+07 | 2000 | 9 | 0 | 144,222 | 9 | 2002 | 0.203 | |
| 3,818,182 | 2000 | 42 | 1.1E+07 | 1.43E+07 | 2000 | 18 | 0 | 212,121 | 18 | 2016 | 0.062 | |
| 13,703,620 | 2000 | 44 | 4.5E+07 | 6.00E+07 | 2000 | 13 | 0 | 1,054,125 | 13 | 2004 | 0.065 | |
| 3,880,000 | 2000 | 44 | 1.7E+07 | 2.20E+07 | 2000 | 23 | 2 | 184,762 | 21 | 1998 | no solution | |
| 4,382,727 | 2000 | 45 | 8.2E+06 | 1.09E+07 | 2000 | 20 | 5 | 292,182 | 15 | 1995 | 0.041 | |
| 4,545,455 | 2000 | 45 | 1.4E+07 | 1.89E+07 | 2000 | 18 | 4 | 324,675 | 14 | 1996 | no solution | |
| 1,727,273 | 2000 | 45 | 6.1E+06 | 8.17E+06 | 2000 | 19 | 0 | 90,909 | 19 | 2007 | 0.121 | |
| 1,401,818 | 2000 | 45 | 7.5E+06 | 9.99E+06 | 2000 | 16 | 0 | 87,614 | 16 | 2004 | no solution | |
| 1,454,545 | 2000 | 45 | 1.9E+06 | 2.52E+06 | 2000 | 19 | 10 | 161,616 | 9 | 1990 | 0.025 | |
| 5,016,000 | 2000 | 46 | 6.1E+06 | 8.09E+06 | 2000 | 20 | 0 | 250,800 | 20 | 2050 | 0.019 | |
| 2,409,091 | 2000 | 46 | 6.6E+06 | 8.83E+06 | 2000 | 7 | 0 | 344,156 | 7 | 2030 | 0.042 | |
| 1,878,306 | 2000 | 46 | 6.5E+06 | 8.72E+06 | 2000 | 20 | 0 | 93,915 | 20 | 2023 | 0.132 | |
| 7,000,000 | 1997 | 47 | 3.8E+07 | 5.02E+07 | 1997 | 21 | 0 | 333,333 | 21 | 2015 | no solution | |
| 4,165,060 | 2002 | 47 | 1.6E+07 | 2.10E+07 | 2002 | 14 | 0 | 297,504 | 14 | | 0.087 | |
| 3,885,765 | 2000 | 48 | 1.5E+07 | 1.93E+07 | 2000 | 13 | 0 | 298,905 | 13 | 2015 | 0.080 | |
| 11,149,600 | 2000 | 48 | 3.6E+07 | 4.78E+07 | 2000 | 21 | 0 | 530,933 | 21 | 2011 | 0.110 | |
| 6,803,886 | 2000 | 49 | 1.3E+07 | 1.72E+07 | 2000 | 11 | 0 | 618,535 | 11 | 2011 | 0.030 | |
| 7,550,909 | 2000 | 50 | 1.4E+07 | 1.92E+07 | 2000 | 19 | 5 | 539,351 | 14 | 1995 | 0.041 | |
| 19,869,411 | 2000 | 50 | 3.5E+07 | 4.73E+07 | 2000 | 12 | 5 | 2,838,487 | 7 | 1995 | 0.031 | |
| 9,940,125 | 2000 | 50 | 2.5E+07 | 3.34E+07 | 2000 | 21 | 0 | 473,339 | 21 | 2022 | 0.058 | |
| 23,900,000 | 1996 | 51 | 4.4E+07 | 5.90E+07 | 1996 | 19 | 0 | 1,257,895 | 19 | 2001 | 0.033 | |
| 4,591,150 | 2000 | 52 | 8.4E+06 | 1.12E+07 | 2000 | 15 | 0 | 306,077 | 15 | 2001 | 0.030 | |
| 3,183,595 | 2000 | 52 | 1.9E+06 | 2.58E+06 | 2000 | 17 | 0 | 187,270 | 17 | 2011 | 0.009 | |
| 6,385,900 | 2000 | 54 | 6.9E+06 | 9.14E+06 | 2000 | 17 | 0 | 375,641 | 17 | 2013 | 0.016 | |
| 3,032,300 | 2000 | 55 | 5.3E+06 | 7.11E+06 | 2000 | 8 | 0 | 379,038 | 8 | 2001 | 0.026 | |
| 4,100,000 | 2000 | 56 | 1.2E+07 | 1.58E+07 | 2000 | 16 | 0 | 256,250 | 16 | 2001 | 0.060 | **0.057 for >40 in/yr** |

## *Annex C. BioCycle Estimates for 2002 (using fraction landfilled for 2000 and with April 2004 Corrections)*

| State | Reported Solid Waste Generated 2002 | Fraction landfilled 2000 | Estimated Solid Waste Landfilled |
|---|---|---|---|
| Alabama[a] | 7,537,333 | 0.71 | 5,351,507 |
| Alaska[a] | 1,081,560 | 0.82 | 886,880 |
| Arizona | 4,962,000 | 0.83 | 4,118,460 |
| Arkansas | 4,061,128 | 0.54 | 2,193,009 |
| California | 72,000,000 | 0.57 | 41,040,000 |
| Colorado | 7,673,778 | 0.90 | 6,906,400 |
| Connecticut | 3,474,981 | 0.12 | 416,998 |
| Delaware | 2,747,205 | 0.41 | 1,126,354 |
| Florida | 25,726,175 | 0.56 | 14,406,658 |
| Georgia | 12,302,534 | 0.61 | 7,504,546 |
| Hawaii | 1,275,913 | 0.44 | 561,402 |
| Idaho | 1,090,000 | 0.61 | 664,900 |
| Illinois | 15,428,491 | 0.71 | 10,954,229 |
| Indiana | 16,228,824 | 0.61 | 9,899,583 |
| Iowa | 3,828,808 | 0.65 | 2,488,725 |
| Kansas | 7,846,080 | 0.91 | 7,139,933 |
| Kentucky | 6,529,846 | 0.70 | 4,570,892 |
| Louisiana | 3,272,331 | 0.83 | 2,716,035 |
| Maine | 1,844,059 | 0.21 | 387,252 |
| Maryland[b] | 11,172,882 | 0.42 | 4,692,610 |
| Massachusetts | 12,779,688 | 0.26 | 3,322,719 |
| Michigan | 19,041,775 | 0.73 | 13,900,496 |
| Minnesota | 5,881,543 | 0.35 | 2,058,540 |
| Mississippi | 3,909,508 | 0.84 | 3,283,987 |
| Missouri | 10,935,989 | 0.62 | 6,780,313 |
| Montana[a] | 1,527,881 | 0.61 | 932,007 |
| Nebraska | 2,395,101 | 0.77 | 1,844,228 |
| Nevada | 5,313,203 | 0.86 | 4,569,355 |
| New Hampshire | 1,327,598 | 0.62 | 823,111 |
| New Jersey | 18,865,390 | 0.45 | 8,489,426 |
| New Mexico | 2,968,729 | 0.91 | 2,701,543 |
| New York | 24,784,000 | 0.46 | 11,400,640 |
| North Carolina | 13,500,000 | 0.73 | 9,855,000 |
| North Dakota | 4,270,000 | 0.89 | 3,800,300 |
| Ohio | 13,748,996 | 0.79 | 10,861,707 |
| Oklahoma | 4,489,028 | 0.89 | 3,995,235 |
| Oregon[a] | 4,772,536 | 0.56 | 2,672,620 |
| Pennsylvania | 10,881,798 | 0.50 | 5,440,899 |
| Rhode Island | 1,497,240 | 0.76 | 1,137,902 |
| South Carolina | 11,464,547 | 0.63 | 7,222,665 |
| South Dakota | 688,000 | 0.61 | 419,680 |
| Tennessee | 9,852,194 | 0.55 | 5,418,707 |
| Texas | 45,300,000 | 0.65 | 29,445,000 |
| Utah | 3,949,096 | 0.90 | 3,554,186 |
| Vermont | 700,000 | 0.57 | 399,000 |
| Virgina | 21,331,253 | 0.62 | 13,225,377 |
| Washington | 10,470,805 | 0.60 | 6,282,483 |
| West Virginia | 1,963,791 | 0.75 | 1,472,843 |
| Wisconsin | 13,542,140 | 0.60 | 8,125,284 |
| Wyoming | 682,000 | 0.89 | 606,980 |
| **US TOTAL** | **492,917,758** | **0.61** | **302,068,604** |

[a] Estimated based on national average per capita generation rate (no data from the survey).

