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Empirical Method for Calculating Methane Emissions from Time-Variable Arisings of Solid Waste in Landfill Sites

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ABSTRACT

An empirical method is developed that enables the equilibrium method for the calculation of methane emissions to be extended to take account of variations in the waste stream sent to a site. This method is a useful alternative to the complex exponential decay model because it provides a means to calculate trends in methane emissions from landfill sites when accurate values for all of the input parameters are not available.

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by

M J T Milton

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) provides guidelines [1] to assist countries in the process of calculating annual emissions of greenhouse gases required to fulfil their obligations under the Framework Convention on Climate Change (FCCC).

The calculation of methane emissions from the anaerobic decay of organic matter in solid waste sites presents particular problems because it accounts for between 5 and 20% of all methane emissions globally, yet cannot be estimated accurately because of the lack of robust information about both the amount of waste sent to solid waste sites and the details of the decay process [2, 3].

2. IPCC TIER 1 AND TIER 2 METHODS

The current IPCC guidelines [1] provide a choice of two methods for calculating methane emissions from solid waste. The Tier 1 method is based on the assumption that if the amount of waste sent to a site remains constant, then after a sufficiently long period, the rate of methane emission will reach equilibrium at a value Q given by:

$$Q = L_o R \qquad (1)$$

where L_0 is the specific methane potential of the waste and R is the mass of waste placed in the site per year.

It is clear that this equilibrium approach has limitations if:

- the mass of waste placed in the site varies from year to year;
- the calculation is used to estimate emissions shortly after the site has opened or closed;
- conditions in the site vary;
- the methane potential of the waste placed in the site varies from year to year.

The Tier 2 methodology was introduced by the IPCC in 1996 to overcome these limitations and is applicable when data on the time variation of waste arising is available. This approach assumes that the rate of generation of methane by anaerobic decay varies exponentially. Hence, the amount of methane generated in year T by the decay of waste placed in the site in year t is:

$$q_{T,t} = kR_t L_o e^{-k(T-t)} \qquad (2)$$

where:

R_t = amount of waste placed in the site in year *t*
L_o = specific methane potential of the waste
k = decay constant for the process.

The Tier 2 methodology has some disadvantages, primarily associated with the requirement for valid estimates for R_t and k as a function of time. If such data is not available, then there may not be any significant benefit in choosing the Tier 2 methodology.

Equation (2) in the form presented here is correctly normalised so that the total amount of methane generated during the complete decay process from waste placed in landfill in year *t* is:

$$Q_t = \int_t^\infty q_{T,t} dT = R_t L_o k \left[\frac{-e^{-k(T-t)}}{k} \right]_t^\infty = R_t L_o \quad (3)$$

The Tier 2 method is usually implemented by evaluating (2) for values of *T* and *t* spaced at one year intervals. When this is the case, equation (2) must be normalised so that the infinite summation yields the correct value $R_t L_o$. If *A* is the constant required to normalise (2) in this case then:

$$Q_t = A \sum_{T=t}^{\infty} q_{T,t} = A R_t L_o k \sum_{T=t}^{\infty} e^{-k(T-t)} = A R_t L_o k [1 + e^{-k} + e^{-2k} + e^{-3k} ....] \quad (4)$$

Applying the standard formula for the sum of a geometric series, we find that the value of *A* required to normalise Q_t to $R_t L_o$ is:

$$A = \frac{1 - e^{-k}}{k} \quad (5)$$

Figure 1 shows an example of the emission of methane in successive years from a constant waste arising between 1980 and 2000. Figure 2 shows the reduction in emissions achieved by decreasing the waste sent to landfill by 4% each year. Both Figures assume a decay constant of 15 years and a specific methane emission potential normalised so that the waste sent to site in 1960 emits 10 units of methane in the first year.

Figure 1 : Total Methane Emission each year for constant waste arising each year from *1980 to 2000*