[b] Corrected from April 2004 *BioCycle*.

## *Annex D. Percent Methane in Landfill Gas*

### *Background*

Data from 195 landfill projects (gas-to-energy projects and flares) were analyzed to evaluate the percent methane (by volume) in landfill gas. The data were submitted by Waste Management, Inc. to the Department of Energy's Energy Information Administration (EIA) and included the total amount of landfill gas captured in 2002 for each project and the average percent methane for 2002. The database has 32 projects at closed sites and 163 projects at active sites. The amount of gas collected at all of the projects in 2002 totaled 134 billion standard cubic feet.

### *Results*

The results are summarized in Table D-1 and indicate that the default value of 50% methane currently used in preparing the US inventory of methane emissions from landfills is a reasonable estimate. The database is given in Tables D-2 and D-3.

**Table D-1. Summary Statistics for Percent Methane**

| Summary statistics | Percent methane |
|---|---|
| Average (across projects) | 50.3 |
| Average (weighted by gas flow rate) | 50.6 |
| Median | 51.0 |
| Standard deviation | 6.5 |
| 95% confidence interval for the mean | 49.4 to 51.2 |
| Range | 16 to 61 |
| 95% of the measurements are less than | 58 |
| 95% of the measurements are greater than | 39 |
| Average at active sites | 50.7 |
| Average at closed sites | 50.2 |

## Table D-2. Percent Methane at Active Sites

| No. | Site | State | Million $ft^3$ captured in 2002 | Average percent methane |
|---|---|---|---|---|
| 1 | Chastang | AL | 377 | 50 |
| 2 | Tonitown | AR | 499 | 52 |
| 3 | Two Pine | AR | 624 | 50 |
| 4 | Butterfield | AZ | 68 | 47 |
| 5 | Altamont (Flare) | CA | 459 | 54 |
| 6 | Altamont (Recip. Engines) | CA | 40 | 53 |
| 7 | Altamont (Turbine) | CA | 1,359 | 54 |
| 8 | Bradley | CA | 4,730 | 39 |
| 9 | El Sobrante | CA | 994 | 33 |
| 10 | Guadalupe | CA | 425 | 54 |
| 11 | Kirby Canyon | CA | 652 | 58 |
| 12 | Lancaster | CA | 104 | 26 |
| 13 | Redwood | CA | 653 | 50 |
| 14 | Simi Valley | CA | 915 | 48 |
| 15 | TriCities | CA | 340 | 38 |
| 16 | WM of Colorado - DADS LF | CO | 285 | 47 |
| 17 | DRPI | DE | 112 | 45 |
| 18 | Central Sanitary (Flare) | FL | 451 | 40 |
| 19 | Central Sanitary (Power) | FL | 1,929 | 56 |
| 20 | Gulf Coast | FL | 733 | 51 |
| 21 | Medley | FL | 1,608 | 52 |
| 22 | Naples | FL | 799 | 49 |
| 23 | Okeechobee | FL | 1,064 | 50 |
| 24 | Springhill/Recycle | FL | 497 | 50 |
| 25 | Bolton Road/SSL | GA | 993 | 53 |
| 26 | Live Oak | GA | 2,076 | 52 |
| 27 | Pine Bluff | GA | 1,121 | 50 |
| 28 | R & B | GA | 276 | 51 |
| 29 | Superior | GA | 71 | 49 |
| 30 | Des Moines (Power) | IA | 1,178 | 57 |
| 31 | Chain of Rocks | IL | 683 | 54 |
| 32 | CID Areas 1, 2, and 3 (Flare) | IL | 5 | 55 |
| 33 | CID Areas 1, 2, and 3 (Power) | IL | 1,092 | 56 |
| 34 | Countryside Landfill | IL | 1,297 | 53 |
| 35 | DeKalb County RDF | IL | 189 | 54 |
| 36 | Envirofil of IL Landfill | IL | 190 | 49 |
| 37 | Five Oaks RDF | IL | 312 | 56 |
| 38 | Kankakee (Flare) | IL | 5 | 57 |
| 39 | Kankakee (Power) | IL | 266 | 58 |
| 40 | Laraway RDF | IL | 83 | 47 |
| 41 | Milam (minimal flaring) | IL | 407 | 59 |
| 42 | Settler's Hill (Flare) | IL | 410 | 55 |
| 43 | Settler's Hill (minimal flaring) | IL | 1,325 | 55 |
| 44 | Tazewell (Flare) | IL | 193 | 55 |
| 45 | Tazewell (Power) | IL | 366 | 56 |
| 46 | Woodland (Power) | IL | 277 | 58 |

| No. | Site | State | Million ft$^3$ captured in 2002 | Average percent methane |
|---|---|---|---|---|
| 47 | Woodland RDF (Flare) | IL | 961 | 57 |
| 48 | Deercroft (Flare) | IN | 526 | 59 |
| 49 | Deercroft (Power) | IN | 535 | 59 |
| 50 | Earthmovers | IN | 586 | 51 |
| 51 | Jay County Landfill | IN | 653 | 56 |
| 52 | Liberty Landfill | IN | 555 | 56 |
| 53 | Oak Ridge RDF | IN | 732 | 55 |
| 54 | Prairie View (Flare) | IN | 400 | 58 |
| 55 | Prairie View (Power) | IN | 532 | 58 |
| 56 | Twin Bridges (Flare) | IN | 205 | 61 |
| 57 | Twin Bridges (Power) | IN | 518 | 61 |
| 58 | Rolling Meadows RDF | KS | 572 | 50 |
| 59 | Outer Loop (flare & pipeline) | KY | 1,534 | 52 |
| 60 | Magnolia | LA | 730 | 48 |
| 61 | Barre (Martone) Flare | MA | 99 | 45 |
| 62 | Barre (Martone) Sold | MA | 140 | 51 |
| 63 | Chicopee | MA | 632 | 49 |
| 64 | Fitchburg | MA | 814 | 46 |
| 65 | Granby (Holyoke) | MA | 328 | 47 |
| 66 | Sandy Hill | MD | 1,813 | 53 |
| 67 | Crossroads | ME | 729 | 55 |
| 68 | Autumn Hills RDF (open flares) | MI | 323 | 58 |
| 69 | Eagle Valley RDF | MI | 598 | 54 |
| 70 | Hastings Landfill | MI | 214 | 50 |
| 71 | Peoples Landfill | MI | 371 | 51 |
| 72 | Pine Tree Acres Landfill | MI | 864 | 51 |
| 73 | Tri-City RDF | MI | 68 | 50 |
| 74 | Venice Park (Flare) | MI | 239 | 51 |
| 75 | Venice Park (Power) | MI | 467 | 50 |
| 76 | Westside Landfill | MI | 502 | 59 |
| 77 | Woodland Meadows RDF | MI | 1,426 | 58 |
| 78 | Burnsville Sanitary Landfill | MN | 605 | 50 |
| 79 | Elk River Landfill | MN | 526 | 50 |
| 80 | Spruce Ridge Landfill | MN | 341 | 52 |
| 81 | Pecan Grove San | MS | 1,419 | 52 |
| 82 | Piedmont | NC | 171 | 49 |
| 83 | WM - Douglas County RDF | NE | 569 | 54 |
| 84 | Turnkey (2 T/Gs) | NH | 1,508 | 52 |
| 85 | Turnkey (4 E/Gs) | NH | 596 | 53 |
| 86 | Turnkey (4 Flares) | NH | 1,014 | 52 |
| 87 | Chaffee | NY | 827 | 45 |
| 88 | High Acres (Flare) | NY | 511 | 57 |
| 89 | High Acres (Power) | NY | 518 | 57 |
| 90 | Mill Seat | NY | 20 | 58 |
| 91 | Akron (Hardy Road) | OH | 325 | 53 |
| 92 | American | OH | 871 | 57 |
| 93 | Cuyahoga Regional | OH | 1,529 | 52.6 |
| 94 | Evergreen (pipeline) | OH | 946 | 56 |

| No. | Site | State | Million ft$^3$ captured in 2002 | Average percent methane |
|---|---|---|---|---|
| 95 | Geneva | OH | 295 | 52 |
| 96 | Pinnacle Road | OH | 451 | 56.9 |
| 97 | Stony Hollow | OH | 503 | 58.8 |
| 98 | Suburban | OH | 361 | 55 |
| 99 | East Oak | OK | 587 | 50 |
| 100 | Quarry | OK | 580 | 50 |
| 101 | Columbia Ridge | OR | 223 | 51 |
| 102 | Riverbend | OR | 704 | 56 |
| 103 | Alliance | PA | 2,752 | 55 |
| 104 | Arden | PA | 1,105 | 37 |
| 105 | Dauphin Meadows | PA | 564 | 49 |
| 106 | Evergreen | PA | 221 | 35 |
| 107 | Grand Central (Flares) | PA | 90 | 48.44 |
| 108 | Grand Central (Sale) | PA | 2,161 | 50.32 |
| 109 | GROWS | PA | 3,105 | 53 |
| 110 | Kelly Run | PA | 352 | 39 |
| 111 | Lake View (Engines) | PA | 510 | 56 |
| 112 | Lake View (Flare) | PA | 477 | 56 |
| 113 | Laurel Highlands | PA | 360 | 47 |
| 114 | Monroeville | PA | 1,666 | 45 |
| 115 | Mountain View | PA | 1,289 | 49 |
| 116 | Northwest | PA | 638 | 52 |
| 117 | Pine Grove | PA | 1,358 | 43 |
| 118 | Pottstown (Flare) | PA | 869 | 47 |
| 119 | Pottstown (Power) | PA | 1,316 | 42 |
| 120 | Shade (RCC) | PA | 788 | 42 |
| 121 | South Hills (Arnoni) | PA | 394 | 37 |
| 122 | Southern Alleghanies | PA | 1,498 | 40 |
| 123 | Tullytown | PA | 2,777 | 54 |
| 124 | Valley | PA | 1,656 | 48 |
| 125 | Oakridge | SC | 387 | 51 |
| 126 | Palmetto | SC | 2,200 | 52 |
| 127 | Richland | SC | 896 | 51 |
| 128 | Chestnut Ridge (Flare) | TN | 276 | 50 |
| 129 | Chestnut Ridge (Power) | TN | 554 | 57 |
| 130 | Iris Glen | TN | 309 | 48 |
| 131 | Quail Hollow | TN | 238 | 46 |
| 132 | West Camden | TN | 256 | 50 |
| 133 | Atascocita | TX | 2,365 | 49 |
| 134 | Austin Community | TX | 841 | 40 |
| 135 | Baytown | TX | 1,472 | 48 |
| 136 | Bluebonnett | TX | 578 | 49 |
| 137 | Coastal Plains | TX | 1,091 | 49 |
| 138 | Comal County | TX | 374 | 50 |
| 139 | Conroe - 6 | TX | 309 | 48 |
| 140 | Covel Gardens | TX | 662 | 50 |
| 141 | DFW (Flare) | TX | 228 | 49 |
| 142 | DFW (Power) | TX | 1,139 | 49 |

| No. | Site | State | Million ft$^3$ captured in 2002 | Average percent methane |
|---|---|---|---|---|
| 143 | Hillside | TX | 225 | 50 |
| 144 | New Boston | TX | 150 | 50 |
| 145 | Security | TX | 629 | 50 |
| 146 | Skyline | TX | 449 | 51 |
| 147 | Westside | TX | 505 | 49 |
| 148 | Amelia | VA | 770 | 53 |
| 149 | Atlantic | VA | 1,221 | 51 |
| 150 | Bethel | VA | 1,047 | 52 |
| 151 | Charles City | VA | 1,163 | 51 |
| 152 | King George | VA | 709 | 50 |
| 153 | Middle Pennisula | VA | 1,281 | 47 |
| 154 | Kennewick/Wenatchee | WA | 176 | 45 |
| 155 | Olympic View | WA | 585 | 53 |
| 156 | Deer Track Park Landfill | WI | 238 | 42 |
| 157 | Metro (no flaring) | WI | 1,344 | 52 |
| 158 | Pheasant Run (Flare) | WI | 349 | 54 |
| 159 | Pheasant Run (Power) | WI | 1,277 | 55 |
| 160 | Ridgeview RDF (Flare) | WI | 46 | 54 |
| 161 | Ridgeview RDF (Power) | WI | 147 | 53 |
| 162 | Timberline Trail RDF | WI | 293 | 56 |
| 163 | Valley Trail RDF | WI | 748 | 56 |

## Table D-3. Percent Methane at Closed Sites

| No. | Site | State | Million ft$^3$ captured in 2002 | Average percent methane in 2002 |
|---|---|---|---|---|
| 164 | New Milford Landfill (Engine) | CT | 694 | 55 |
| 165 | New Milford Landfill (Flare) | CT | 65 | 54 |
| 166 | BJ Landfill (BEP) | GA | 444 | 53 |
| 167 | BJ Landfill (CSMG) | GA | 199 | 31 |
| 168 | Button Gwinnett | GA | 405 | 48 |
| 169 | Rolling Hills Landfill | GA | 247 | 45 |
| 170 | Boundary Road Landfill | ID | 31 | 52 |
| 171 | Greene Valley (Power Generation) | IL | 2,042 | 54 |
| 172 | HOD Landfill | IL | 172 | 49 |
| 173 | Lake LF (Flare) | IL | 6 | 59 |
| 174 | Lake LF (Power Generation) | IL | 1,677 | 57 |
| 175 | Wheeler (Flare) RDF | IN | 19 | 58 |
| 176 | Wheeler (Power) RDF | IN | 230 | 58 |
| 177 | Valley View Landfill | KY | 39 | 49 |
| 178 | Hunt Road | MA | 100 | 43 |
| 179 | Cereal City | MI | 270 | 16 |
| 180 | City Sand | MI | 638 | 49 |
| 181 | White Lake Landfill | MI | 210 | 53 |
| 182 | Rumble Landfill 1 | MO | 261 | 50 |
| 183 | Rumble Landfill 2 | MO | 261 | 50 |
| 184 | Cinnaminson | NJ | 97 | 41 |
| 185 | Landfill & Development Co. (Flare) | NJ | 341 | 44 |
| 186 | Parklands LF | NJ | 264 | 37 |
| 187 | Monroe Livingston (Power Generation) | NY | 403 | 56 |
| 188 | Oyster Bay Regional Park | NY | 426 | 40 |
| 189 | Elda RDF | OH | 1,073 | 50 |
| 190 | Powell Road Landfill | OH | 170 | 40 |
| 191 | Seriff Road | OH | 150 | 40 |
| 192 | Elizabethtown Landfill | PA | 65 | 29 |
| 193 | Brookfield Sanitary Landfill | WI | 74 | 45 |
| 194 | Omega Hills North Landfill | WI | 1,742 | 53 |
| 195 | Stone Ridge Landfill | WI | 176 | 43 |

## *Annex E. Methane Oxidation - Literature Review*

### *Conclusions*

The rate of methane oxidation and the fraction of methane oxidized vary widely and depend on many site-specific factors. The widely-used value of 10 percent oxidized appears to be a reasonable and probably conservative estimate. The percent of methane oxidized may be much higher at landfills with efficient gas recovery systems.

### *Percent of Methane Oxidized*

An estimate of 10 percent oxidized is widely used in procedures for estimating methane emissions from landfills. Jensen and Papatti (2002) note that experts at an Intergovernmental Panel on Climate Change (IPCC) workshop in 1995 and at an international symposium in 1997 agreed to use 10 percent oxidized as a standard value. This estimate has been implemented in several national inventories. In guidance provided to the States for estimating emissions, EPA recommended a factor of 10 percent oxidized (EPA 1995). In a life-cycle assessment of emissions and sinks, EPA (2002) estimated that 10 percent of the methane is oxidized and recommended using that factor when estimating methane emissions from landfills.