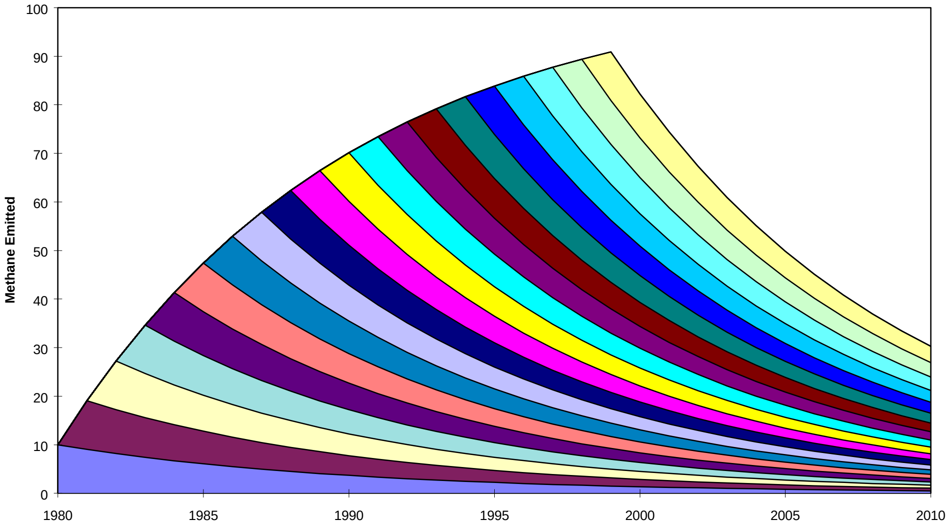
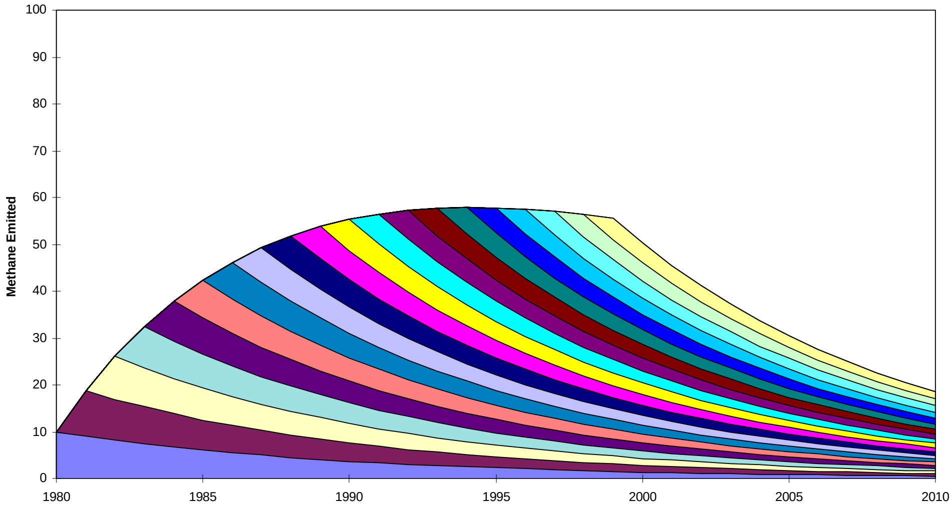


Figure 2 : Total Methane Emission each year for 4% decrease in waste arising each year from *1980 to 2000*



3. RECONCILIATION OF THE TIER 1 AND 2 METHODS

It is possible to demonstrate the mutual consistency of the Tier 1 and Tier 2 methods by applying equation (2) to the case of constant waste input. If R_t remains constant, then the amount of methane generated in year T is given by:

$$Q_T = \int_{-\infty}^{T} q_{T,t}\,dt = RL_o k \int_{-\infty}^{T} e^{-k(T-t)}\,dt = RL_o \left[e^{-k(T-t)} \right]_{-\infty}^{T} = RL_o \qquad (6)$$

Hence the Tier 2 methodology yields the Tier 1 result in the equilibrium condition.

4. SITES OPENING AND CLOSING

The Tier 2 methodology can be used to calculate the amount of methane generated at time T from a site that opened at $T\text{-}c_1$ and closed at $T\text{-}c_2$.

$$Q_T = \int_{T-c_1}^{T-c_2} q_{T,t}\,dt = RL_o k \int_{T-c_1}^{T-c_2} e^{-k(T-t)}\,dt = RL_o \left[e^{-kc_2} - e^{-kc_1} \right] \qquad (7)$$

5. APPLICATION OF TIER 2 IN THE UK

A number of studies have applied the Tier 2 methodology to the UK. In 1996 a study [3] divided UK landfills into two types in order to apply the Tier 2 methodology to each type separately. Subsequent direct measurements of methane fluxes [4] indicated that UK sites could be stratified into four different categories. The application of the Tier 2 methodology [5] to these four categories gives a result within 5% of the measured value.

The experience gained in the UK indicates that improvements in emission estimates are achieved through a combination of:

- direct flux measurements using a combination of different methods [6], and
- stratification of sites within a country according to characteristics that influence their methane emissions.

6. QUASI-EQUILIBRIUM METHOD

As described above, if R_t is not constant as a function of time, then the Tier 1 methodology may be inaccurate. However, if there is insufficient information about the time series of R_t, the complexity of the Tier 2 methodology may not be justified. In this case, an empirical extension to the Tier 1 methodology may be a useful alternative.

Suppose R increases linearly, so that R_t is given by:

$$R_t = R_B[1 + r(t - T_B)] \qquad (8)$$

where R_B is the mass of waste placed in the site in the "base year" T_B and r is the fractional increase each year. Since equation (8) describes a linear increase, it presumes that the site could not have been in operation before a time t_i given by:

$$t_i = T_B - 1/r \tag{9}$$

The amount of methane generated in any year *T* can then be calculated by substituting (8) into (2) and integrating to give:

$$Q_T = \int_{-\infty}^{T} Q_{T,t} dt = R_B L_o k \int_{-\infty}^{T} [1 - rT_B + rt] e^{-k(T-t)} dt \tag{10}$$

Thus if the site opened in year T_o:

$$Q_T / R_B L_o = k \int_{T_o}^{T} [1 - rT_B + rt] e^{-k(T-t)} dt$$

$$= [1 - r(T_B - T) - r/k](1 - e^{-k(T-T_o)}) + r(T - T_o) e^{-k(T-T_o)} \tag{11}$$

In the base year, T_B, the amount of methane generated is:

$$Q_{TB} / R_B L_o = [1 - r/k] \ (1 - e^{-k(T-T_o)}) + r(T_B - T_o) e^{-k(T_B - T_o)} \tag{12}$$

It can also be seen that in the case where the Tier 2 methodology is valid, and waste arisings follow the linear relationship of equation (8), equations (11) and (12) are exact.