The estimate of 10 percent oxidized is based on a few laboratory and field studies of oxidation. Mancinelli and McKay (1985) performed laboratory experiments on a simulated landfill gas mixture and showed 10 percent of the methane was oxidized. Czepiel et al (1996) performed laboratory studies of soil samples from a New Hampshire landfill and concluded that 20 percent of the methane was oxidized at the time the methane flux measurements were made (in October with no gas recovery). Using a soil climate model, the annual whole landfill oxidation rate was estimated as 10 percent.

Liptay et al (1998) reported that the mean oxidation rate measured at 6 New England landfills ranged from 24 to 35 percent, or about 30 percent in the warm summer period. This study concluded the results were consistent with those of Czepiel (1996), who developed a best estimate of 10 percent oxidized on an annual basis. Doorn and Barlaz (1995) cited a United Kingdom study that showed an upper bound estimate for oxidation of 40 to 50 percent and recommended a value of 10 percent based on expert judgment. Börjesson (1997a) cited a study in Germany that showed reductions in methane fluxes of 10 to 30 percent by oxidation (Lubina et al, 1996).

Based on measurements at one landfill in the former USSR, Nozhevnikova (1993) reported that 70 percent of the methane was oxidized during the summer and about 50 percent was oxidized in an average year. Another landfill with more “fresh” wastes had higher flux rates of methane and lower oxidation. The study recommended using a value of 30 percent oxidized in estimating national emissions.

When an efficient gas recovery system is in place, some studies indicate that all of the methane escaping capture may be oxidized. Börjesson (1997b) reported that measurements at a Swedish landfill with a gas extraction system and organic cover soil showed the landfill acted as a net sink for atmospheric methane, and oxidation was enhanced by drawing oxygen into the soil. Bogner et al (1997 and 1999) reported negative (inward) fluxes of methane from measurements of a landfill in Illinois. The negative flux was attributed to high capacities for methane oxidation in soils that have a lower methane concentration than in previous years because of the optimization of the gas recovery system.

The landfill cover can be designed to enhance oxidation. Humer and Lechner (1999) reported on large scale outdoor experiments that used sewage sludge compost over municipal solid waste. Two test cells showed no methane emitted, while two other cells showed no methane in some locations and high concentrations in other locations. The two test cells with methane emissions did not have a gas distribution layer (coarse gravel), and the sludge compost layer was thinner (0.3 to 0.4 m vs. 0.8 m). The paper concluded that it is possible to completely oxidize methane from a landfill with 10 to 15 m of municipal solid waste under summer conditions in Austria.

***Factors Affecting Oxidation***

Numerous studies have documented the factors that affect oxidation and suggest that oxidation rates depend on several site-specific factors. Börjesson (1997b) discussed these factors: temperature (oxidation increases with temperature), moisture (there is an optimum water content - a thick water film suppresses the diffusion of methane and oxygen and can decrease oxidation), soil porosity, oxygen penetration (oxidation decreases rapidly below 3 percent oxygen), and methane concentration. Börjesson (1997a) found that seasonal and diurnal variations in methane flux rates were due primarily to changes in the soil temperature. The higher methane flux rates in September to May and higher rates at nights were likely caused by the inhibitory effect of lower soil temperatures on methane-oxidizing microorganisms. Nozhevnikova (1993) reported that laboratory studies of methane oxidation showed that when temperatures decreased from 25°C to 5-7°C, oxidation rates decreased by a factor of 3 to 5.

Bogner et al (1997) reported studying methane oxidation rates at an Illinois landfill from June to December 1995. Methane oxidizing conditions with no methane emissions persisted into full winter conditions of soil freezing in December. Measurements made when the gas recovery system was shut down showed oxidation rates increased with methane concentration. The paper concluded that in a well-aerated landfill soil, the primary controlling variable appears to be methane concentration, and secondarily, aeration status (oxygen availability).

***References***

Bogner, J., K. Spokas, and E. Burton (1999), "Temporal Variations in Greenhouse Gas Emissions at a Midlatitude Landfill," *Journal of Environmental Quality*, 28:278-288.

Bogner, J., K. Spokas, and E. Burton (1997), "Kinetics of Methane Oxidation in a Landfill Cover Soil: Temporal Variations, a Whole-landfill Oxidation Experiment, and Modeling of Net $CH_4$ Emissions, *Environmental Science and Technology*, 31:2504-2514.

Börjesson, G. and B. Svensson (1997a), "Seasonal and Diurnal Methane Emissions from a Landfill and Their Regulation by Methane Oxidation," *Waste Management and Research,* 15:33-54.

Börjesson, G. (1997b), "Methane Oxidation in Landfill Cover Soils," Doctoral dissertation, Swedish University of Agricultural Sciences, Uppsala, pp. 17-28.

Czepiel, P., B. Mosher, P. Crill, and R. Harriss. (1996), "Quantifying the Effect of Oxidation on Landfill Methane Emissions," *Journal of Geophysical Research*, 101( D11):16721-16730.

Doorn, M. and M. Barlaz (1995), " Estimate of Global Methane Emissions From Landfills and Open Dumps," Prepared for U.S. Environmental Protection Agency, Office of Research and Development, Durham, NC, EPA-600/R-95-019, February, pp. 4-8, 30-31.

EPA (2002), *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks,* U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C., EPA/530-R-02-006, June.

EPA (1995), *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions,* U.S. Environmental Protection Agency, EPA/230-B-95-001, January.

Humer, M. and P. Lechner (1999), "Micobial Methane Oxidation for the Reduction of Landfill Gas Emissions," *Proceedings of the Fifteenth International Conference on Solid Waste Technology and Management*, December 12-15, 1999, Philadelphia, PA.

Jensen, J. and R. Papatti (2002), "$CH_4$ Emissions from Solid Waste Disposal," *Background Papers- IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories,* p. 429.

Liptay, K., J. Chanton, P. Czepiel, and B. Mosher (1998), "Use of Stable Isotopes to Determine Methane Oxidation in Landfill Cover Soils," *Journal of Geophysical Research*, 103( D7):8243-8250.

Mancinelli, R. and C. McKay (1985), “Methane-Oxidizing Bacteria in Sanitary Landfills,” *Proceedings of the First Symposium on Biotechnical Advances in Processing Municipal Wastes for Fuels and Chemicals*, August 1984, Minneapolis, Minnesota, pp. 437-450.

Nozhevnikova, A., A. Lifshitz, V. Lebedev, and G. Zavarzin (1993), “Emission of Methane into the Atmosphere from Landfills in the Former USSR,” *Chemosphere*, 26(1-4):401-417.

## *Annex F. Emission Reduction Equations for Landfill Gas Energy Projects*

EASTERN RESEARCH GROUP, INC.

# MEMORANDUM

**TO:** Brian Guzzone, Meg Victor, and Chris Voell, U.S. EPA LMOP

**FROM:** Amy Alexander, Jeanette Alvis, Clint Burklin, and Ruth Mead, ERG

**DATE:** November 18, 2002

**SUBJECT:** Draft Revised LMOP Emission Reduction Equations for Landfill Gas Energy Projects

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## 1.0 INTRODUCTION

The purpose of this memorandum is to identify differences and suggest recommendations for methodologies and default assumptions used to calculate direct and avoided emission reductions from electricity-generating and direct-use landfill gas energy (LFGE) projects. We compare the current calculations used in the ICF emission inventory (presented in ICF's 11/30/01 memorandum[1]), the SCS equations used to derive the emission factors in the LMOP Landfill/Project database (2/13/02 e-mail transmittal of these equations is in Appendix A), and other assumptions and procedures ERG has researched. Where we identify assumptions, we provide their basis and references. Through several discussions involving LMOP, ERG, SCS, ICF, and other EPA staff, we have developed draft revised equations for determining emission reductions from LFGE projects. We recommend adoption of these revised calculation procedures to be used universally for the LMOP Landfill/Project database, LMOP territory managers' target spreadsheets, LMOP inventory and accomplishment tracking in *iSTAR*, the environmental benefits calculator (a potential future addition to the LMOP Web site), LFG curves and analysis reports, the LFGcost model (where applicable), and other requests involving environmental benefit calculations. The revised equations are those agreed upon at the October 9, 2002 conference call with LMOP, ERG, SCS, and ICF.

We understand that LMOP would like to establish this uniform set of calculation procedures in order to provide consistent and accurate emission reduction results. All parties involved with these equations recognize that there are a range of reasonable assumptions for factors such as the default heat rate, and the values vary depending on engine design and site-specific characteristics. However, for purposes of consistency and ease of determination, all parties agree with the need to establish universal emission reduction equations for LFGE projects.

Section 2.0 presents the current and draft revised emission reduction calculations and provides documentation supporting the suggested revised equations. Section 3.0 discusses the equations used in the LMOP Landfill/Project database to calculate estimated MW capacity and LFG utilization (mmscf/day) from the waste-in-place (tons) when these data are not available in the database. Sources referenced throughout this memorandum are listed in Section 4.0.

## 2.0 DIRECT AND AVOIDED EMISSION REDUCTIONS FROM LFGE PROJECTS

Sections 2.1 through 2.4 discuss the differences and draft revisions to calculations of (1) direct emission reductions from electricity-generating projects, (2) avoided emission reductions from electricity-generating projects, (3) direct emission reductions from direct-use projects, and (4) avoided emission reductions from direct-use projects, respectively. We have used the ICF inventory equations to represent both the SCS and ICF equations because they generally follow the same procedures and use similar assumptions. When the equations or assumptions used by SCS differ significantly from the ICF equations, we will distinguish between them. The bolded terms in the equations highlight the differing factors that will be discussed in the bullets following the equations.

### 2.1 Direct Emission Reductions from Electricity-Generating Projects

<u>ICF/SCS Equation:</u>
generating capacity (MW) * **0.85 [default capacity factor]** * 8,760 hrs/yr * 1,000 kW/MW * **10,000 Btu/kWh [IC engine heat rate] * 1 cf $CH_4$/1,030 Btu [methane heating value]** * 0.0423 lbs $CH_4$/cf $CH_4$ * short ton/2,000 lbs * 0.9072 MT/short ton * MMT/$10^6$ MT * 21 [GWP of $CH_4$] = $MMTCO_2E$/yr

- ***SCS equation difference***. SCS uses a methane heating value of **1,000 Btu/cf $CH_4$** instead of the 1,030 Btu/cf $CH_4$ used by ICF.

Draft Revised Equation:

generating capacity (MW) * **0.93 [default gross capacity factor]** * 8,760 hrs/yr * 1,000 kW/MW * **11,700 Btu/kWh [default heat rate] * cf $CH_4$/1,012 Btu [methane heating value]** * 0.0423 lbs $CH_4$/cf $CH_4$ * short ton/2,000 lbs * 0.9072 MT/short ton * MMT/$10^6$ MT * 21 [GWP of $CH_4$] = $MMTCO_2E$/yr

- ***Default gross capacity factor***. In place of the current capacity factor of 0.85, ERG recommends applying a gross capacity factor of 0.93 (i.e., 93%) to the MW capacity of the engine or turbine. The gross capacity factor is defined as the product of the availability factor and the load factor, and is used to determine the gross quantity of methane (expressed as carbon dioxide equivalents) consumed by the engine-generator or turbine-generator set. The availability factor is the fraction of time that a system is available for producing power. The typical reasons that a generating system would not be available for producing power include the time when the engine-generator set is taken out of service for routine maintenance and repairs, and the time when other system components such as blowers, compressors and dehumidifiers are also taken out of service for the same reasons. The load factor is the normal operating load of the system when it is "available" (i.e., not shutdown for maintenance and repairs).

  LMOP's *Project Development Handbook*[2] states that capacity factors can range from 80% to 95%. Four LFGE project developers were contacted about typical availability and load factors for reciprocating engines and gas turbines used at LFGE projects.

  Availability factor: For the availability factor of the overall system, Ameresco and SCS recommended using 0.93; GRS recommended a value between 0.9 and 0.95; and EMCON/OWT recommended using 0.95. Based on the range of estimates, we suggest 0.93 as a representative availability factor.

  Load factor: All project developers agreed that the typical load factor for electricity-generating LFGE projects was close to 1.0. A load factor of 1.0 is well-representative for several reasons. The reciprocating engines and gas turbines used for LFGE electricity projects are designed by manufacturers for full load operation, and will operate most efficiently at full load, provided gas is available. Project developers also reported that projects are designed so the LFG supply matches the equipment capacity. Electricity-generating equipment are sized to use all of the LFG available in order to maximize their return on investment. To achieve this, it is common to have multiple engines or turbines at one LFGE project site in order to add or remove them as the amount of LFG fluctuates over time. This practice allows engines and turbines to be transferred between different project sites and facilitates full load operation.

<u>Gross capacity factor:</u> Multiplying the typical availability factor of 0.93 by the typical load factor of 1.0 results in an overall gross capacity factor of 0.93. Therefore, we suggest using an average gross capacity factor of 0.93 for all LFGE projects that generate electricity. Based on the data presented above, LMOP agreed that 0.93 is a reasonable capacity factor to be used for determining direct emission reductions from electricity-generating projects. (Note that this memo does not address the issue of whether and how to take credit for back-up flares, which is being considered separately by LMOP.)

- ***Default heat rate***. ERG recommends using a default heat rate of 11,700 Btu/kWh. The current default heat rate is 10,000 Btu/kWh. This value is widely used in the industry for electricity generation in general, but is not specific to LFG engines and turbines. LMOP's *Project Development Handbook*[2] uses example heat rates of 12,000 Btu/kWh for IC engines and combustion turbines (above 5 MW) and 8,500 Btu/kWh for combined-cycle combustion turbines.

The heat rate information for reciprocating engines in Table 1 was obtained from three sources: published literature from two manufacturers, direct communication with one manufacturer, and information provided by a distributor of the engines. The heat rate information provided by the manufacturers and distributors of engines is based on the lower heating value (LHV) of the fuel. Manufacturers and distributors of engines use the LHV in their calculations because it most closely represents the useable energy in the fuel. However, EPA has traditionally used the higher heating value (HHV) of fuels when developing regulations and when communicating environmental information. Further discussion about the differences between LHV and HHV is included in Appendix E. The distributor providing information on the Waukesha engine data noted that "10,000 Btu/kWh (LHV) is commonly used as a simplified default heat rate for grid-based electricity." This heat rate is equivalent to 11,100 Btu/kWh (HHV) and falls between the 1 and 3 MW Caterpillar engines and between the 1 and 2 MW Waukesha engines. Discussions with project developers confirm that these are the most common engine sizes used for LFGE projects, with the 1 MW engines being the "real work horses" of the LFG industry. Therefore, we recommend selecting an engine heat rate of 11,250 Btu/$kWh_e$ (HHV). This heat rate lies between the heat rates of the 1 MW engines and the next larger engine, but is closer to the value for the 1 MW engine, reflecting the greater use of this engine size.

**Table 1. Heat Rate Data for Reciprocating Engines**

| Engine and Model | Heat Rate-LHV (Btu/bhph) | Engine Size | Heat Rate-LHV (Btu/$kWh_e$) | Heat Rate-HHV (Btu/$kWh_e$) | Reference |
|---|---|---|---|---|---|
| Caterpillar 3516 | 7,414-7,548 | 0.8-1.0 $MW_s$ | 10,450-10,650 | 11,600-11,800 | Manufacturer's literature |
| Caterpillar 3616 | 6,580-6,780 | 3.0-3.3 $MW_s$ | 9,275-9,560 | 10,300-10,600 | Manufacturer's literature |
| Waukesha (standard) | 7,300 | typical | 10,293 | 11,400 | Manufacturer discussion |
| Waukesha (low $NO_x$) | 7,800 | typical | 11,000 | 12,200 | Manufacturer discussion |
| Waukesha | | 1 $MW_e$ | 10,526 | 11,696 | Distributor information |
| Waukesha | | 2 $MW_e$ | 9,660 | 10,740 | Distributor information |
| Waukesha | | 3 $MW_e$ | 8,876 | 9,862 | Distributor information |
| Jenbacher | 6,715 | 0.7 $MW_e$ | 9,468 | 10,520 | Manufacturer's literature |

$MW_s$ = MW measured as shaft energy

$MW_e$ = MW measured as electrical output of generator

Heat Rate-LHV = Heat rate based on the lower heating value of the fuel

Heat Rate-HHV = Heat rate based on the higher heating value of the fuel

(Btu/$kWh_e$) = Heat rate measured as the electrical output of the generator

Table 2 contains heat rate information for gas turbines provided by Solar Turbines. Solar Turbines has manufactured the majority of gas turbines used for domestic LFGE projects. In discussions with Solar Turbines, they recommended the three turbines in Table 2 for LFG applications. Additional discussions with the Los Angeles County Sanitation District and GRS, a LFGE project developer, confirmed that the Centaur and Taurus turbines are frequently chosen for turbine applications, and are likely the most common turbines used in U.S. LFG applications. Based on a simple average of the heat rates in Table 2, we recommend using a heat rate of 13,000 Btu/kWh$_e$ (HHV) for gas turbines.