7. EVALUATING TRENDS

An important application of emission inventory data is to evaluate the trend in emissions which is usually expressed in fractional form as:

$$\rho = \frac{Q_T - Q_{TB}}{Q_T} = 1 - \frac{Q_{TB}}{Q_T} \tag{13}$$

Substituting (11) and (12) into (13) shows that the value of ρ is independent of both R_B and L_o. Hence, the trend ρ can be calculated from knowledge of the rate of change of waste arisings *r* without any information about the absolute value of the arisings in the base year (R_B) or the methane potential of the waste (L_o). This is the basis of the quasi-equilibrium method proposed here.

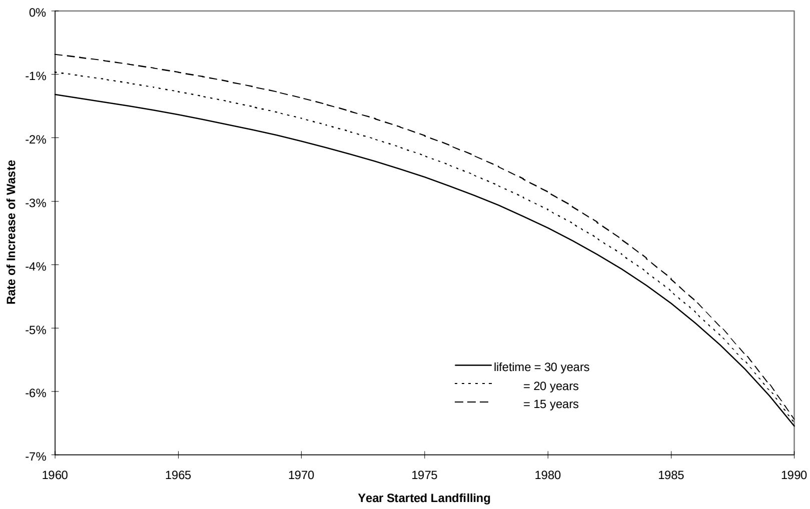
A particular condition imposed on some emissions is that they should not increase over a stated time period. The condition for the fractional trend ρ to be zero can be found by setting $Q_T = Q_{TB}$ which results in the equation:

$$1 = \left[\frac{T_R - T_K}{T - T_B} + 1 \right] e^{kTo} \left[e^{-kT} - e^{-kT_B} \right]$$

$$= \left[\frac{T_R - T_K}{T - T_B} + 1 \right] e^{-k(T-T_o)} \left[1 - e^{-k(T_B - T)} \right] \tag{14}$$

where $T_R = 1/r_o$
r_o = rate of growth of waste required to meet the condition $Q_T = Q_{TB}$
$T_k = 1/k$

Equation (14) can be re-arranged to calculate the rate of growth (r_o) required to meet the criterion of no increase in emissions between T_B and T. Figure 3 gives an example of the rate of decrease in landfilling for sites opened between 1960 and 1990, required to meet the criterion of no growth in emissions between 1980 and 2010. The values for the waste decay constant of 30, 20 and 15 years are shown.



8. UNCERTAINTY IN AN ESTIMATED TREND

If the trend ρ is calculated from the estimated emissions Q_T and Q_{TB} (equation (13)), then we calculate the uncertainty in the trend following the standard methodology advocated by ISO [7]:

$$u(\rho)^2 = (1-\rho)^2 \left[\frac{u(Q_{TB})^2}{{Q_{TB}}^2} + \frac{u(Q_T)^2}{{Q_T}^2} + \frac{Q_T}{Q_{TB}} \cdot \text{cov} \right] \tag{15}$$

where $u(\rho)$ = uncertainty in ρ
$u(Q_T)$ = uncertainty in Q_T
$u(Q_{TB})$ = uncertainty in Q_{TB}
cov = covariance Q_T and Q_{TB}

9. CONCLUSION

A methodology has been developed that enables a correction to be made to the straightforward equilibrium method to allow for variations in the rate of waste input. This method is particularly useful when the accurate data required to apply the full Tier 2 methodology is not available. It is directly applicable to the calculation of trends in methane generation relative to a specified base year. Since it only requires information about the year in which waste was first sent to landfill, the rate of change of waste arisings and the decay constant, it is well suited to use as a policy tool in the planning of landfill emissions.

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Figures in Quasi Equilibrium notebook.xls