**Table 2. Heat Rate Data for Gas Turbines**

| Manufacturer and Model | Size ($MW_e$) | Heat Rate-LHV ($Btu/kWh_e$) | Heat Rate-HHV ($Btu/kWh_e$) |
|---|---|---|---|
| Solar - Centaur 40 | 3.5 $MW_e$ | 12,240 | 13,600 |
| Solar - Centaur 50 | 4.6 $MW_e$ | 11,630 | 12,922 |
| Solar - Taurus 60 | 5.5 $MW_e$ | 11,225 | 12,472 |

Reference: Equipment data sheets provided by Solar Turbines.

$MW_e$ = MW measured as electrical output of generator

Heat Rate-LHV = Heat rate based on the lower heating value of the fuel

Heat Rate-HHV = Heat rate based on the higher heating value of the fuel

($Btu/kWh_e$) = Heat rate measured as the electrical output of the generator

When determining a combined average heat rate for all electricity-generating projects, we recommend using a ratio of the heat rates of the two primary project types, reciprocating engines and gas turbines, weighted by their relative populations. Since these two project types currently account for over 80% of the total LFGE project capacity for electric generation, the other project types would have very little impact on an average project net capacity factor, and can be ignored. In addition, the remaining 20% of electricity-generating projects (e.g., boiler/steam turbines) have heat rates similar to those of LFG-fired engines and turbines. As of August 20, 2002 the LMOP database lists 583 MW of reciprocating engine capacity and 186 MW of gas turbine capacity. Using the ratio of these capacities yields a MW-weighted heat rate of 11,700 Btu/$kWh_e$ (HHV) for use on all LFGE projects that generate electricity.

The Chief Engineer at Waukesha Engines, who was also a Senior Engineer at Superior Engines, estimated that reciprocating engine heat rates have dropped approximately 5% since the early 1990's. A representative of Caterpillar engines confirmed this same efficiency change for their engines. However, Solar Turbines estimated that the heat rates of their turbines have only decreased by 1% to 2% since the early 1990's. Although the LMOP emission reduction equations could be adjusted to represent the heat rate requirements of engines employed at older LFGE project sites, LMOP decided that the added complexity of this adjustment was not justified considering its limited effect and the overall uncertainties of the calculations. Based on the information provided above, LMOP recommended an overall heat rate of 11,700 Btu/$kWh_e$ be used for all electricity-generating projects, regardless of their start-up year.

- ***Methane heating value***. Upon suggestion from ICF, LMOP recommended using a methane heating value of 1,012 Btu/scf (HHV), from the *Chemical Engineers' Handbook*[3]. This heating value is within the thermodynamic property range for methane and is similar to the heat content of 1,000 Btu/scf (HHV) used by SCS and EIA's *Instructions for Voluntary Reporting of Greenhouse Gases*[4]. Note that this suggested default is slightly lower than the methane heating value of 1,030 Btu/scf used in the ICF inventory equations, and lower than the heating value of natural gas, as discussed in Section 2.4.

- ***Simplified equation factor comparison***. Table 3 shows the simplified equation factors, in terms of both $MMTCO_2E$/MW-yr and MMTCE/MW-yr, for direct emission reductions from electricity-generating projects using ICF's equation, SCS' equation, and the draft revised equations. The equation factors are representative of the simplified equations as "generating capacity (MW) * equation factor = $MMTCO_2E$/yr for carbon dioxide equivalents or MMTCE/yr for carbon equivalents." For comparison, Table 3 also shows the results of using these equation factors to calculate direct emission reductions for a typical 5 MW capacity

LFGE project. The SCS equation factors are currently used to determine emission reductions in the LMOP Landfill/Project database, and the ICF equations are used for the annual inventory.

**Table 3. Comparison of Equation Results for Direct Emission Reductions from Electricity-Generating Projects**

| Equation Source | Simplified Equation Factors | | Results for 5 MW Capacity LFGE Project | |
|---|---|---|---|---|
| | **$MMTCO_2E$/MW-yr** | **MMTCE/MW-yr** | **$MMTCO_2E$/yr** | **MMTCE/yr** |
| ICF | 0.0291 | 0.0079 | 0.1455 | 0.0395 |
| SCS | 0.0300 | 0.0082 | 0.1500 | 0.0410 |
| Draft Revision | 0.0380 | 0.0104 | 0.1900 | 0.0520 |
| **Difference between ICF and revised equation results for 5 MW capacity LFGE project:** | | | 23% higher | |
| **Difference between SCS and revised equation results for 5 MW capacity LFGE project:** | | | 21% higher | |

## 2.2 Avoided Emission Reductions from Electricity-Generating Projects

ICF Equation:

generating capacity (MW) * **0.85 [default capacity factor]** * 8,760 hrs/yr * 1,000 kW/MW * **1.64 lbs $CO_2$/kWh [electricity $CO_2$ emission factor]** * short ton/2,000 lbs * 0.9072 MT/short ton * MMT/$10^6$ MT = $MMTCO_2E$/yr

- ***SCS equation difference***. Although the equation submitted by SCS has a different approach than ICF's equation, the simplified equation factor of 0.00152 for MMTCE/yr programmed into the LMOP Landfill/Project database by SCS is very similar to ICF's simplified equation factor of 0.00151 for MMTCE/yr. Based on this fact and Mr. Paleyanda's February, 21, 2002 e-mail (attached in Appendix B), we are assuming that ICF's equation accurately represents the current method for determining avoided emission reductions from electricity-generating projects in the LMOP Landfill/Project database, as well as the ICF annual inventory.

Draft Revised Equation:

generating capacity (MW) * **0.85 [default net capacity factor]** * 8,760 hrs/yr * 1,000 kW/MW * **1.46 lbs $CO_2$/kWh [2002 electricity $CO_2$ emission factor]** * short ton/2,000 lbs * 0.9072 MT/short ton * MMT/$10^6$ MT = $MMTCO_2E$/yr

- ***Default net capacity factor***. ERG recommends continuing to apply a net capacity factor of 0.85 (i.e., 85%) to the MW capacity of the engine or turbine. The justification for use of this factor is described below.

  As discussed in Section 2.1, the gross capacity factor is defined as the product of the availability factor and the load factor, and is used to determine the gross quantity of methane (expressed as carbon dioxide equivalents) consumed by the engine-generator or turbine-generator set. Since LFGE projects must use a portion of their electrical output to operate on-site equipment such as blowers, compressors, and dehumidifiers, the net electrical output that offsets conventional power is less than the gross electrical output of the engine-generator set. The fraction of electricity consumed by on-site equipment is defined as the parasitic factor and is used to define the net capacity factor of the system. Thus, multiplying the gross capacity factor by (1 - parasitic factor) results in the net capacity factor.

  LMOP's *Project Development Handbook*[2] estimates that parasitic loads range from 2% for IC engines to 6% or higher for combustion turbines. EMCON/OWT and SCS recommend parasitic factors of 0.08 (i.e., 8%) and 0.12 (i.e., 12%) for reciprocating engine and gas turbine projects, respectively. These factors yield the following net capacity factors for electricity-generating LFGE projects

  Net capacity factor for reciprocating engines = (0.93) * (1-0.08) = 0.856

  Net capacity factor for gas turbines = (0.93) * (1-0.12) = 0.818

When developing a net capacity factor that would apply to all electricity-generating LFGE projects, we recommend considering the relative proportion of electricity generated by the two primary project types, reciprocating engines and gas turbines. Since these two project types currently account for over 80% of the total LFGE project capacity for electric generation, the other project types would have very little impact on an average project net capacity factor, and can be ignored. As of August 20, 2002 the LMOP database lists 583 MW of reciprocating engine capacity and 186 MW of gas turbine capacity. Using the ratio of these capacities yields a MW-weighted net capacity factor of 0.85 for use on all LFGE projects that generate electricity. This average net capacity factor would be used to calculate the net amount of conventional electricity generation that is displaced by the LFGE project and the corresponding power plant emissions that are avoided. Based on the data presented above, LMOP agreed that 0.85 is a reasonable capacity factor to be used for determining avoided emission reductions from electricity-generating projects.

- ***Electricity carbon dioxide emission factor***. LMOP has been directed to use a $CO_2$ emission factor of 1.46 lbs/kWh to determine avoided emission reductions from LFGE electricity projects for 2002. Likewise, a $CO_2$ emission factor of 1.55 lbs/kWh is to be used for 2001 reduction estimates. These emission factor values originated from a memo[5] distributed to EPA's Air Pollution Prevention Division. The memo provides a $CO_2$ emission factor of 1.64 lbs/kWh for year 2000 and a factor of 1.20 lbs/kWh for year 2005. The $CO_2$ emission factors of 1.46 lbs/kWh for 2002 and 1.55 lbs/kWh for 2001 were developed by taking the difference between factors for years 2000 and 2005 and distributing the difference over 5 years.

Although the electricity $CO_2$ emission factors presented above are to be used for determining avoided emission reductions from LFGE electricity projects in the LMOP Landfill/Project database, we suggest continuing to use state-specific electricity emission factors for non-database emission reductions (e.g., feasibility studies, individual data requests, etc.). Currently, state-specific factors are used by ERG and

SCS in site-specific feasibility studies. Using a power plant carbon dioxide emission factor specific to the state where the electricity-generating project resides will help account for the varying fossil fuel mix between states, which leads to varying carbon dioxide emissions. In addition, EIA's *Instructions for Voluntary Reporting of Greenhouse Gases*[4] recommends the use of state-specific rather than national factors. We recommend implementing these state-specific emission factors using state-level output rates from EPA's *E-GRID2000*[6] for the most recent year data are available (1998 at present).

- ***Simplified equation factor comparison***. Table 4 shows the simplified equation factors, in terms of both $MMTCO_2E$/MW-yr and MMTCE/MW-yr, for avoided emission reductions from electricity-generating projects using ICF's equation and the draft revised equation. The equation factors are representative of the simplified equations as "generating capacity (MW) * equation factor = $MMTCO_2E$/yr for carbon dioxide equivalents or MMTCE/yr for carbon equivalents."

**Table 4. Comparison of Equation Results for Avoided Emission Reductions from Electricity-Generating Projects**

| Equation Source | Simplified Equation Factors | | Results for 5 MW Capacity LFGE Project | |
|---|---|---|---|---|
| | $MMTCO_2E$/MW-yr | MMTCE/MW-yr | $MMTCO_2E$/yr | MMTCE/yr |
| ICF | 0.0055 | 0.0015 | 0.0275 | 0.0075 |
| Draft Revision | 0.0049 | 0.0013 | 0.0245 | 0.0065 |
| **Difference between ICF and revised equation results for 5 MW capacity LFGE project:** | | | 11% lower | |

## 2.3 Direct Emission Reductions from Direct-Use Projects

ICF/SCS Equation:

**LFG collected (mmscf/day)** * 365 days/yr * $10^6$ cf/mmscf * 0.5 cf $CH_4$/cf LFG [$CH_4$-to-LFG ratio] * 0.0423 lbs $CH_4$/cf $CH_4$ * short ton/2,000 lbs * 0.9072 MT/short ton * MMT/$10^6$ MT *

21 [GWP of $CH_4$] = $MMTCO_2E$/yr

Draft Revised Equation:

**LFG utilized (mmscf/day)** * 365 days/yr * $10^6$ cf/mmscf * 0.5 cf $CH_4$/cf LFG [$CH_4$-to-LFG ratio] * 0.0423 lbs $CH_4$/cf $CH_4$ * short ton/2,000 lbs * 0.9072 MT/short ton * MMT/$10^6$ MT * 21 [GWP of $CH_4$] = $MMTCO_2E$/yr

- ***LFG collected vs. LFG utilized***. The draft revised equation for direct emission reductions from direct-use projects is identical to the current equation. We want to point out, however, that the LFG flow rate from which these direct emission reductions are calculated should represent the amount of LFG utilized by the LFGE project, not the amount of LFG collected at the landfill. It is common for the landfill to collect more gas than is utilized by a direct-use boiler, and to flare the excess. We believe the LMOP Landfill/Project database typically contains the flow rate to the utilization project rather than the total gas collected at the landfill. In cases where the amount of LFG utilized by the LFGE project is unavailable, then the amount of LFG collected can serve as a reasonable estimate for LFG utilized. [Note: Consideration of flared emissions is a separate issue currently under discussion by LMOP.]

- ***Simplified equation factors***. The resulting simplified equations, in terms of both $MMTCO_2E$/yr and MMTCE/yr, for direct emission reductions from direct-use projects are:
  LFG utilized (mmscf/day) * 0.0735 = $MMTCO_2E$/yr for carbon dioxide equivalents, or
  LFG utilized (mmscf/day) * 0.0201 = MMTCE/yr for carbon equivalents.
  [Note: The MMTCE/yr equation above matches the calculation currently used to determine emission reductions in the LMOP Landfill/Project database.]

### 2.4 Avoided Emission Reductions from Direct-Use Projects

ICF/SCS Equation:

**LFG collected (mmscf/day)** * 365 days/yr * $10^6$ cf/mmscf * 0.5 cf $CH_4$/cf LFG [$CH_4$-to-LFG ratio] * **0.12059 lbs $CO_2$/cf $CH_4$ [direct-use $CO_2$ emission factor]** * short ton/2,000 lbs * 0.9072 MT/short ton * MMT/$10^6$ MT = $MMTCO_2E$/yr

- ***SCS equation difference***. The direct-use carbon dioxide emission factor used by SCS for the LMOP Landfill/Project database is different from the emission factor in ICF's equation. SCS uses an equivalent of 0.116 lbs $CO_2$/cf $CH_4$, as compared to ICF's factor of 0.12059 lbs $CO_2$/cf $CH_4$. The equivalent factor in SCS' equation is derived from a mass balance approach where it is assumed that all of the carbon contained in the methane will be converted to carbon dioxide once it is combusted (i.e., 21.12 tons $CH_4$/mmcf $CH_4$ * 44 tons $CO_2$/16 tons $CH_4$ * 2,000 lbs/ton * mmcf/$10^6$ cf = 0.116 lbs $CO_2$/cf $CH_4$).

<u>Draft Revised Equation:</u>

**LFG utilized (mmscf/day)** * 365 days/yr * $10^6$ cf/mmscf * 0.5 cf $CH_4$/cf LFG [$CH_4$-to-LFG ratio] * **1,012 Btu/cf $CH_4$ [methane heating value] * cf natural gas/1,050 Btu [natural gas heating value] * 0.12059 lbs $CO_2$/cf natural gas [direct-use $CO_2$ emission factor]** * short ton/2,000 lbs * 0.9072 MT/short ton * MMT/$10^6$ MT = MMT$CO_2$E/yr

- ***Direct-use carbon dioxide emission factor***. The equation used by SCS and ICF uses an emission factor of 0.12059 lbs $CO_2$/cf $CH_4$, which is provided as a natural gas emission factor in Appendix B of EIA's *Instructions for FORM EIA-1605: Voluntary Reporting of Greenhouse Gases*[4]. An ICF memo[7] dated May 18, 1999 had cited this emission factor from the 1998 version of these instructions. This natural gas emission factor is also used in the most current version (2002), which shows that this emission factor has not changed since 1998 and remains to be the suggested value for commercial natural gas. Therefore, LMOP would like to continue using a $CO_2$ emission factor of 0.12059 lbs/cf natural gas for avoided emission reductions from direct-use projects.

  In calculating the emissions avoided through the direct-use of LFG, we assume that the biogenic methane used by the LFGE project is displacing the fossil-derived natural gas on a one-to-one heating value basis. The great majority of direct-use projects displace natural gas. This is a conservative assumption because displacing the LFG with another type of fossil fuel, such as coal, oil, or LPG, would result in higher avoided emission reductions since these fuels have higher carbon contents than natural gas. Since we are assuming a Btu of LFG replaces a Btu of natural gas, we suggest using a ratio of heating values for LFG and natural gas to correctly convert from LFG utilized to natural gas avoided. As shown in the revised equation above, combining the assumption that LFG contains approximately 50% methane, by volume, with the revised methane heating value of 1,012 Btu/cf $CH_4$ results in a LFG heating value of 506 Btu/cf LFG. This LFG heating value is then divided by the heating value of natural gas (1,050 Btu/cf) to result in the cubic feet of natural gas displaced by the LFG. LMOP agrees with this calculation method for determining avoided emission reductions from direct-use projects.

- ***LFG collected vs. LFG utilized***. We want to point out that the LFG flow rate from which these avoided emission reductions are calculated should represent the amount of LFG utilized by the LFGE project, as discussed in Section 2.3.

- ***Simplified equation factor comparison***. Table 5 shows the simplified equation factors, in terms of both $MMTCO_2E$/mmscfd-yr and MMTCE/mmscfd-yr, for avoided emission reductions from direct-use projects using ICF's equation and the possible revision (which is the same as SCS' equation). The equation factors are representative of the simplified equations as "LFG utilized (mmscf/day) * equation factor = $MMTCO_2E$/yr for carbon dioxide equivalents or MMTCE/yr for carbon equivalents." For comparison, Table 5 also shows the results of using these equation factors to calculate avoided emission reductions for a LFGE project utilizing 2 mmscf/day of LFG. The equation factor represented by the ICF equation is currently used to determine emission reductions in the LMOP Landfill/Project database.

**Table 5. Comparison of Equation Results for Avoided Emission Reductions from Direct-Use Projects**

| Equation Source | Simplified Equation Factors | | Results for a LFGE Project Utilizing 2 mmscf LFG/day | |
|---|---|---|---|---|
| | $MMTCO_2E$/mmscfd-yr | MMTCE/mmscfd-yr | $MMTCO_2E$/yr | MMTCE/yr |
| ICF | 0.0100 | 0.0027 | 0.0200 | 0.0054 |
| Draft Revision (matches SCS equation) | 0.0096 | 0.0026 | 0.0192 | 0.0052 |
| **Difference between ICF and revised equation (SCS equation) results for a LFGE project utilizing 2 mmscf LFG/day:** | | | 4% lower | |

## 3.0 ESTIMATING GENERATING CAPACITY AND LFG UTILIZED FROM WIP

Currently, the LMOP Landfill/Project database calculates emission reductions using generating capacity (MW) for electricity-generating projects and LFG utilized (mmscf/day) for direct-use projects. If these data are not available in the database, then a default factor of 300 cfm LFG/million tons waste-in-place (WIP) is used to estimate the amount of LFG utilized, which in turn allows the estimation of generating capacity. According to Mr. Paleyanda's e-mail dated November 21, 2002 (attached in Appendix C), this default factor was based primarily on SCS' experience with landfill projects, and was confirmed as a conservative estimate using E-PLUS for a 10-year old landfill. In addition, Appendix D contains a September 3, 2002 memo from SCS to EPA that provides further explanation of the methodology used to generate the default factor of 300 cfm LFG/million tons WIP. Tom Bilgri, Director of EMCON/OWT's LFG Design Center, agreed that this default factor is commonly used in the LFG industry to provide rough estimates of LFG flow rates. Sections 3.1 and 3.2 demonstrate how this default factor is used in the LMOP Landfill/Project database to estimate generating capacity or LFG utilized when these data are unknown. The bolded terms in the equations highlight the differing factors that will be discussed in the bullets following the equations. It is important to note that these equations assume that all of the LFG collected would be utilized in the LFGE project.

### 3.1 Estimating Generating Capacity (MW) for Electricity-Generating Projects

SCS Equation:

300 cfm LFG/$10^6$ tons WIP * **500 Btu/cf LFG** * 60 min/hr * **kWh/10,000 Btu [default heat rate]** * MW/1,000 kW = 0.9 MW/$10^6$ tons WIP,

which equates to: generating capacity (MW) = 0.9 * million tons WIP

Draft Revised Equation:

300 cfm LFG/$10^6$ tons WIP * **0.5 cf $CH_4$/cf LFG [$CH_4$-to-LFG ratio]** *

**1,012 Btu/cf $CH_4$ [methane heating value]** * 60 min/hr * **kWh/11,700 Btu [default heat rate]** * MW/1,000 kW = 0.778 MW/$10^6$ tons WIP,

which equates to: generating capacity (MW) = 0.778 * million tons WIP

- ***Methane heating value***. As described in Section 2.1, LMOP recommends using a methane heating value of 1,012 Btu/cf $CH_4$, as suggested by ICF. Multiplying this heating value by the assumption that 50% of LFG is methane, by volume, results in a LFG heating value of 506 Btu/cf, which is slightly higher than the 500 Btu/cf LFG used in SCS' equation.

- ***Default heat rate***. As discussed in detail in Section 2.1, LMOP recommends using a default heat rate of 11,700 Btu/kWh, in place of the heat rate of 10,000 Btu/kWh used in SCS' equation above.

- ***Simplified equation factor comparison***. Table 6 shows the simplified equation factors, in terms of MW capacity/million tons WIP, for estimating generating capacity for electricity-generating projects using the SCS equation and the draft revised equation. The equation factors are representative of the simplified equations as "generating capacity (MW) = equation factor * million tons WIP." For comparison, Table 6 also shows the results of using these equation factors to estimate generating capacity for a LFGE project at a landfill with 5 million tons WIP. The equation factor represented by the SCS equation is currently used to estimate MW capacity for electricity-generating projects in the LMOP Landfill/Project database.

**Table 6. Comparison of Equation Results for Estimating Generating Capacity for Electricity-Generating Projects**

| Equation Source | Simplified Equation Factors (MW capacity/million tons WIP) | MW Capacity for LFGE Project at Landfill With 5 Million Tons WIP |
|---|---|---|
| SCS | 0.900 | 4.500 |
| Draft Revision | 0.778 | 3.890 |
| **Difference between SCS and revised equation results for LFGE project at landfill with 5 million tons WIP:** | | 14% lower |

### 3.2 Estimating LFG Utilized (mmscf/day) for Direct-Use Projects

SCS Equation:

300 cfm LFG/$10^6$ tons WIP * 1,440 min/day * mmscf/$10^6$ cf = 0.432 mmscfd/$10^6$ tons WIP,

which equates to: LFG utilized (mmscf/day) = 0.432 * million tons WIP

- There is no suggested revision for the SCS equation above. Therefore, this equation is considered the final equation to be used for estimating LFG utilized for direct-use projects.

## 4.0 REFERENCES


1. Memorandum from Diana Pape, ICF Consulting, to Brian Guzzone, U.S. EPA, entitled *Methodology for Tracking LMOP Accomplishments in STAR Data Base System*. November 30, 2001.

2. *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook*. U.S. Environmental Protection Agency, Landfill Methane Outreach Program. EPA-430-B-96-0004. September 1996. Part I, Page 3-15. http://www.epa.gov/lmop/products/products.htm#1.

3. *Chemical Engineers' Handbook*. John H. Perry, ed. McGraw-Hill Book Company: New York, 1963. Page 9-9.

4. *Instructions for Form EIA-1605, Voluntary Reporting of Greenhouse Gases, For Data Through 2001*. U.S. Department of Energy, Energy Information Administration. February 2002. Page 16 and Appendix B. http://www.eia.doe.gov/oiaf/1605/forms.html.

5. Memorandum from Jeremy Symons, U.S. EPA, to U.S. EPA/APPD, entitled *Emission Factors*. November 16, 1998.

*6. Emissions & Generation Resource Integrated Database, E-GRID2000 (Version 2.0)*. U.S. Environmental Protection Agency, Acid Rain Program. September 2001. http://www.epa.gov/airmarkets/egrid/index.html.

7. Memorandum from ICF Consulting, to U.S. EPA/LMOP, entitled *Emission Factors, Global Warming Potentials, Unit Conversion, Emissions, and Related Facts*. May 18, 1999.